

From food waste to transport biomethane, a
comprehensive scenario-based waste to energy
conversion pathway trade-off and whole systems
modelling analysis

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Abstract

This thesis outlines the design of a novel methodological, Excel modelling and integrated whole systems analysis approach for elucidating key material, energy and financial cost-benefit trade-off arising from deployment of Food Waste (FW) to Transport Biomethane conversion (FWtTBC) pathway across the Northern Powerhouse (NPH) city and metropolitan county regions and more specifically across Leeds city region which embodies a more in-depth case study analysis. To this end, the research established that real-world representative values for household FW collection and FW to biomethane conversion potential (45-90m³) to be sufficient across NPH city and metropolitan county regions to be financially self-sufficient for FWtTBC pathway deployment attributed to key revenue streams against deployment cost.

Here the case specific scenario study of FWtTBC pathway deployment at NPH Leeds city region using Malting Organics Treatment Facility demonstrated that there exists sufficient AD food waste capacity (50,000 tonnes) to accommodate FW collected from the entire population of Leeds city. Assessment of total revenue against cost of FWtTBC pathway deployment has returned a decent payback period of 2 to 10 years under realistic real world operational conditions, whilst also having outlined the significant revenue contribution derived from RTFO and avoided FW landfill tax. It is consequently advised for such policies to remain in place for the foreseeable future.

Moreover, the research established a number of policy recommendations across each relevant chapters that is thought to be effective in mitigation key risk factors that could undermine successful pathway deployment either financially or operationally. Namely these include policy recommendations to optimize household FW disposal and capture rate, FW supply flexibility and FW collection logistics in addition to those that endeavour to safeguard RTFO, biomethane sales and avoided FW landfill tax revenues.

Future research will should focus on using real-world operational data availability pertaining specifically to FWtTBC pathway deployment across a single or select few regions, which would enable the adopted modelling approach to achieve much greater specificity and accuracy in its intended findings and outcomes. It is hoped for findings of this and future similar research to be used to support real-world FWtTBC pathway deployment in key regions of need, to help facilitate the actual real-world deployment process at any suitable scale of implementation.

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Nomenclature

AW	Animal Waste
APW	Animal processing waste
AD	Anaerobic Digestion
ATF	Alternative Transport Fuels
AR	Assessment Reports
AFVs	Alternative Fuelled Vehicles
AEA	Allocated Emission Allowances
Bg	Biogas
Bm	Biomethane
BECCS	Bioenergy Energy with Carbon Capture Storage
CBM	Compressed Biomethane
C&I	Commercial and Industrial
CAEC	Chicken and Egg Conundrum
CF	Conversion Factors
CCMS	Climate Change Mitigation Strategies
CAP	Climate Action Plan
CCRT	Climate Change Roadmap Targets
CCRM	Climate Change Roadmap
CCS	Climate Change Strategy
CNG	Compressed Natural Gas
CCS	Carbon Capture Storage
CIS	Climate Investment Stimulus
CFS	Climate Funding Strategy
CSF	Common Strategic Framework
CAF	Climate Action Funding
CCA	Climate Change Act
CHP	Combined Heat and Power
CT	Collection Time
CC	Capital Cost
CD	Collection Distance
COD	Chemical Oxygen Demand
CC	Climate Change
COP	Conference of Parties
CAPEX	Capital Expenditure
DFI	Dedicated Financial Instruments
DECC	Department of Energy and Climate Change
DEC	Data Evaluation Criteria
ETS	Emission Trading System
ERDF	European Regional Development Fund
ESF	European Social Fund
EMFF	European Maritime and Fisheries Fund
EAFRD	European Agricultural Fund for Rural Development
EV	Electric Vehicles
EU-TS	EU's transport sector
ESLEM	European Strategy for Low-Emission Mobility
EFSI	European Fund for Strategic Investment
EU	European Union
EC	European Commission
EPD	Elementary Process Diagram

EC	Extremely Emission Cost
ERD	Experimental Route Determination
ECCP	European Climate Change Programme
ESIF	European Structural and Investment Fund
EBITDA	Earning before interest, taxes, depreciation, amortization
FWtTBC	Food Waste to Transport Biomethane conversion
FPD	Financial Process diagram
FWC	Food waste collection
FW	Food Waste
FMPD	Financial Metric Process Diagram
FIT	Feed In Tariffs
FE	Fuel Emission
FTIR	Fourier Transform Infrared IR
GR	Geographical Regions
GHG	Green House Gas
GLA	Greater London Area
GW	Green Waste
GTL	Global Temperature level
GSL	Global Sea Level
GL	Greater London
GR	Geographical Regions
GDS	Government Design System
GDP	Gross domestic product
HH&C	Household and Commercial
HH	Household
HET	Heat, Electricity, and Transport
HDV	Heavy Duty Vehicle
HES	High Emission Sector
HHFW	Household Food Waste
HRT	Hydraulic retention time
IPCC	International Panel on Climate Change
IR	Infrared
IRR	Internal Rate of Return
IEA	International Energy Agency
LNG	Liquid Natural Gas
LBM	Liquified biomethane
LCC	Leeds City Council
LIE	Lock-In Effect
LA	Local Authority
LC	Labour Hourly Cost Rate
LCA	Life Cycle Assessment
MFW	Mixed Food Waste
MS	Member States
MAFF	Multi-Annual Financial Framework
MFVW	Mixed Food and Vegetable Waste
MWH	Megawatt Hour
NPH	Northern Powerhouse
NG	Natural Gas
NS	Nuclear Safety
NAP	National Adaptation Programme
NIR	Near Infrared
NPV	Net Present Value
OPD	Operational Process Diagram

Obj	Objective
ONS	Office for National Statistics
OLR	On-loading rate
PPP	Public Private Partnership
PC	Postcode
QCP	Quality Control Protocol
RE	Renewable Energy
RET	Renewable Energy Technologies
RES	Renewable Energy Source
RF	Research Framework
RES	Renewable Energy Sector
RES-E	Renewable Energy Sector Electricity
RES-H	Renewable Energy Sector Heat
RES-T	Renewable Energy Sector Transport
RED	Renewable Energy Directive
RFT	Road Freight Transport
RPT	Road Passenger Transport
RTFC	Renewable transport Fuel Certificates
RHI	Renewable Heat Incentive
R&D	Research and Development
RMP	Research Methodology Process
RS	Refuel Station
RO	Route Optimization
ROI	Return on Investment
SE	Socio-Economic
SET	Strategy Energy Technology
SE	Smart Energy
ST	Sustainable Transport
SEAP	Sustainable Energy Action Plan
SCAPE	School of Chemical and Process Engineering
SCE	Stakeholder Collaborator Evaluation
SRT	Solid Retention Time
TE	Techno-Economic
TS	Transport Sector
TT1	Total end to end
TT2	Total collection Time
TR	Total Revenue
TRC	Total Revenue Cost
TEC	Total Emission Cost
TC	Total Capital
UNCED	United Nations Conference on Environment and Development
UNFCCC	UN Framework Convention on Climate Change (UNFCCC)
UCO	Unused Cooking Oil
WDF	Waste Data Flow
WRAP	Waste Resources Action Programme
WRc	Water Research Centre
WS	Whole Systems
aOPD	Advanced Operational process diagram
bOPD	Basic operational process diagram

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Chapter 1. Research Introduction

1.1 Overview

This thesis focuses specifically on modelling waste, emission pollution, and socio-economic trade-off via implementation of an AD-based food waste to biogas (Bg) & biomethane (Bm) conversion pathways (AD-FWtBCP) within the UK to help address a key pillar of UK's climate adaption or mitigation strategy for the waste, transport and energy sector. The research adopts a whole-system based approach focusing on the intersection of techno-economic and socio-economic elements in the modelling process, with results consequential to policy design, business application and stakeholder investment decision making.

The key research gap lies in addressing the fragmentation of sufficient readily available data, which can otherwise be consolidated to establish and drive useful findings and actionable decision-making process moving forward using the AD-FWtBCP pathway as a novel paradigm that is highly applicable across other critical industries where similar trends arise.

To this end an evidence based whole-systems based scientific approach will be adopted by combining relevant data to attain applicable and actionable findings in form of cross-benefit trade-off arising from policy and business investment recommendations whose implementation will yield highly scalable socio-economic (SE) and techno-economic (TE) benefits across governmental, industry (business) and (public) individual stakeholders.

It is worth noting that the broader research relevance of this thesis towards climate change and its key scientific contribution arises not from the findings, but rather the innovative design of a novel whole-system based methodology designed to be both geographical scalable and cross-applicable to other industries to determine a unique set (SE & TE) of cost benefits trade-offs arising from the implementation of various critical waste-to-energy conversion pathways (WtECP) using food waste to biomethane conversion pathway (FWtBCP) as a paradigm example.

The greater contribution of this research is thus for adoption of a unique whole-system based approach to inspire and enable future similar research across other critical WtECP of interest and concern to support UK's current efforts towards climate change mitigation.

1.1.1 Thesis research theme and prevailing developments

The research theme is set within the context of climate change alongside changing global dynamics including COVID and Brexit that constitutes complex interconnected system-level challenges whose effective solution would benefit strongly from adoption of a whole-system based approach. Central to these challenges includes enabling sector-wide emission decarbonisation and waste reduction in a manner that promotes techno-economic transition and socio-economic protection with most research to-date only focus on each individual area but not the integral whole.

Relevant historical and prevailing developments surrounding industry development, scientific consensus and mitigation strategies in counter-measure to climate change at the UK and EU level are consequently outlined for adding sufficient context to the current research. With all

focus entailing an overall significant time bound emission reduction across all sectors, and more notably so from high emission sections, developments in policy, legislation, technology alongside social-economic indicators which collectively affected change across the UK overall emission and decarbonisation efforts to-date are consequently paramount to enable change.

1.1.2 Research challenge and Context

Here decarbonisation across heat, electricity and transport (HET) sector presents the greatest challenges and opportunities for the UK to meet its ambitious short to long-term climate change emission reduction targets. More specifically, these targets stipulate an emission reduction of 51%, 78% and 80% (relative to 1990 levels) respectively by 2025, 2035 and 2050, which given progress to-date, indicate urgent need for deployment of more aggressive policies and measures.

Consequently, any strategic investment and technology deployment made across these 3 high priority sectors (relative to other sectors) will likely yield the greatest benefit in form of emission reduction, financial returns and other positive socio-economic impacts. Such benefits can be further amplified through R&D alongside investment in innovative waste to energy conversion solutions and technologies, which constitutes a highly desirable area of innovation and deployment to assist UK's decarbonisation efforts given their high cost-effectiveness and added benefits of simultaneous waste reduction. It is hoped for such deployments to also drive notable socio-economic and technology transition benefits to simultaneously address socio-economic challenges brought about by Brexit (price inflation) and COVID-19 (income disparity and population health).

In light of above, UK's technology transition roadmap must thus enable deployment of novel RET with greater emission and waste reduction potential in a manner that seeks to equitably distribute any consequential improvements in the socio-economic wealth of society. This being especially important to address increasing socio-economic poverties arising from Brexit and COVID-19, namely cost of living inflation and loss of sector-specific income, respectively.

1.1.3 Research gap and opportunity

To-date there still lacks sufficient integrated academic research with set aims and goals to explore critical elements surrounding cost-benefit trade-off arising from implementation of existing RET and any future RET transition pathways attributed largely to barriers in data access and lack of perceived research interest or real-world demand.

Here the Food Waste to Biogas Conversion Pathway (FWtBCP) constitute one example where there exists readily surmountable barriers of information access which if sufficiently addressed, constitutes a highly pragmatic and rewarding solution that is a universally applicable, technology ready, rapidly scalable and deployable. The pathway involves supply chain and physical deployment of food waste destined for anaerobic digestion as the primary and renewable energy source to produce either biogas for heat and electricity generation for household or industrial application or biomethane as transport fuel for heavy-duty vehicles.

With tangible benefits being significant, the barrier (of information access) readily surmountable and integrated research sufficiently lacking, this thesis will thus focus on elucidating key cost-benefit trade-off arising from implementation of the FWtBCP to drive real-world deployment by adopting a novel whole-system based interdisciplinary modelling approach.

1.1.4 Research approach

The approach adopts an integrated analytical framework and case-study based scenario analysis using Leeds as an archetypal example, from which city and wider regional or national impacts can be estimated with sufficient confidence alongside proposal of key policy, business model and investment recommendations to help real-world stakeholders guide the FWtTBC implementation process.

These ultimately are encapsulated by key research elements, namely research background, problems and opportunity, gaps, originality and impact, challenge, boundaries and limitations to support these core research aims and objectives as elaborated below in greater detail.

1.2 Background

1.2.1 Overview

This section further elaborates on the sequence of chronological, significant events surrounding climate change (historical observations and data, international consensus, roadmaps & targets, solutions) briefly summarized in the research theme chapter above alongside the consequential relevance and significance of the proposed current research topic as outlined by this thesis.

1.2.2 Climate change data

The current research is conducted under the broader scientific context of anthropogenic climate change arising from excessive human induced Green House Gas (hereafter referred to as CO₂) emission, with observable symptoms of global warming (Cook et al., 2013), sea level rise (NASA, 2019; NOAA, 2015) and increased frequency of extreme weather events (Christidis et al., 2011; Doocy et al., 2013; NASA, 2017; NCA, 2014) becoming more destructive and evident (NASA, 2017).

This since prompted the establishment of strong scientific consensus on climate change (Anderegg et al., 2010; Doran & Zimmerman, 2009) and global governance structures centred on key international agreements (Table 1) aimed at elevating multi-national efforts towards reducing CO₂ emissions to tackle climate change (UNFCCC, 2014a, 2014d, 2014b, 2014c).

Table 1. Summary of key events in support of scientific notion and international consensus on the phenomenon of climate change to-date

<i>Historical events</i>	<i>Year</i>	<i>Purpose</i>
<i>International Panel on Climate Change (IPCC) established</i>	<i>1988</i>	<i>Serve as international scientific body to assess risks of anthropogenic climate change (UCSUSA, 2007) through its assessment reports (AR) on climate change</i>
<i>United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro (also called Rio Earth summit)</i>	<i>1992</i>	<i>Platform for members states of United Nations to collaborate internationally on development issues, led to agreements on UNFCCC which paved way for subsequent developments, i.e. Kyoto protocol and Paris agreement</i>
<i>UN Framework Convention on Climate Change (UNFCCC) Enters into force</i>	<i>1994</i>	<i>Promote international efforts to tackle climate change by stabilizing CO₂ concentrations "at level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 2014a)</i>

<i>Kyoto protocol adopted</i>	1997	<i>Ratify international commitment to combat climate change via international negotiation (UNFCCC, 2014b), and entered into force in February 16, 2005 (UNFCCC, 2014d).</i>
<i>COP21 Paris agreement established</i>	2015	<i>Ratify international commitment to combat climate change via international negotiation (EC, 2016f)</i>
<i>IPCC Assessment reports</i>	1990-present	<i>5 iterations of IPCC assessment reports (AR1-AR5), with 6th report to be completed by 2022.</i>

Source: (UNFCCC, 2014a, 2014d, 2014b, 2014c; United Nations, 2019)

1.2.3 IPCC roadmaps

A key long-term achievement of these historical developments is IPCC's assessment reports (AR), which through its 6 iterations (AR1 to AR6) to-date, established robust scientific evidence and expert opinion on the causes and effects of anthropogenic climate change, with increasing atmospheric CO₂ concentrations (aCO_{2c}) and CO₂ emissions (CO_{2e}) cited to be causally linked to current rise in global temperature trends (IPCC, 2014, 2019).

In its most recent AR (AR6), the IPCC further warned 'that unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1.5°C or even 2°C will be beyond reach', and with climate change to 'increase in all regions in the coming decades' as a direct consequence (IPCC, 2022). The urgent global imperative for accelerating renewable energy (RE) technology deployment towards accelerating sector wide decarbonisation on a local, regional and global scale.

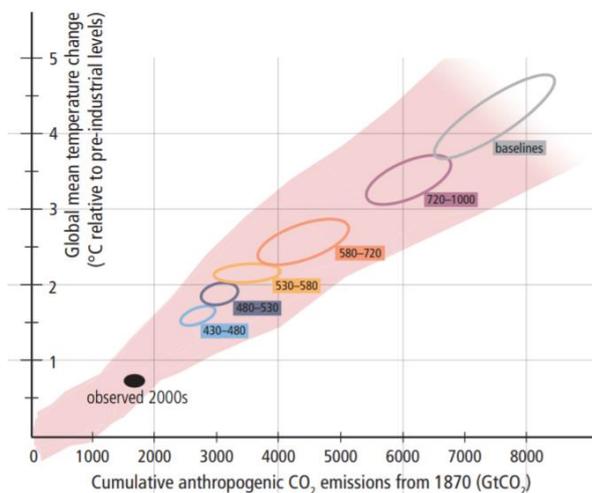


Figure 1. IPCC Scenarios predication for cumulative CO₂ emissions against global mean temperature change (IPCC, 2014)

The IPCC report findings along with other key climate change developments highlighted in Table 1 collectively prompted key emission reduction targets for major global players through key international agreements, i.e. Kyoto protocol, COP21 Paris agreement, amongst which the EU constitutes a global leader in tackling climate change through ratification of its own climate change mitigation strategies (CCMS), climate action plan (CAP), targets (CCT) and roadmap milestones (CCRM) (Figure 2).

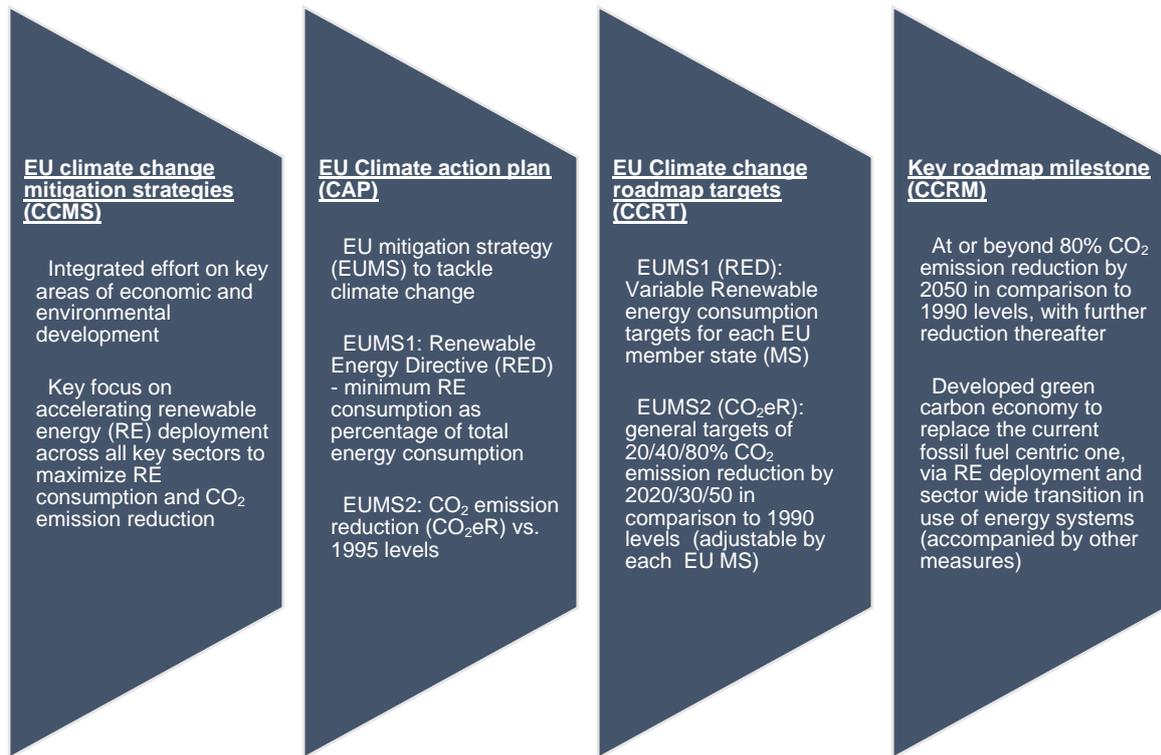


Figure 2. Summary of key EU climate change mitigation strategies (CCMS), climate action plan (CAP), targets (CCT) and roadmap milestones (CCRM) (IPCC, 2014) aimed at decarbonising its major emission sectors for tackling climate change for CO₂ emissions by sector over time as % of 1990 levels (as seen in Figure 3) (EU, 2016)

1.2.4 UK climate targets and strategies in context of EU climate action plan

A key intended roadmap milestone of these collective EU efforts would be to rapidly accelerate CO₂ emissions reduction trends for meeting an emission reduction target of 80% or greater by 2050 to avoid catastrophic consequences of climate change through legislative & regulatory enforcement alongside sector-specific policy support (Figure 3).

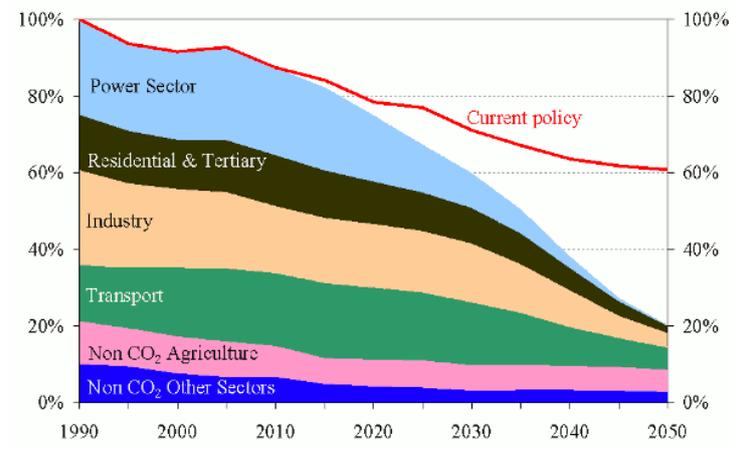


Figure 3. The transition to a low-carbon EU economy on 2050 (CO₂ emissions by sector over time as % of 1990 levels) (EU, 2016)

In honouring EU's CAP (EC, 2016d), the UK stipulated its own climate change strategy (CCS) in support of its domestic RE consumption and CO₂ emission reduction targets of 37%, 57%, 78% and 80% by 2020, 2030, 2035 and 2050 respectively.

To-date, UK's CCS has diversified investments in a wide mix of Renewable Energy Technologies (RET) and infrastructures, including solar, tidal, wind and bioenergy (Gov.uk, 2009; UK.GOV, 2017) for decarbonising emission across all sectors. Here bioenergy represents the only non-intermittent renewable energy source (RES) that can be produced on-demand to offset potential shortfalls in other RES whose energy production is highly dependent on weather and climate conditions, and consequently represents a critical field of renewable energy (RE) investment (UK.GOV, 2017). The impetus for bioenergy investment is further supported by recommendations set out by IPCC's AR5, which highlighted greatest emission savings achievable via rapid deployment of Bioenergy Energy with Carbon Capture Storage (BECCS) and reforestation (IPCC, 2014).

1.2.5 UK Transport Sector emission contribution and reduction – challenges and opportunities

One notable high emission sector which faces complex decarbonisation challenges is the UK's transport sector (Figure 4) given the current lack of mitigation strategies beyond light to medium vehicle electrification (OLEV, 2013) to offset likely emission increases arising from anticipated future increase in passenger and heavy-duty vehicle (HDV) transportation demand and activity (UK.Gov, 2019).

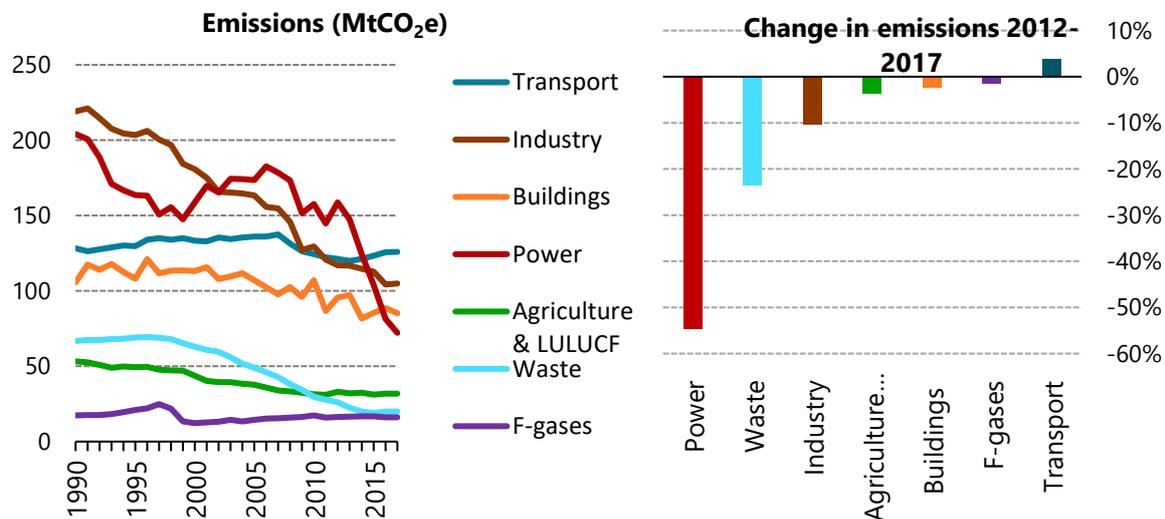


Figure 4. UK Transport sector 2012-2017 (Left) Overall emissions and (Right) Change in emissions (UK.Gov, 2019)

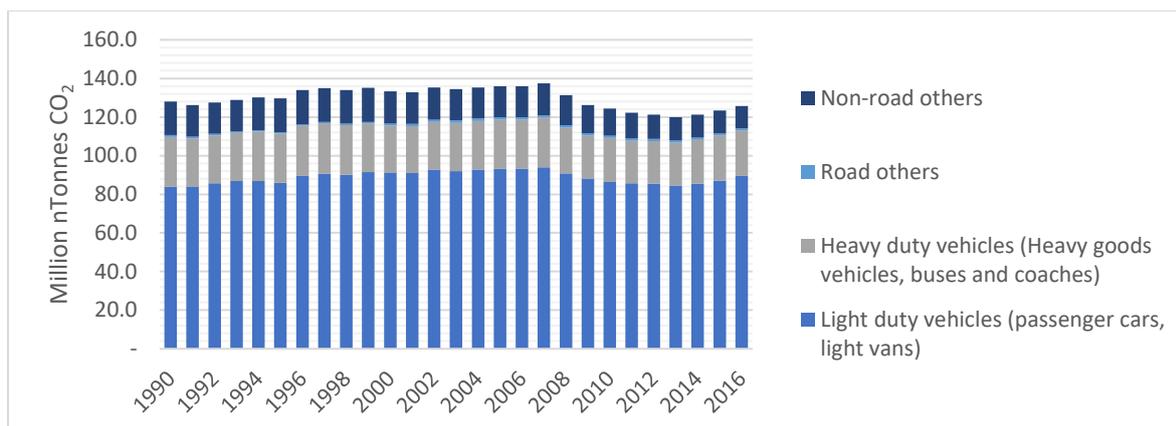


Figure 5. UK transport sector emissions by transport vehicle type (Gov.UK, 2017)

To-date, the HDVs sector constitutes UK's second largest TS CO₂ emission contributor after passenger vehicle sector emissions (Figure 5). Notable emerging opportunities for decarbonising UK's HDV sector includes partial electrification and gasification of HDV fleets, such as refuse collection vehicles (Scholfield & Carroll, 2014), buses (AirQualityNews, 2019; WYCA, 2019) and freight vehicles, with many cities currently undergoing this transition through new trial and scheme implementations (Table 2) (AirQualityNews, 2019; Scholfield & Carroll, 2014).

Table 2. Summary of emerging clean or renewable energy trial and scheme implementation for HDVs within UK cities

Fuel mix (Fuel A / Fuel B)	HDV type	HDV type (location)
50/50 Diesel/ Electric	Hybrid HDV ¹	Local Buses (Leeds) (WYCA, 2019)
50/50 Diesel /Natural Gas	NG HDV ²	Local truck fleets (Atkins-Cennex, 2015) (UK cities)
50/50 Diesel/Biomethane	BM HDV ³	Local truck fleets (UK cities) (Atkins-Cennex, 2015)
		Refuse vehicles (Leeds) (Scholfield & Carroll, 2014)
		Buses (Nottingham) (AirQualityNews, 2019)

¹Electric HDV, refers to battery powered HDV

²Natural Gas HDV, refers to either Compressed Natural Gas (CNG) or Liquid Natural Gas (LNG) HDV

³Biomethane HDV refers to either Compressed Biomethane (CBM) or Liquefied biomethane (LBM) HDV

It is anticipated for the adoption of natural gas and biomethane transport fuel to extend into the longer term, with key archetypal developments including the expansion of the northern gas network in conjunction with natural gas (NG) or biomethane (BM) refuelling stations and bus or other HDV fleets across the UK.

Such developments are also driven by a strong mix of progressive policy incentives including introduction of new Low Emission Vehicle zones, clean energy funding for low emission vehicles (WYCA, 2019) and ban on sales of new petrol or diesel vehicles by 2030 (gov.uk, 2021). To this end, one area of concern is the availability of suitable feedstocks for meeting anticipated biogas or biomethane demand, in addition to the sustainability of their production.

1.2.6 Bioenergy sources – challenges and opportunities for future developments

Presently, a high proportion of bioenergy is derived from dedicated biomass crops, whose production process is often resource intensive and expensive if economy of scale is not sufficiently achieved. Another challenge is their finite scalability especially in smaller countries such as UK with limited land that can be repurposed for bioenergy crop growth, thus necessitating the need for alternative bioenergy feedstock contribution.

To-date, anaerobic digestion of food waste constitutes the most suitable short to medium term solution for transport bioenergy production that is readily deployable in a scalable, sustainable and cost-effective manner with proven technology and sufficient baseline of existing infrastructure (food waste recycling schemes, anaerobic digestion plants) present.

This pathway for deployment, which hereafter is referred to in this thesis as Food Waste to Transport Biomethane Conversion (FWtTBC) pathway (Figure 6), is however often overlooked and/or not fully implemented to a suitable scale given real-world challenges of data availability, diminishing local council funding for trial-to-scheme implementation and consequently, lack of stakeholder confidence.

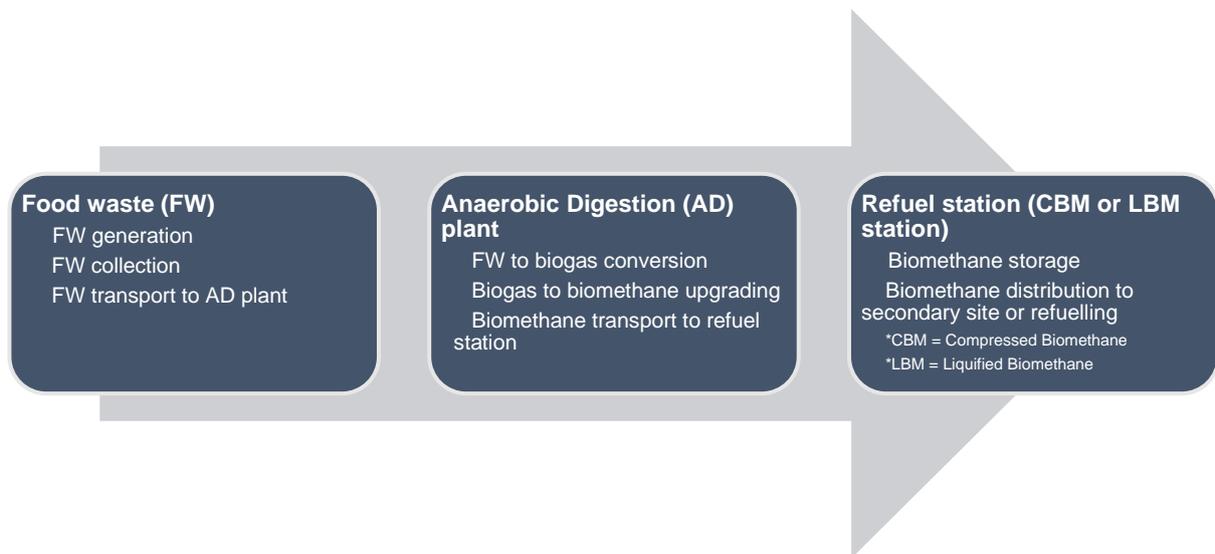


Figure 6. FWtTBC (Food Waste to Transport Biomethane Conversion) Pathway components (title in bold) and processes (underline title)

1.2.7 The Food Waste to Transport Biomethane Conversion (FWtTBC) pathway

To-date there exist extremely limited academic research exploring a whole-system cost-benefit trade-off arising from FWtTBC pathway deployment on a sufficiently adequate geographical and time scale to help derive meaningful findings informing stakeholder decision making on investment and policy. A key barrier to this arises from insufficient availability of consolidated research data and suitable methodology focusing specifically on critical elements (i.e. mass, energy, emission, economy, finance, social metrics) driving FWtTBC pathway deployment.

Present real-world deployment of FWtTBC pathway research, trials and schemes are consequently locked into stagnation by means of lock-in effect (LIE) (Figure 7) and chicken and egg conundrum (CAEC) occurring at the whole systems level, which experiences a significant degree of cross-reinforcement between lack of R&D and investment confidence affecting deployment.

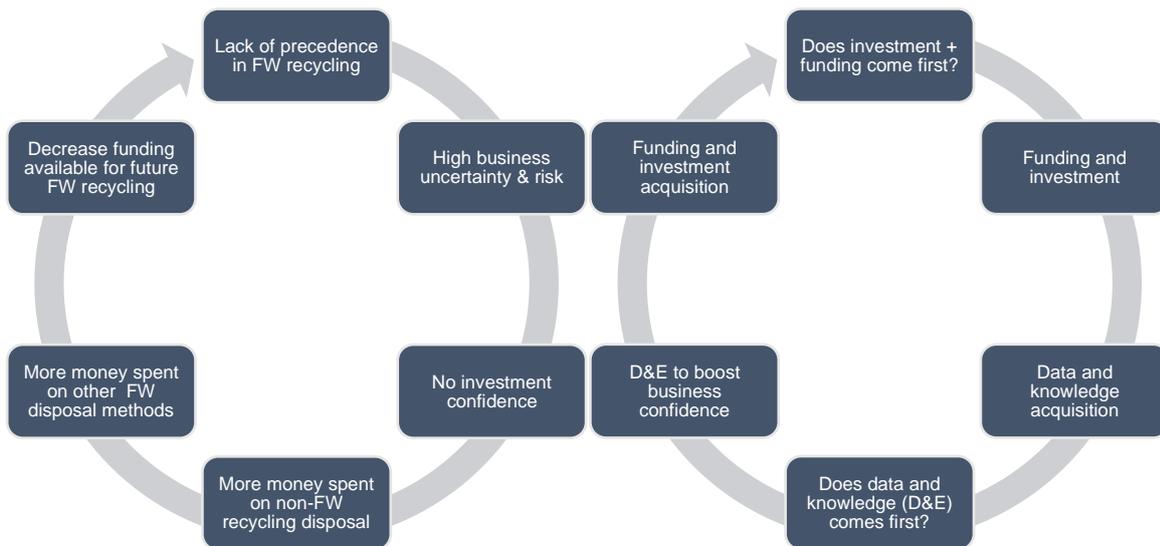


Figure 7. (Left) Lock-In Effect that reinforces the status quo of non-implementation of FWtTBC pathway trials and schemes, (Right) Chicken And Egg Conundrum (CAEC) responsible for non-implementation of FWtTBC pathway trials and schemes, with both effects hampering deployment.

To address FWtTBC pathway R&D and deployment challenges presented by the LIE and CAEC effect, a whole-system modelling approach must be developed for evaluating cost-benefit trade-off of real-world application of pathway deployment under different existing or forthcoming trials and schemes. This integrated modelling approach will form the centrepiece of this thesis, with the ultimate aim to establish tangible outcomes in form of socio-economic and environmental cost-benefits arising from FWtTBC pathway deployment, and in-so-doing inspire further academic research for applicable pathways facing similar issues of LIE and CAEC effect.

1.3 Research focus and gap

Following from the above overview and background intro, this research will thus focus specifically on designing a bespoke whole-system based modelling approach to model trade-offs between qualitative and quantitative metrics of the FWtTBC pathway (Figure 8) critical to key stakeholder decision making for driving its deployment.

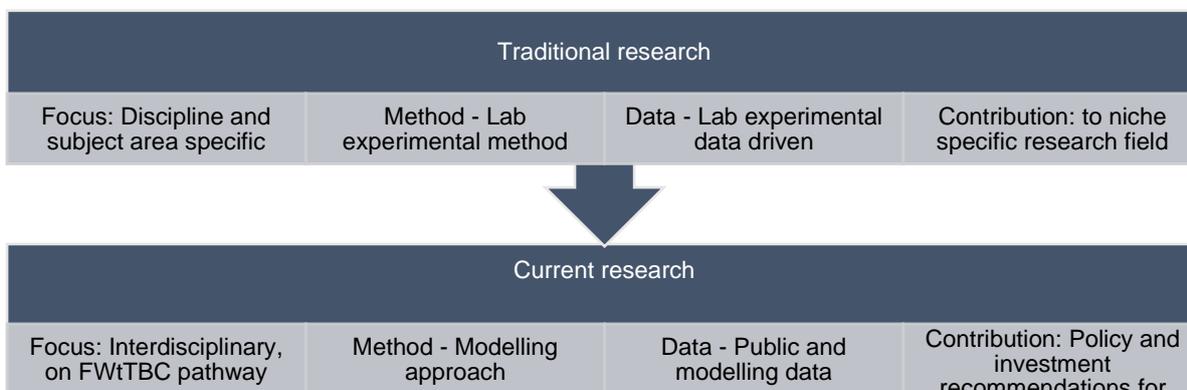


Figure 8. Research gap and opportunity - highlights in differences between traditional and current research that constitute the knowledge gap

All findings will consequently be utilized to address the critical research gap of “methodological approach and research data integration” as often found to be lacking in most traditional academic research occurring in the field of waste to energy conversion, despite their indisputable importance for overcoming real-world pathway deployment challenges (see Figure 9).

Research scope of focus	Research areas
<ul style="list-style-type: none"> • Current traditional research - each research focus individually on one bullet pointed area only or subcomponent of each such area [see right] in depth with limited focus • Integrated research - research encompass all areas (see right) with greater focus to areas of key metric input & output (i.e. FW, biogas & biomethane, emission savings, revenue derived and total capital or operational costs) across the entire pathway 	<ul style="list-style-type: none"> • (1) FW quantity and characterisation from defined outlet source • (2) FW to biogas and/or biomethane conversion yield (in lab or AD plant) • (3) Compressed or Liquified Biomethane fuel economy and/or associated costs • (4) Capital and operational costs of food waste collection trials <u>OR</u> AD plant operations <u>OR</u> refuel station

Figure 9. Research scope of focus and area

To this end, a broad array of analytical methods including whole-system based modelling and analysis of energy, emission (CO₂), financial, socio-techno-economic trade-off will be adopted to establish actionable policy incentive and investment decision making recommendations for driving FWtTBC pathway deployment, as opposed to focusing on in-depth findings in any one specific area.

The modelling process will adopt a mix of real-world case study approaches designed to specifically evaluate key trade-off in FWtTBC pathway components as mentioned above by looking at outputs at progressive geographical (i.e. localized postcode, city and regional) scales of implementation, and with results being transferrable and extrapolatable to current and any future planned FWtTBC pathway trials and schemes.

1.4 Contribution and novelty

This research endeavours to demonstrate indisputable precedence and originality through the highly interdisciplinary approach adopted, and with specific focus on a range of key metrics outputs to up to a scientifically suitable standard to ensure outcomes are adequate for driving high-level policy, investment and deployment decisions.

Further contributions attainable through downstream knock-on effects of achieving the abovementioned outcomes would also be to increase stakeholder confidence towards implementing the FWtTBC pathway to bolster UK’s FW recycling and road HDV sector decarbonisation efforts, as well as to inspire similar research adopted for implementation of other similar pathways to assist in their consequent deployment (Figure 10).

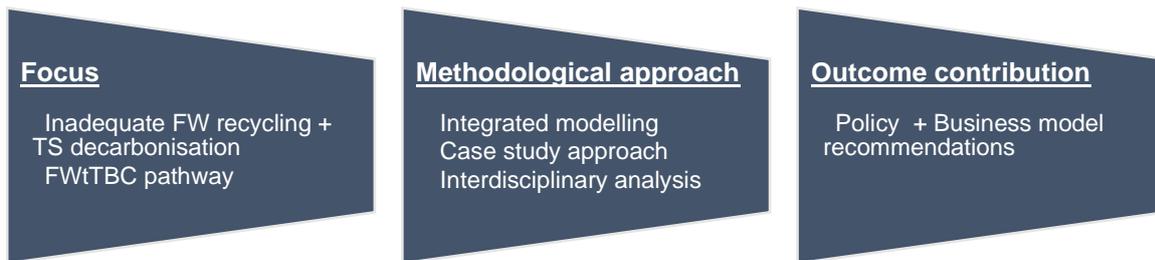


Figure 10. Summary of research focus, methodological approach and outcome contribution

In summary, the research endeavours to contribute to the the broader field of emerging interdisciplinary academic research focusing on surmounting critical real-world system level challenges commonly attributed to the CAEC and LIE effect by using the FWtTBC pathway as an archetypal example to inspire similar research adopted for deployment of other similar pathways to assist in their consequential deployment.

1.5 Research Challenges and Opportunities

Preparatory background research work has outlined the 3 key research challenges of (1) data acquisition, (2) integrated whole systems methodology design and (3) case study scenario design to establish intended range of scientifically robust outputs & findings deployable for key stakeholder (on policy, investment & pathway deployment) recommendations (see

Figure

11).



Figure 11. Research challenges overview

The research challenge on data acquisition arises predominately from prevalent fragmentation of currently available body of critical data metrics and relevant conversion factors for modelling more complex systems. A simple example entails combining data on annualized household food waste output with their biogas or biomethane yield potential alongside energy sales price and AD capital or operational costs for estimating total biomethane yield, revenue and returns on AD investment to a reasonable degree given input of suitable data.

For integrated whole systems methodology design, the key research challenge of striking a sufficient balance between breadth and depth of coverage in its modelling and analytical approach must be met to attain suitable trade-off cost-benefit outcomes relevant to policy and investment decision making by key stakeholders. To this end, application of excel modelling approach and integration of all findings within the techno-economic and social technical framework will be adopted to derive both quantitative findings (mass, energy, emissions and financial data) with their practical (qualitative) implications in form of technology transition and social benefits arising from various FWtTBC pathway deployment scenarios.

Any case study scenarios chosen for excel modelling must also be of sufficient relevance to real-world FWtTBC pathway deployment that could strongly benefit from any modelling outcomes where existing relevant trials or schemes relating to one or more component of the pathway, i.e. food waste recycling, anaerobic digestion, and/or biomethane refuel station deployment, are already in-place and where data is simultaneously sufficiently available.

Here the aim is to apply modelling derived insight for regions that could benefit maximally from such insights to overcome the aforementioned CAEC and LIE effect to sufficiently lower their barrier (i.e. perceived business or investment risks) towards deployment of key components of the FWtTBC pathway (Figure 12).

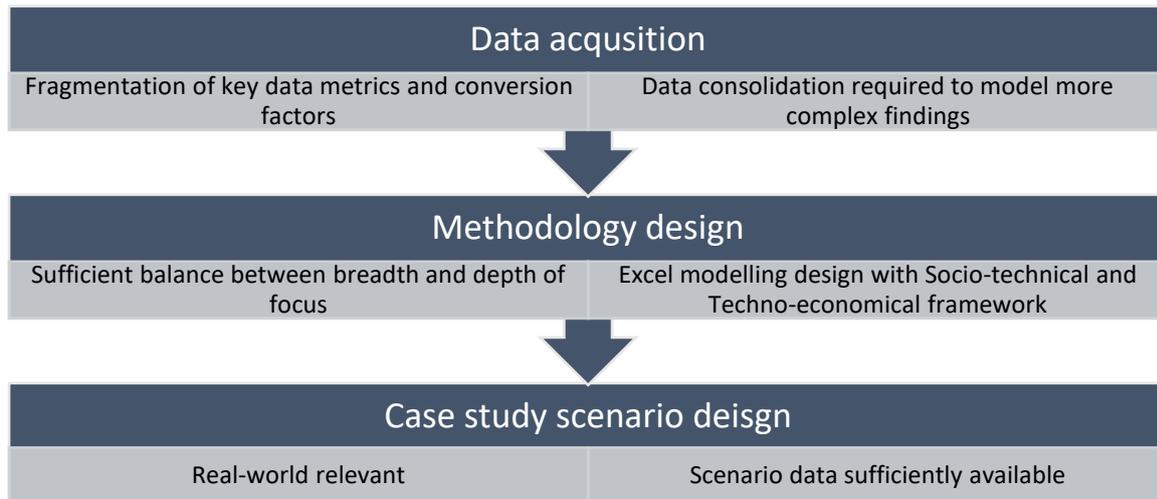


Figure 12. Research challenge expanded with summary details

Leeds and the Northern Powerhouse (NPH) for example, constitutes strong city and greater-metropolitan region of interest for case study modelling given their historical and present efforts towards deployment of all FWtTBC pathway components. This is notably evident for Leeds, as indicated by Leeds City Council's (LCC's) Rothwell food waste collection trial and commitment to implement citywide food waste scheme for the foreseeable future, alongside past (albeit unsuccessful) attempts to develop AD plant site operations at undisclosed strategic locations and present CNG fuel station development efforts at the Lower Aire Valley region.

The cumulative trends to date suggests sufficient application of critical data driven insight could significantly promote and enhance rate of success in deployment in one or more of the FWtTBC pathway components across Leeds, from which tangible benefits can ultimately be realized to set a strong precedent for city regions under similar circumstances to follow suit.

A set of critical boundaries are also integrated into the modelling and analytical approach to indicate research areas that could be further explored but are restricted to help maintain specific depth and breadth of the current research's focus, as outlined in the next section.

1.6 Boundaries and limitations

This research is subjected to 4 key boundaries that defines its scope and specificity of focus on (1) feedstock input and bioenergy output, (2) case study geographical coverage, (3) pathway infrastructure and (4) Bioenergy end-use application (see Figure 13 and Figure 14).

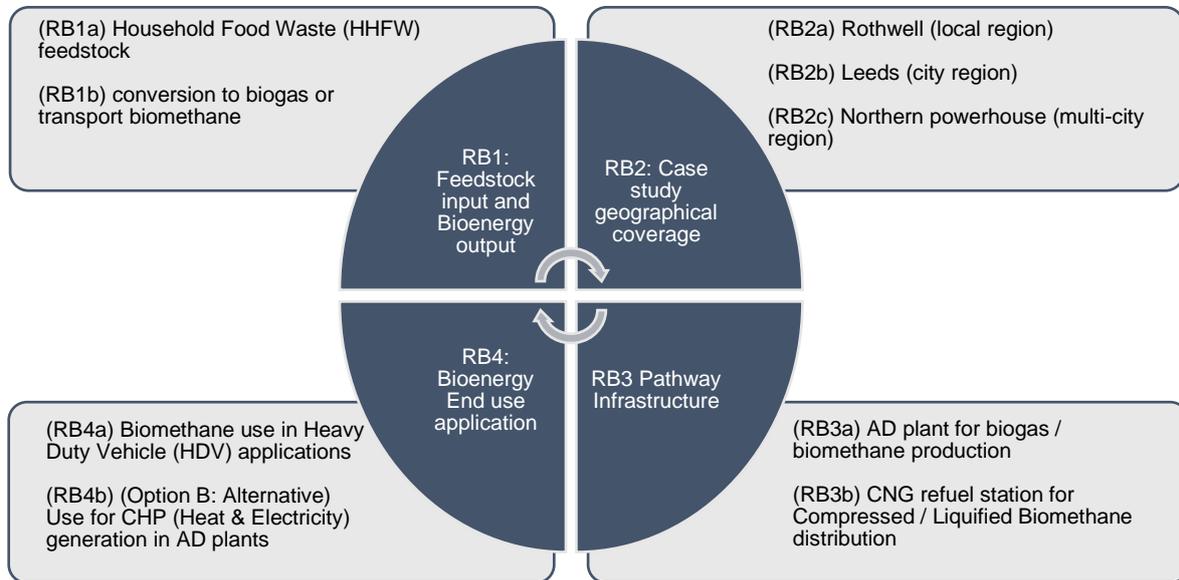


Figure 13. 4 Research boundary (RB) overview and details

This research also defined a number of key limitations pertaining to data availability (raw input data and conversion factors), methodology and expected findings that can serve as an excellent foundation for future studies, as outlined in Figure 14 below.

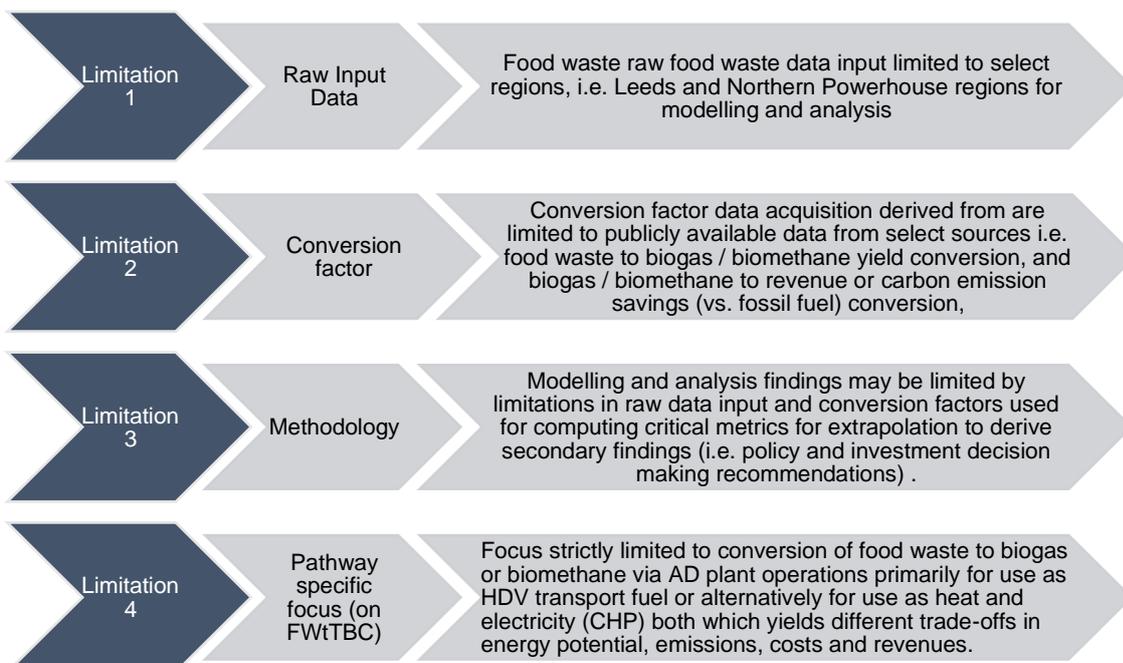


Figure 14. Summary of limitations based on specified study boundaries

1.7 Aims and objectives

Below summarizes the above intro into 4 key overall aims and for each of these, specific objectives, in a top-down approach, with outputs having demonstrable application potential and impact towards driving stakeholder confidence for enabling the FWtTBC pathway.

Aim 1 - Collect source verified data sets with strong scientific integrity on for the household food waste (HHFW) to transport biomethane (FWtTBC) conversion pathway, with specific considerations on:

- Objective (Obj.) 1.1 Identify and establish key pathway data parameters at local or intra-city, city level and regional or multi-city level scale, with results being extrapolatable to pathway deployment at national level.
- Obj. 1.2 Identify and establish novel methodological approach for collection of reliable data across key parameters as specified in Obj. 1 and to ensure their integration being robust and sufficient for elucidating critical quantitative metrics and qualitative findings
- Obj. 1.3 Conduct data collection for all identified pathway parameters as specified in Obj. 1 from mix of reliably academic and non-academic online sources

Aim 2 - Establish high-level metric outputs of FWtTBC pathway that can be used to conduct cost-benefit trade-analysis for pathway deployment under different case study scenarios outlined in Aim 3, with specific focus on:

- Obj. 2.1 Evaluating historical, present and projected future household FW output potential against AD FW feedstock input capacity potential and biofuel refuel station capacity potential
- Obj. 2.2 Establish operational process diagrams illustrating flow of key technical (mass, energy and emission) and financial metrics (using outputs of aim 1) associated with each FWtTBC pathway component (of FW collection, AD operations, refuel station)
- Obj. 2.3 Establish whole-systems qualitative metrics for conducting social-techno-economic analysis (when used in conjunction with outputs of Obj. 2.2) on FWtTBC pathway deployment

Aim 3 - Establish detailed case study outputs from implementing FWtTBC pathway under 3 case study scenarios of varying geographical scope of coverage (Rothwell, Leeds, Northern Powerhouse Region).

- Obj. 3.1. Establish boundary condition criteria and parameters associated with identifying suitable case study scenario regions that can most readily benefit from FWtTBC pathway deployment based on historical, present and future developments

- Obj. 3.2 Establish quantitative and qualitative cost-benefit trade-offs arising from FWtTBC pathway deployment pertaining to each scenario using same method as outlined in aim 2 (Obj. 2.1-2.3)
- Obj. 3.3 Conduct general sensitivity analysis by assessing impacts of potential changes to critical case study parameters, i.e. population, AD plant capacity for FW recycling, FW output per individual, on cost-benefit trade-offs of FWtTBC pathway deployment to determine suitable target-oriented deployment strategies

Aim 4 – Establish policy and investment recommendations that suitably informs target-oriented FWtTBC pathway deployment strategies, more specifically on:

- Obj. 4.1 Maximise reduction in FW output, FW collection, biogas or biomethane generation by leveraging existing local AD plant capacity based on total household FW outputs
- Obj. 4.2 Maximise key financial metrics such as return on investment, total revenue generation from biogas or biomethane sales and policy driven tariff incentives in manner which bolsters stakeholder and investor confidence

Chapter 2. Literature review

2.1 Introduction and Overview

This literature review presents 8 interconnected themes that collectively outline the real-world relevance and significance of the present research on (i) conducting trade-off cost-benefit modelling and analysis of FWtTBC pathway deployment alongside (ii) elucidate appropriate levels of policy support and optimum deployment scenarios and strategies, and (iii) communicate transferability of research outcomes across for deployment of other suitable and relevant pathways.

To this end, the literature review brings all research objectives to the broader context of historical developments of climate change directives and pledges at the UK national and EU international landscape, and how consequently, they have shaped the UK's domestic climate change and renewable energy project deployment, directives, and policies.

The review also provides an overview of 4 key high-priority sectors, namely, (i) waste, (ii) anaerobic digestion, (iii) bioenergy, and (iv) transport sector that are critical to the deployment of FWtTBC pathway. These sectors also collectively, along with other renewable energy sectors, stands at the forefront of government and industry driven focus to assist UK in meeting its short, medium and long term climate change targets, policies and directives (i.e. on emission and waste reduction).

Here the 8 interconnected themes adopts a top-down approach, by firstly focusing on bridging the science behind the historical development of Climate Change (CC) (theme 1) with developments of CC adaptation and mitigation strategies within the EU (theme 2) and UK (theme 3). This is then followed by developments of UK's renewable energy landscape (theme 4) with a narrowing focus towards bioenergy generation and food waste to transport biomethane conversion (FWtTBC) pathway deployment which constitutes an emerging opportunity for decarbonising UK's transport sector (theme 5) and barriers and opportunities (theme 6). To this end, other sustainability and bioenergy research relevant to the FWtTBC pathway are also brought to light (theme 7), to demonstrate the feasibility and real-world demand in adopting integrated whole-system based research approach to promote real-world pathway deployment (theme 8).

To this end, key barriers towards FWtTBC pathway implementation will also be reviewed to add context to real-world deployment challenges which is commonly attributed to the Chicken and Egg Conundrum (CAEC) and Lock-in Effect (LIE).

This culminates in the conclusion and summary theme which outlines summarizing perspectives of the relevance and application of research content, method and envisioned outcomes with respect to themes 1-8 of the literature review within the real-world context (see Figure 15).

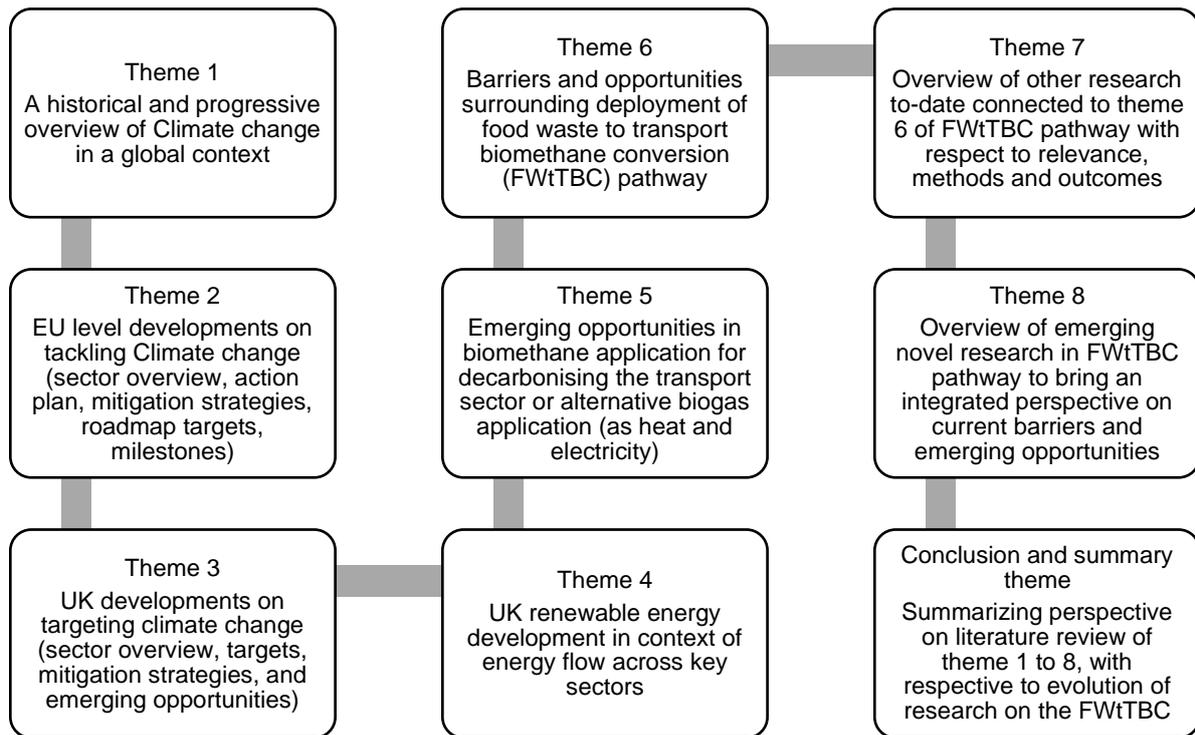


Figure 15. Summary of literature review flow of topics

2.2 Theme 1: A historical and progressive overview of Climate change in a global context

2.2.1 Historical context and global impact of Climate change

The scientific and public consensus on the phenomenon of Climate Change (CC) and Global Warming (GW) has been widely cemented through a number of key historical developments to-date and observations indicating increasing extreme weather events across the world.

These developments can be distinctly separated into either a scientific experimental data oriented approach or an international development oriented approach, both which are connected and are described separately below.

2.2.2 A scientific observation perspective to climate change

The notion of climate change (CC) was first conceived in 1970s based on initial scientific evidence predicting near-term global warming (GW) (Peterson et al., 2008). This ignited further scientific studies and experiments a decade later, which revealed similar findings.

Notable amongst these experiments, are Hansen et al's climate modelling work and Lorius et al.'s Vostok Ice Core experiment, the latter which further revealed strong positive correlations between 2 key CC and GW indicators of global temperature level (GTL) and atmospheric CO₂ concentration (aCO₂c) over the past 150,000 years (British Antarctic Survey, 2006; Lorius et al., 1985).

These findings were also subsequently found to be in strong agreement with NASA's own climate data recordings which demonstrated a strong positive correlation between rapidly accelerating global aCO₂c, GTL and more concerningly, global sea level (GSL) (Figure 16).

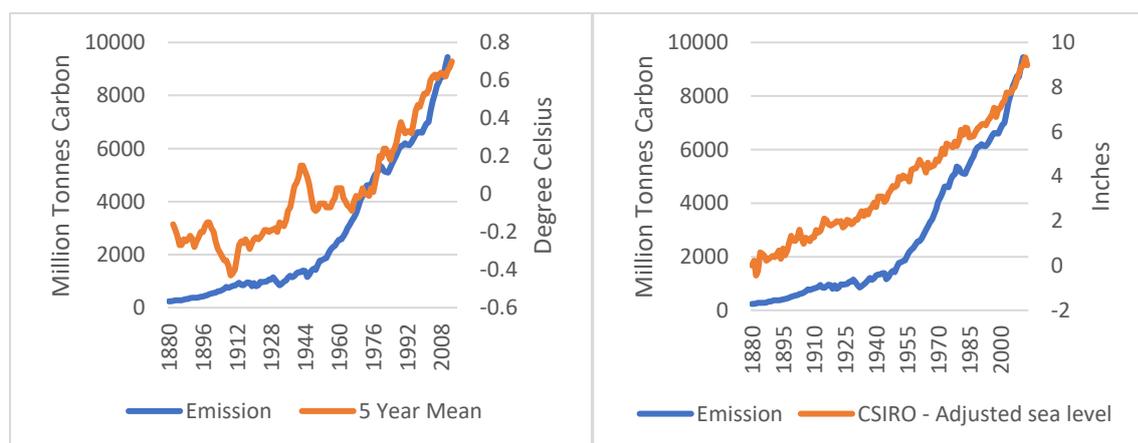


Figure 16. Historical Changes in GHG emissions relative to Temperature (left) and Sea Level (right) (CSIRO, 2015; EPA, 2002, 2016; NASA, 2015; NOAA, 2015)

These observations also evidently revealed the fundamental cause of CC GW to be Green House Gases (GHG) that induces a 'warming effect' by trapping sunlight from within the

Earth's atmosphere. Amongst these Carbon Dioxide (CO₂) and increasingly, Methane (CH₄) and Nitrous Oxide (N₂O) constitutes major GHGs of concern given their cumulatively strong CC GW effect arising from either high atmospheric concentration (i.e. CO₂), global warming potential (i.e. N₂O) or combination thereof (i.e. CH₄) (EPA, 2015). The effects of other GHGs, which mainly constitutes fluorinated gases (i.e. HFC, SF₆, PFC), are relatively minor by contrast given their extremely low atmospheric concentrations (Our world in data, 2019) (see Figure 17).

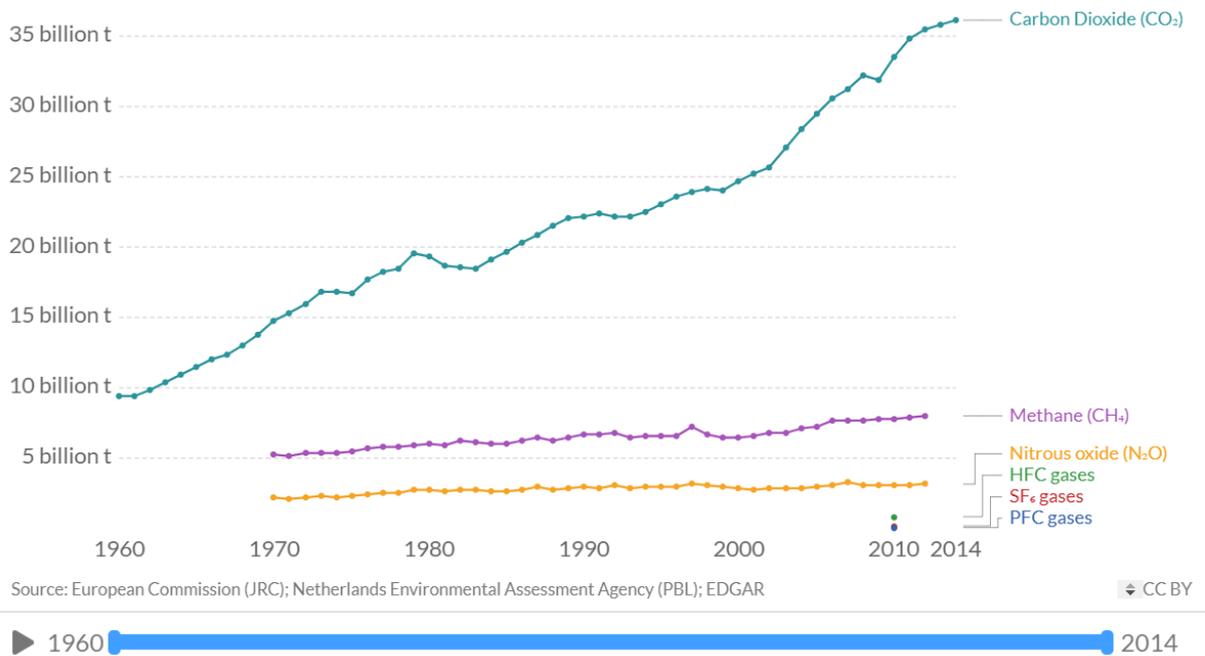


Figure 17. European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). Emission Database for Global Atmospheric Research (EDGAR) (EC, 2022)

To-date, the recoded negative global externalities of anthropogenic CC and GW are universally regarded to outweigh any potential benefits of warmer weather, and includes increased likelihood and intensity of extreme weather events such as heatwaves, draughts, draughts, heavy rainfalls and floods in vulnerable regions across the world (DW, 2018), as shown by CarbonBrief's own findings from over 230 peer reviewed studies on extreme event attribution (CarbonBrief, 2019) (see Figure 18 and Figure 19).

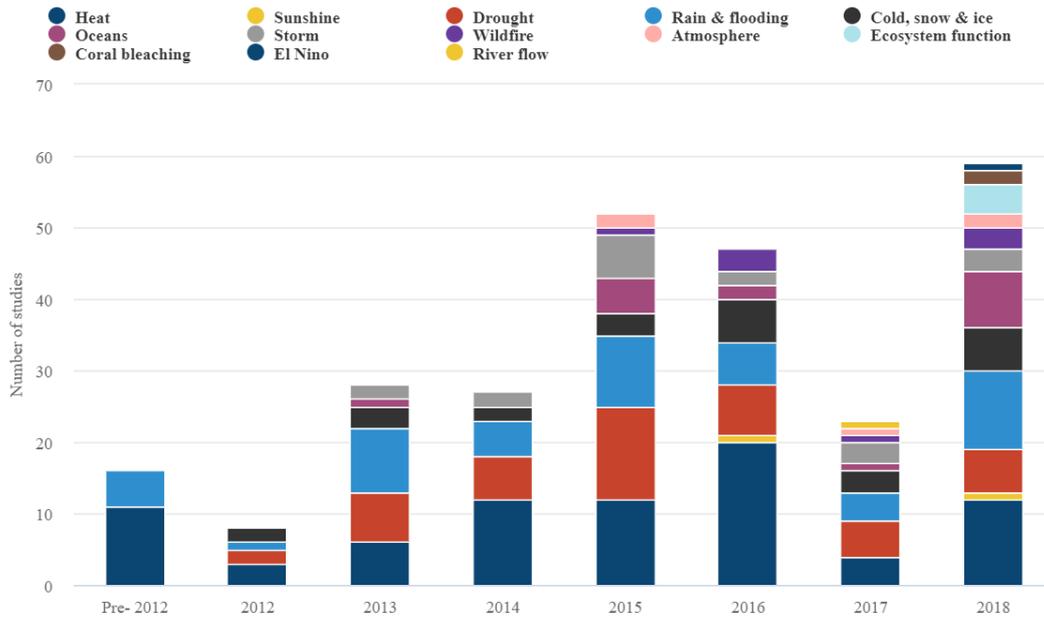


Figure 18. Number of attribution studies by extreme weather event type and year. Note: the total number of events dipped in 2017 because the Bulletin of the American Meteorological Society special report for that year was published in early 2018 rather than late 2017 (CarbonBrief, 2019).

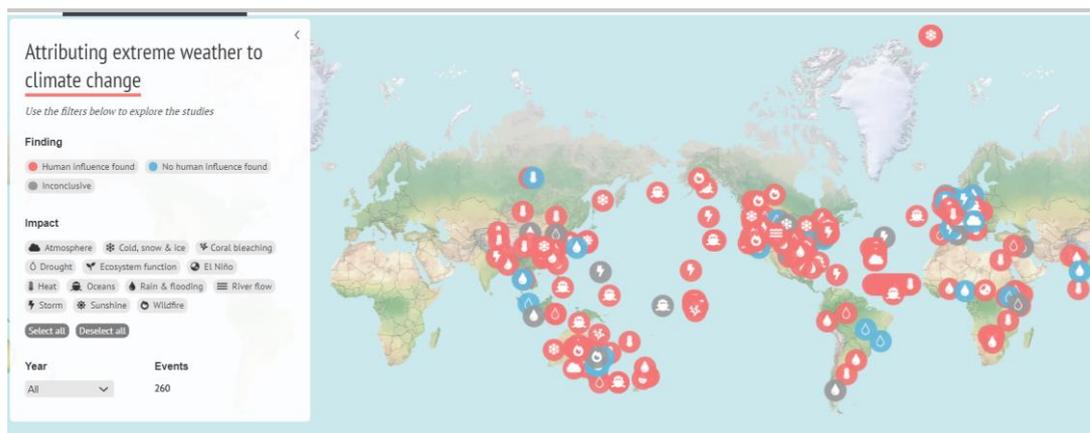


Figure 19. Map of extreme weather events attributed to Climate change (CarbonBrief, 2019)

2.2.3 An international development-oriented approach to climate change

Presently, 4 key developments have led to the current state of joint international collaboration and establishment of a global governance structure towards tackling climate change. These include the (i) International Panel on Climate Change (IPCC) (UNFCCC, 2014d), (ii) United Nations Framework Convention on Climate Change (UNFCCC, also part of the Rio Convention), (iii) Kyoto Protocol and (iv) the COP21 Paris Climate agreement, which collectively ratified over 190 parties in the Climate Action Plans (CAPs) (EC, 2016d) process to-date (EC, 2016f; UNFCCC, 2014c) (Table 3).

These developments consequently enabled each participating country to set appropriate short to long term national climate action targets aimed at reducing Green House Gas (GHG)

emissions (as eluded in the above section) through selective policy, investment and regulatory changes including but not limited to phasing out of fossil fuel power generation, bolstering investment and deployment in renewable energy technology and limiting emission pollution across critical high emission sectors (see Table 3).

Table 3. Summary of historical climate change events to-date (individual references outlined in table)

<i>Historical events</i>	<i>Year</i>	<i>Purpose</i>	<i>Achievements</i>
Establishment of the International Panel on Climate Change (IPCC)	1988	To act as international scientific body for assessing and understanding risks of human-induced climate change (UCSUSA, 2007)	Consistently published high-level scientific studies concerning anthropogenic climate change (UCSUSA, 2007)
Establishment of United Nations Framework Convention on Climate Change	1994	Promote international efforts to tackle climate change by stabilizing GHG concentrations "at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 2014a)	Established IPCC and Kyoto protocol in support of promoting international effort to tackle climate change (UNFCCC, 2014d)
Kyoto protocol	1997	Ratify international commitment to combat climate change via international negotiation (UNFCCC, 2014b)	192 parties ratified in adopting ambitious efforts to combat climate change (UNFCCC, 2014b)
Paris agreement	2015	Ratify international commitment to combat climate change via international negotiation (EC, 2016f)	153 parties ratified in adopting ambitious efforts to combat climate change (UNFCCC, 2014c)

The urgency with which these set climate action targets are to be met and surpassed is further driven by consistent climate projections from numerous reputed scientific bodies overtime of imminent and irreversible long term warming of Earth's climate given continuation of current trend in GHG emissions.

Notable amongst these include the 2015 Earth statement (Global Challenges Foundation, 2015) and IPCC's 5th assessment report (IPCC, 2014), which collectively stated a 5.8 to 6 degree Celsius increase in global temperature by 2100, and of the ensuing severe environmental and socio-economic consequences (Re, 2002). As alluded to in the above section, the alarming symptoms of climate change in form of gradual sea level rises, acceleration in Antarctic ice glacier meltdowns (i.e. in Greenland and West Antarctic) (Tufts University, 2007) and greater region specific occurrence of more extreme weathers within the past decade (i.e. heatwaves in Europe, with fires, droughts, floods and hurricanes in US) have already began to manifest in affecting various vulnerable regions of the world.

Of greater ethical, humanitarian and environmental concern, are critical challenges faced by developing nations, including but not limited to Bangladesh, Indonesia, Kenya and Somalia (Althor et al., 2016), which relies on their natural environment for economic and social prosperity. These countries have to-date not contributed significantly to GHG emissions relative to more developed nations of the west but will likely be inevitably more affected by the long-term effects of climate change as they do not yet possess a robust climate resilience infrastructure.

2.2.4 Summary of global climate change mitigation strategy and role of EU

With growing realization of the wider consequences which climate change poses both on a temporal and geographical level, the urgency with which GHG mitigation needs to be achieved through collaborative international efforts that stemmed from the fruits and labours of IPCC, UNFCCC, Kyoto Protocol and Paris Agreement is clear (Table 3). Consequently, key policy, regulation and legislation driven targets were rapidly developed by major economies of the world in what follows to be EU's own longstanding and self-imposed policy-directed efforts towards tackling climate change.

It is also worth noting the instrumental impacts which the EU played in successfully reaching the Paris agreement through close collaboration with key allies from developed, developing countries and with major economies, i.e. US and China, to strengthen global efforts to combat climate change (EC, 2019n).

The sheer tenacity of such events can perhaps be reflected by EU's own longstanding, deep-rooted history and commitment in tackling climate change which dates back to 1991 from which it first introduced a directive-driven community strategy to limit CO₂ emission and improve energy efficiency that has since expanded into the multi-directive targeted approach known today.

2.3 Theme 2: EU as a key global driver for tackling Climate change

2.3.1 EU's role in tackling climate change on the world stage

Historically speaking, the European Union (EU) constitutes one of the earliest adopters and proponents of the climate change action movement whose noble aim is to address and tackle the escalating issue of climate change. This is quintessentially reflected in the EU's vanguard efforts in both setting its own policy driven targets via numerous initiatives set since 1991 (i.e. EU community strategy and European Climate Change Program) (EC, 2017d), and in its strong contributions to key international climate change bodies and conferences (i.e. COP21, IPCC) that fostered strong international collaborations on tackling climate change to-date.

More specifically the EU has been instrumental in persuading major world economies such as China to agree on a more ambitious GHG reduction target in the COP21 Paris agreement (EC, 2019n), as well as providing significant body of scientific evidence and data to the IPCC assessment reports on climate change through its dedicated scientific funding support (EC, 2019c) (Table 4).

Table 4. EU's contribution to tackling climate change

	Timeline and duration	EU contribution
EU funded research in support IPCC assessment reports	1987-2020 (2 nd to 8 th research framework) (Horizon magazine, 2014)	<ul style="list-style-type: none"> Funding for scientific research and evidence on climate change in support of progressive iterations of IPCC assessment reports to-date (EC, 2019c; Horizon magazine, 2014)

EU community program	1991-2000	<ul style="list-style-type: none"> Set first CO₂ targets for EU countries (EC, 2017d)
European Climate Change Program (ECCP)	ECCP1: 2000-2005 ECCP2: 2005-Present)	<ul style="list-style-type: none"> CO₂ reduction targets for all EU member states Accompany secondary targets for achieving GHG reduction targets (EC, 2017d)
Paris agreement - COP21	2015	<ul style="list-style-type: none"> Operational support of COP21 conference Improve outcome of COP21 by persuading major world economy to set more ambitious CO₂ reduction targets (EC, 2019n)

To-date, the EU continues to play an instrumental role towards the tackling climate change through wider climate conference and panels participation (i.e., COP21 and IPCC), and implementation of EU's very own Climate Action Plan (CAP) which sets out key policy-driven short, medium and long term climate action goals internally for its 27 member states (MS) (via ECCP). These goals respectively set out designated and incremental GHG emission reduction, Renewable Energy share and energy efficiency improvement targets that are both legally binding and non-binding under a trio of consecutive initiatives, namely, EU's climate and energy package, framework and roadmap (Table 5).

Table 5. EU's Climate & Energy Package (2020), Framework (2030) and Roadmap (2050)

	Short term - 2020	Medium Term - 2030	Long term - 2050
Initiative Name	<i>Climate & Energy Package</i>	<i>Climate & Energy Framework</i>	<i>Climate & Energy Roadmap</i>
GHG emission reduction (relative to 1990 levels)	20% (EC, 2016a)	40-45% (EC, 2019c)	80%-95% (EC, 2011b, 2016b)
Renewable Energy share	20% (EC, 2016a)	27% (EC, 2016e)	No data
Energy efficiency improvement	20% (EC, 2016a)	27% (EC, 2016e)	No data

Notes: Green = Legally binding; Red = Not binding; Source: (EC, 2017a, 2017b, 2017c). All targets are application to EU member states as shown in blue in Figure 21 below.

2.3.2 Summary of key roles, targets and strategies of EU member state in tackling climate change

In alignment with the CAP, each EU MS (see Figure 20) have established their own individual climate action targets using EU's stipulated targets as a guideline, with the 2021-2030 medium term targets to be now binding for each MS as a direct consequence of the Paris Agreement and the establishment of EU's effort sharing regulation in 2018 (EC, 2019d).

These national targets also constitute a reflection of each MS's relative wealth as measured by their GDP per capita, with less wealthy nations able to adopt less ambitious targets to help maintain economic growth through use of conventional fuel until sufficient investment capacity is accrued for transitioning into a low carbon economy (EC, 2019d) (Figure 20).

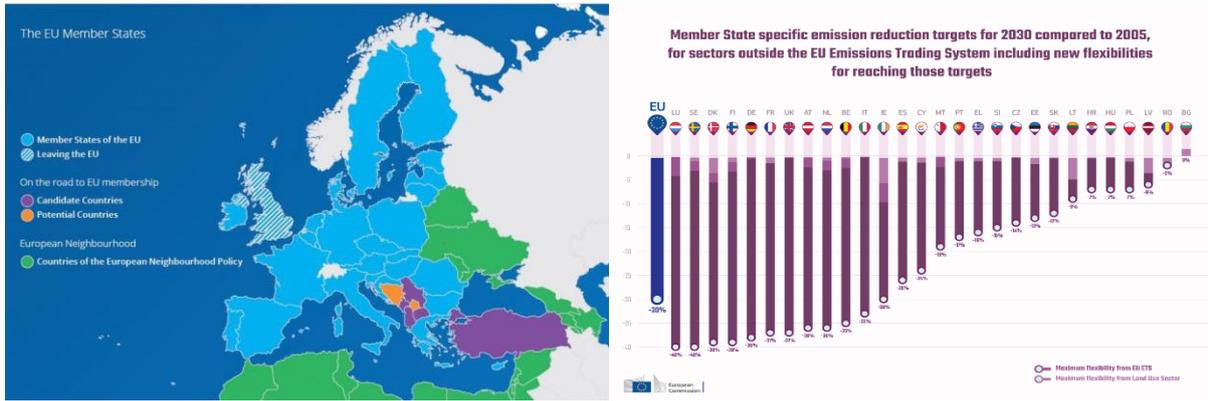


Figure 20. Summary of EU member states (Euromedrights, 2019)

Several key mechanisms were created in further support of each EU MS in meeting their respective climate action targets, and these namely include an emission flexibility measure in form of Allocated Emission Allowances (AEA) and an EU Emission Trading System (EU ETS) (EC, 2019d).

The AEA was adopted by European Commission (EC) since October 2012 and adjusted a year later to ensure consistency with the enlarged EU ETS scope for 2013-2020, which collectively works to create an effective market mechanism that simultaneously enable certain degree of flexibility in each MS’s emission reduction requirement relative to target (Table 6).

Table 6. Mechanism for applying a degree of flexibility for each EU member state (EC, 2019a)

	Mechanism description
Within member state	Overachievement in a given year can be carried over to subsequent years, up to 2020
	Emission allocation up to 5% during 2013-2019
Between member states	During 2013-2019, MS can transfer part of their AEA for given year to other MS under certain conditions

*The GHG emissions for the reference years 2005, 2008, 2009 and 2010 used in AEA calculations were reviewed by technical experts, in consultation with each Member State.

2.3.3 Key focus areas for EU and its MS in tackling climate change

The stipulated climate action targets for each Member States (MS) have in turn prompted a number of key focus areas under the aforementioned ECCP (European Climate Change Packages), which related to the field of energy (supply, demand and efficiency), transport, industry, research, agriculture and sinks (related to forest/agriculture) in the first ECCP (EC, 2019g). This has since expanded into modes of transport (aviation, CO₂, cars and ships), carbon capture storage (CCS), adaptation and renewable energy (RE) implementation with specific focus on biofuels in the second ECCP (EC, 2019j).

The combined efforts of the two ECCP implemented to-date further established a number of industry-specific directives for each MS in support of the broader directives that falls under

their respective climate action targets (Table 6). Namely, these include directive for promoting cogeneration of heat and electricity, renewable energy, biofuels for transport, improving end use energy efficiency in addition to those related to establishment of an emission trading system (2003/87/EC) and scheme for GHG allowance trading (2004/101/EC), with specific set time-bound targets, that constitute the 2 key mechanisms aforementioned above (Environmental law, 2017).

Moving forward, EU has adopted a Strategy Energy Technology (SET) plan in 2018, which determined key research and innovation areas of focus for catalysing its future endeavours in tackling climate change (Figure 21) in line with its existing directives with the long term milestone of achieving 80-95% GHG reduction by 2050.



Figure 21. SET-plan that set out 10 research and innovation actions aligned to the energy union objectives (EC, 2019k)

A key challenge for enabling this involves catalysing significant GHG mitigation across high emission sectors, which, according to previous studies and reports, is not possible without further climate policy intervention. This is further officialised by the 2013 European Commission (EC) study on current sector emission trends within the EU, which is conclusive of the need to introduce new climate change policies (EC, 2016b) if EU is to meet these targets (Figure 22).

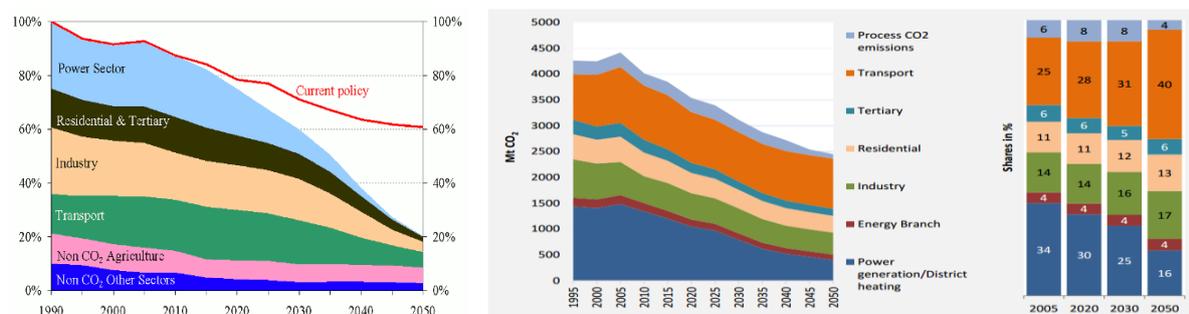


Figure 22. EU 2050 Climate Action Plan (CAP) emission target scenario and scenario without further policy intervention (left) (EC, 2016b) and CO₂ emission evolution scenario without policy intervention (right) (EC, 2013)

In context of EU climate developments made to-date, any such new policy introduced is expected to be progressive and met with dedicated structure and commitment in driving strategic evolution in key focus areas established by the Strategy Energy Technology (SET) plan. Namely, these encompass the fields of renewable energy (RE), sustainable transport (ST), energy efficiency (EE), carbon capture storage (CCS), smart energy (SE) and nuclear safety (NS). It is also worth elucidating that these series of developments to-date strongly reflects the strong hope which the EU places in applying concerted research and innovation efforts to tackling the difficult challenge which it now acknowledges towards meeting the set ambitious CAP targets (of 20-80% GHG mitigation between 2020-2050).

To this end, strong, concerted investment efforts across both R&D and strategic deployment of new elements in the fields of technology, infrastructure and practice (i.e. RE, ST, EE, SE) will likely constitute a fundamental driver of enabling change towards resilience, adaptation and GHG mitigation against climate change.

Previous estimations predicated an investment requirement of £125 billion between 2014-2020, most which expected to be borne by private investors with EU funding in form of dedicated financial instruments (DFI) to act as climate investment stimulus (CIS) in key sectors including energy efficiency, RE, and related infrastructures with new tech innovation and adaptation strategies for climate change (EC, 2011a).

2.3.4 EU solution in tackling climate change via renewable energy sector investments

These dedicated financial instruments (DFI) are further implemented alongside EU's Climate Action Fund (CAF) and longstanding Research Framework (RF) fund and as bulk of EU's climate funding strategy (CFS), within the framework of an integrated funding strategy that bridges innovation with implementation, whilst also adopting a region, sector and industry-specific focus (Figure 23).

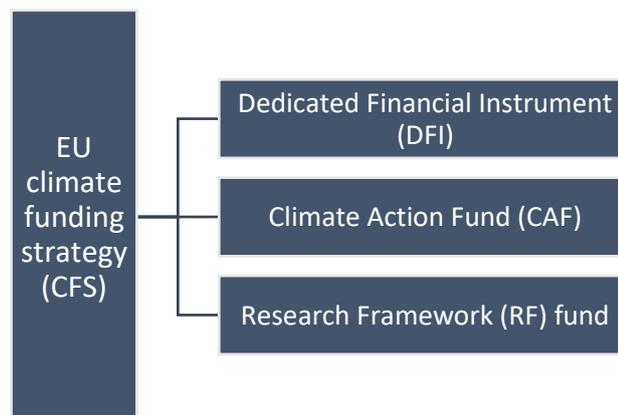


Figure 23. Bulk of EU funding strategy against climate change

2.3.5 European Structural and Investment funds

More specifically, the DFI is specified under 5 European Structural and Investment funds (ESIF) adopted under a common strategic framework (CSF) with the budget specified by the multi-annual financial framework (MAFF) (EC, 2019i) (Figure 24).



Figure 24. European structural and investment funds that constitutes EU's dedicated financial instruments

In the MAFF period of 2014-2020, The ESIF amounts to approximately €644bn in funding that are selectively distributed across a number of key themes, many of which are either directly or indirectly associated with tackling climate change. Namely, these includes environment, protection and resource efficiency (€24bn), research and innovation (€22bn), low carbon economy (€19), climate change adaptation and risk prevention (€13bn), and network infrastructure in transport and energy (€12bn) (EC, 2019h, EC, 2019i) (Figure 25).

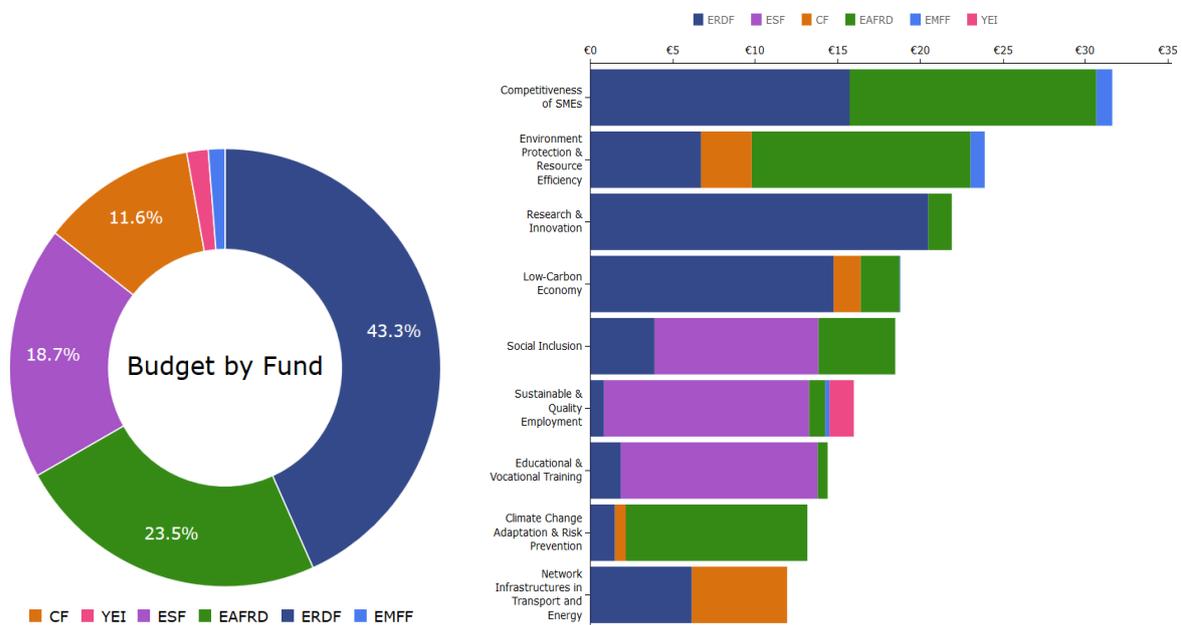


Figure 25. Estimated budget of €644bn (YEI represents youth employment initiative not mentioned in literature above). YEI and EMFF represents 1.6% and 1.2% funding respectively not shown in figure above.

2.3.6 The Climate Action Fund (CAF)

EU's climate action funding (CAF) is also established under the multi-annual financial framework (MAFF) with the goal of mainstreaming climate change mitigation efforts across all EU spending programmes, such as for cohesion policy, agriculture, research and innovation.

Consequently, a significant proportion of the CAF funding also falls within the ESIF, with the remaining funding to serving as dedicated climate funding under other mainstream programs. A prominent example includes CAF being mainstreamed to support the Life Program (under the European Union Solidarity Fund) which traditionally supports environmental and conservation projects throughout the EU (EC, 2019e) . The CAF under the 2014-2020 MAFF period established a funding amount of €206 million (Table 7), representing 20% of total MAFF funding that is to be increased to 25% to constitute €320bn funding for the 2021-2027 funding period (EC, 2019e).

Table 7. EU climate change finance relative to total EU budget from 2014-2020 (EC, 2019I)

(EUR million, commitment appropriations)

Programme	2014-2017				2018-2020 estimates			Total 2014-2020	Total 2021-2027
	2014	2015	2016	2017	2018	2019	2020		
Total EU Budget	118.054	158.606	151.498	154.507	156.623	160.553	164.880	1.064.724	
Budget Climate Change finance	16.098	27.451	31.738	29.792	30.481	31.956	32.606	200.124	320,000
Share of climate	13,6%	17,3%	20,9%	19,3%	19,5%	19,9%	19,8%	18,8%	

2.3.7 EU's Research Framework (RF) fund

The RF fund constitutes a long-established funding for undertaking R&D activities in key evolving themes of interest such as public health and education (EC, 2019f). The theme of climate change established a concrete focus since RF2 since 1987, to which subsequent funding were increasingly allocated until the present. The RF is currently in its 8th iteration under the Horizon 2020 program (or RF8), with an estimated budget allocation of €80bn, of which 35% is expected to address climate change (EC, 2019b) (see Table 8).

Table 8. EU research framework budget (ESPON-European Community, 2007)

Year	1984-1987	1987-1990	1990-1994	1994-1998	1998-2002	2002-2007	2007-2014	2014-2020
Research framework (RF*)	RF1	RF2	RF3	RF4	RF5	RF6	RF7	RF8 (Horizon 2020)
Budget	3.3	5.4	6.6	13.2	14.9	19.3	55.9	80
Cumulative budget	3.3	8.7	15.3	28.5	43.4	62.7	118.6	198.6
Budget relative to total expenditure to date	1.66%	2.72%	3.32%	6.65%	7.50%	9.72%	28.15%	40.28%

*Not 100% but an increasingly significant portion of RF is allocated in tackling climate change since RF2, with the most ambitious to be RF8 to-date.

2.3.8 Summary of EU's progressive climate funding programs

A prominent and common trend across all 3 EU climate funding strategy (CSF) categories is the recent sharp increase in their magnitude towards dedicated climate funding. For CAF, this increase amounts to 100% from 2014 to 2020 and 55% from the funding period of 2014-2020 and 2020-2027 (Table 8). Here the latter further reflects a similarly stark increase in MAFF-based ESIF funding allocation for the same period. Likewise, EU's RF funding have increased at least 43% for the funding periods of 2014 to 2020, with increasing proportions of allocated RF budget expected to contribute to climate research. The historical spending trends in RF further demonstrated a tremendously rapid surge in EU's R&D investment efforts towards addressing climate change since 1987, which amounted to an estimated minimum of 16-fold.

In the wider context, these collective funding also strongly aligns with the goals set out by EU's existing multi-level directives and the Strategic Energy Technology (SET) plan to help enable Europe to transition into an innovation driven, low carbon and climate resilient society.

2.3.9 EU's domestic Renewable Energy Sector (RES) investment in a global context

EU's domestic Renewable Energy Sector (RES) further constitutes a key area of funding and innovation that is central to tackling climate change via GHG mitigation for the EU and beyond in context of EU's other mitigation and adaptation strategies.

To this end, EU undergone strong investments in its domestic RES which in the prevailing periods of 2005-2011 has dominated on the world stage, and remained strong thereafter but has since been surpassed by rapidly surging RES investments by China and USA (Figure 26).

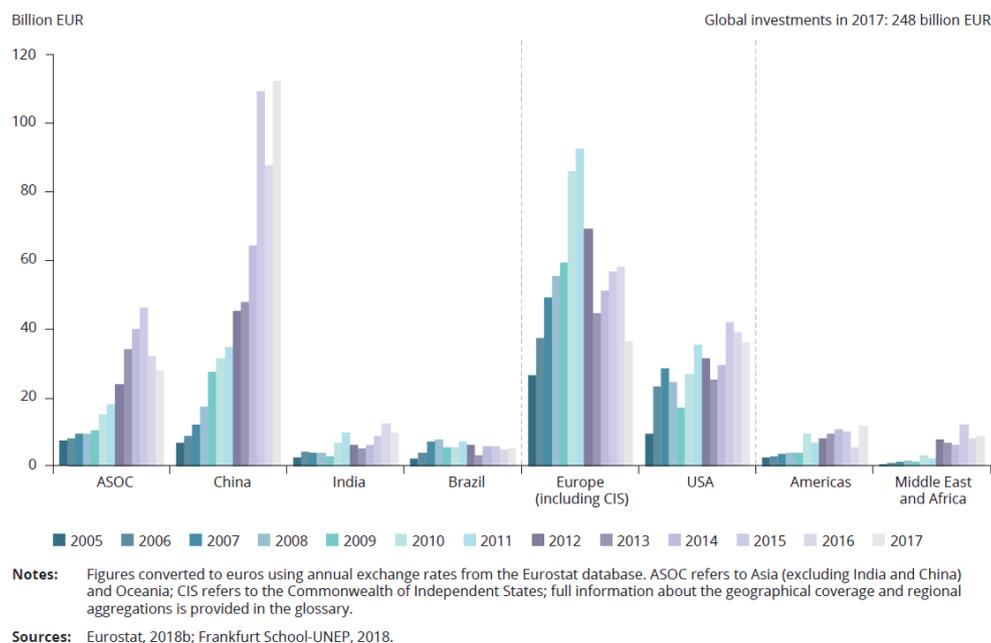


Figure 26. Global investments in Renewable Energy Technology across select regions between 2005 and 2017

To-date, EU's investments in renewable energy collectively reflects its long-term strategy against climate change from a technological investment, innovation and deployment front as

part of its technological strategy, which forms a key pillar of focus amongst other climate mitigation, adaptation and resilience strategies.

2.3.10 EU’s renewable energy investment centric strategy on tackling climate change

To-date, EU dedicated significant efforts towards utilizing its technology strategy to mitigate significant GHG emissions across its member states, focusing especially on high emission sectors (as summarized in Table 9). The deployment process also involves anticipated strong and progressive policy support using a wide range of Renewable Energy technologies and deployment strategies that constitutes what is known as the Renewable Energy mix (EU primary and secondary sectors of focus).

Table 9. EU primary and secondary sectors of focus

Primary sector	Secondary sector	Renewable energy mix
Transport	Renewable energy	Solar
Power	Carbon capture storage	Wind (Onshore & offshore)
Heat and residential		Bioenergy
Industry		Hydrothermal
Agricultural		Deep geothermal
Other sectors		Tidal, wave & ocean energy

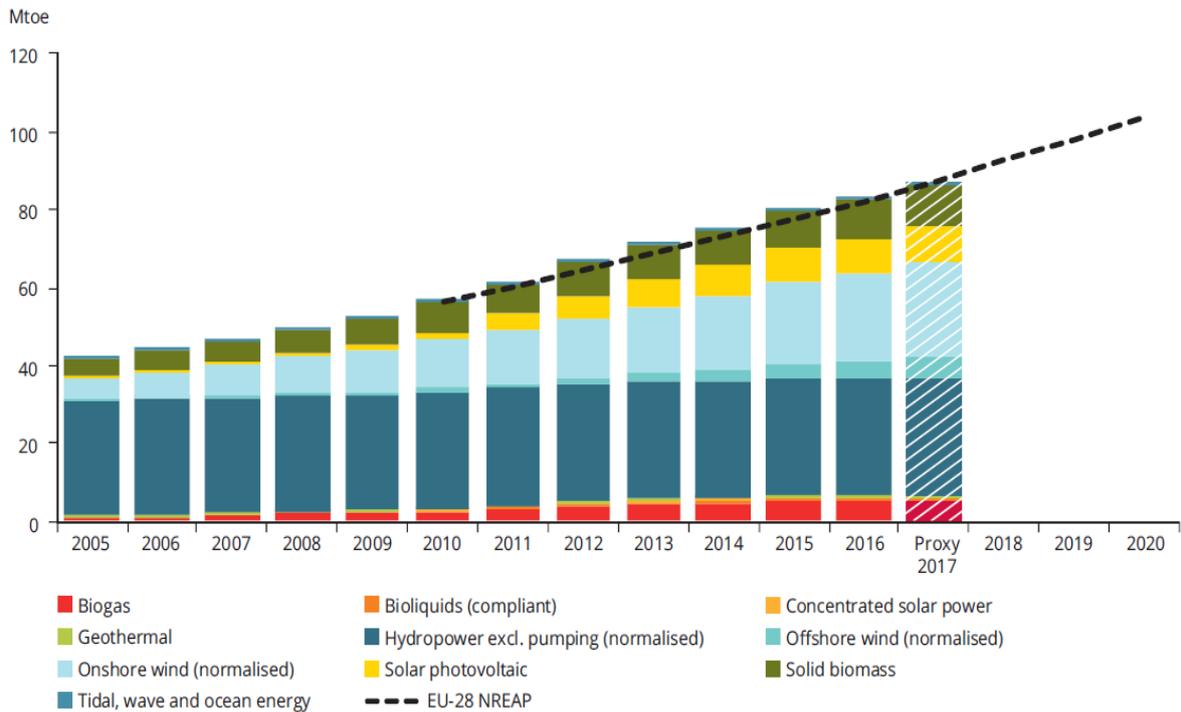
*Outlined by the SET-Plan

2.3.11 EU’s deployment of renewable energy mix

Traditionally, EU’s deployment of its Renewable Energy (RE) mix occurs under the 3 key primary sectors (RES), namely renewable electricity (RES-E), heat (RES-H) and the transport (RES-T) sector.

These 3 RES have undergone progressive evolution of the RE mix since 2005 that amounted to an overall increase in renewable energy adoption. These are more specifically attributed to significant increase in generation and use of bioenergy alongside solar and wind energy in their respective sectors of contribution that amounted to an approximated tripling, doubling and 50% increase in RE adoption within RES-T, RES-E and RES-H sectors, respectively.

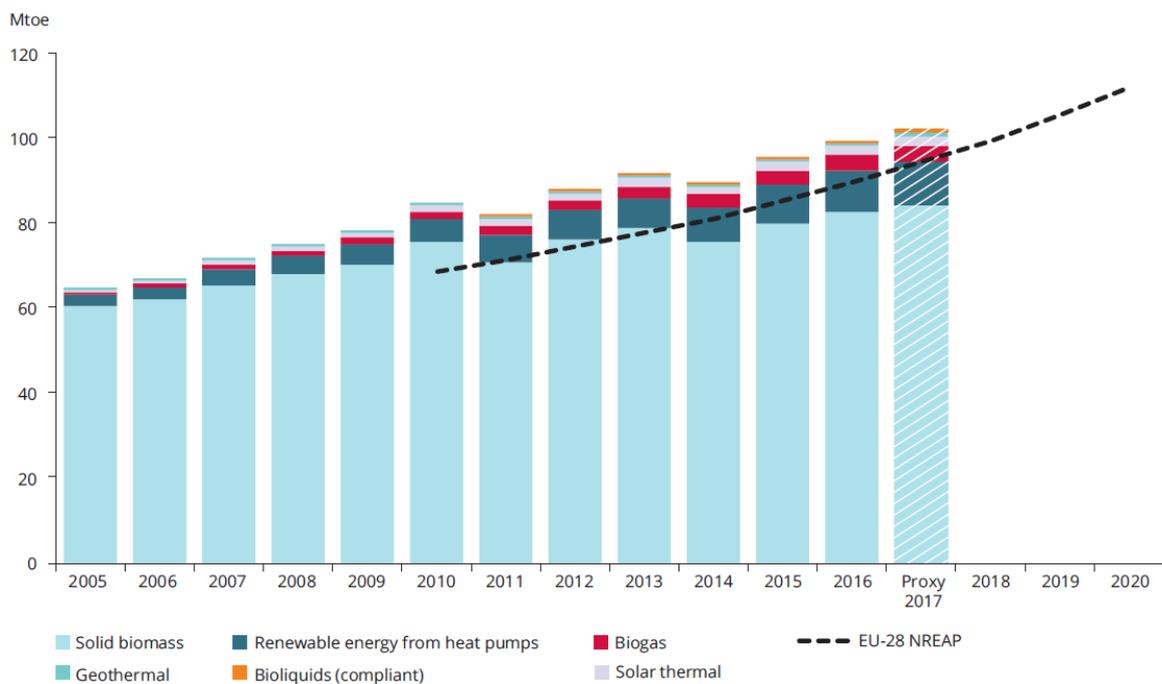
In context of RE application, it is also worth noting that bioenergy to-date represents the most versatile energy source that is functionally applicable across all 3 primary renewable energy sectors (Figure 27, Figure 28 and Figure 29).



Notes: This figure shows the actual final RES-E consumption for 2005-2016, approximated estimates for 2017 and the expected realisations in the energy efficiency scenario of the NREAPs for 2018-2020. Wind power and hydropower are normalised. The consumption of RES accounts for only biofuels complying with the RED sustainability criteria.

Sources: EEA; Eurostat, 2018d; NREAP reports.

Figure 27. EU's Renewable Energy deployment in the Renewable Electricity sector (RES-E)



Notes: This figure shows the actual final RES-H&C for 2005-2016, approximated estimates for 2017 and the expected realisations in the energy efficiency scenario of the NREAPs for 2018-2020. The consumption of RES accounts for only biofuels complying with the RED sustainability criteria.

Sources: EEA; Eurostat, 2018d; NREAP reports.

Figure 28. EU's Renewable Energy deployment in the renewable heat sector (RES-H)

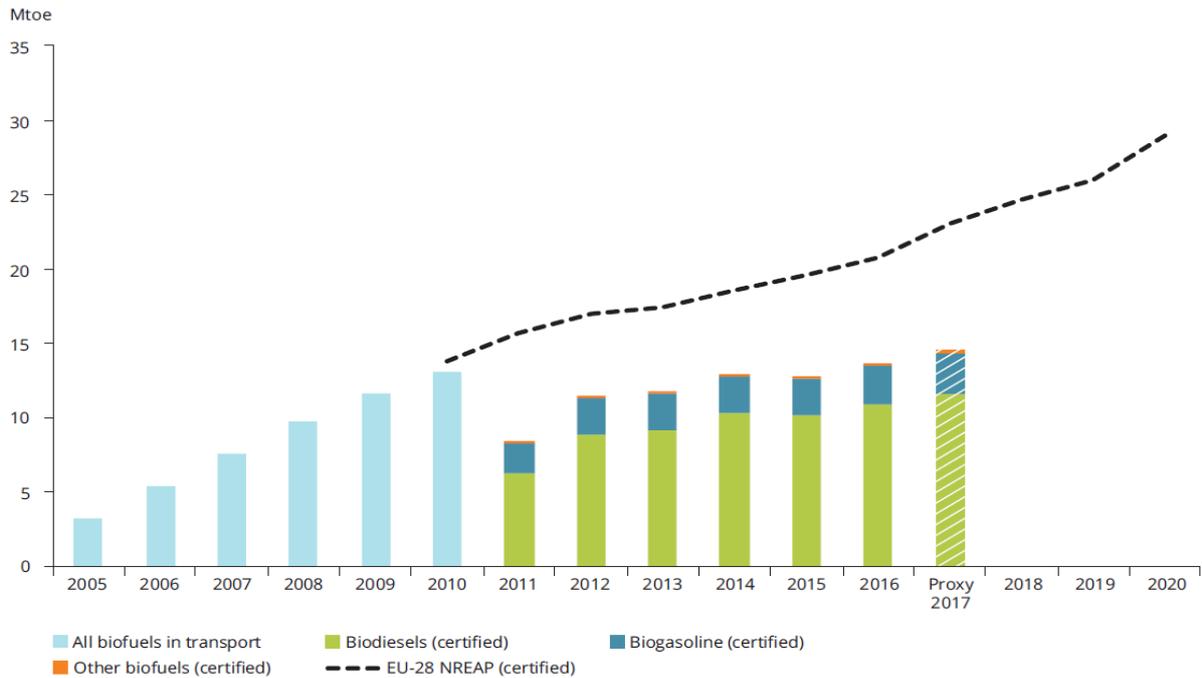


Figure 29. EU's Renewable Energy deployment in the renewable transport sector (RES-H)

Currently a significant proportions of EU MS have already achieved, or are close to achieving their respective 2020 RED (Renewable Energy Directive) targets based on EEA RE data projections (EEA, 2019), with the positive outcome largely attributed to the rapid deployment of the RE mix as stated above (Figure 30).

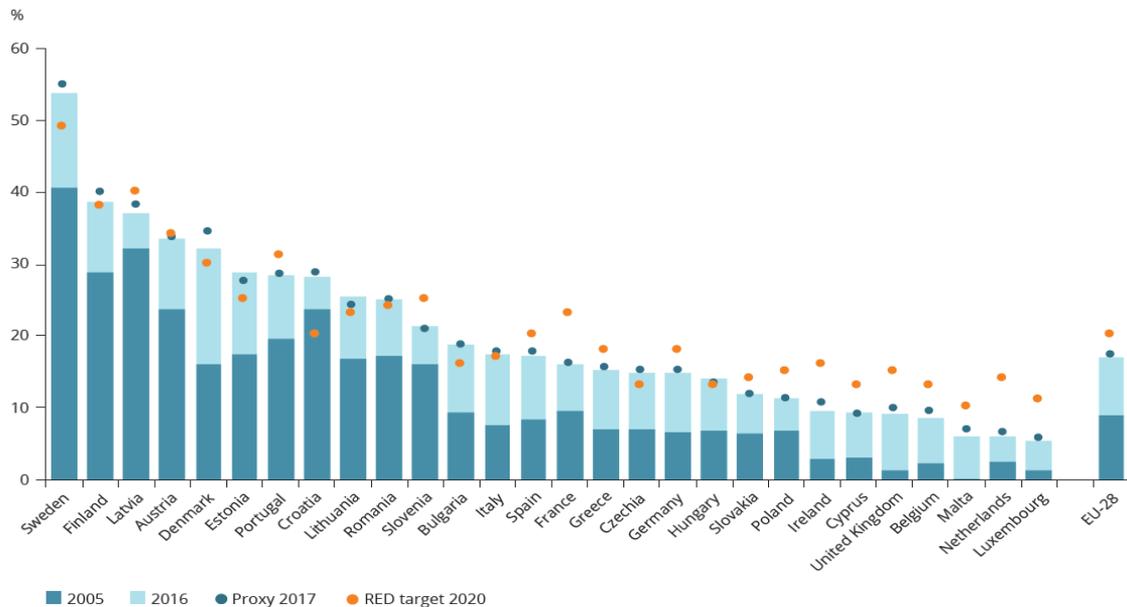


Figure 30. Actual and approximate RES shares in the EU and its Member States (EEA, 2019)

2.3.12 EU's Transport sector in context of Renewable Energy deployment

To-date, EU's transport sector (TS) constitutes key high emission sector that face the greatest decarbonisation challenge given the lack of appropriate renewable energy technologies and fuel options available.

This is further evidenced by data showing transport representing almost a quarter of Europe's GHG emissions but has not seen the same gradual decline in emissions relative to other sectors, with road transport being by far the biggest emitter responsible for over 70% of total transport GHG emissions in 2014 (Figure 31 and Figure 32) (EC, 2019m).

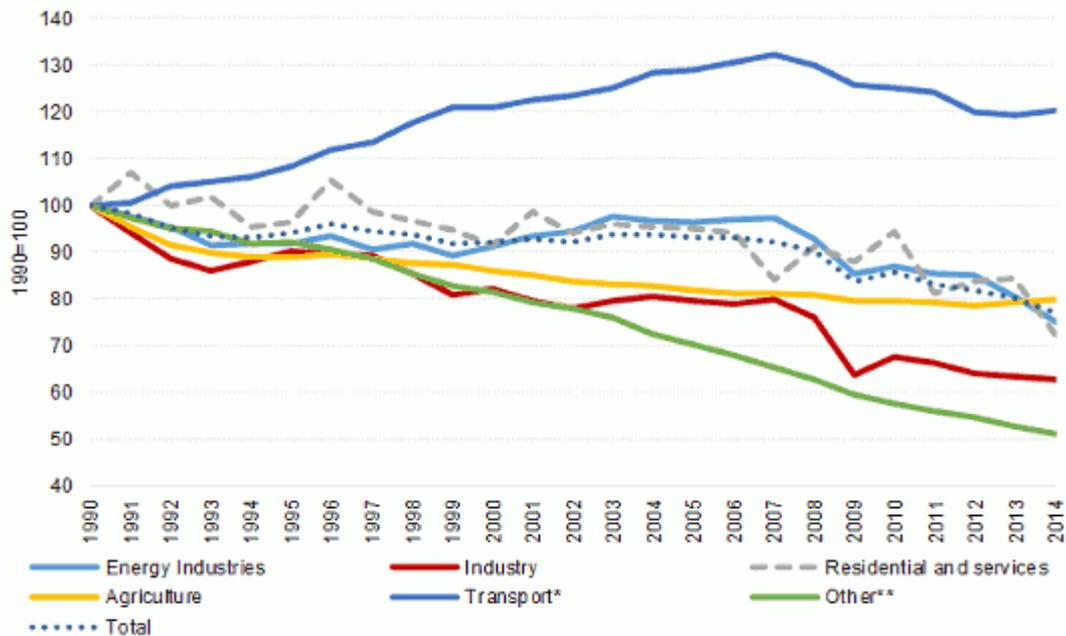


Figure 31. EU major sector emissions benchmarked against 1990 emissions data (EC, 2019m)

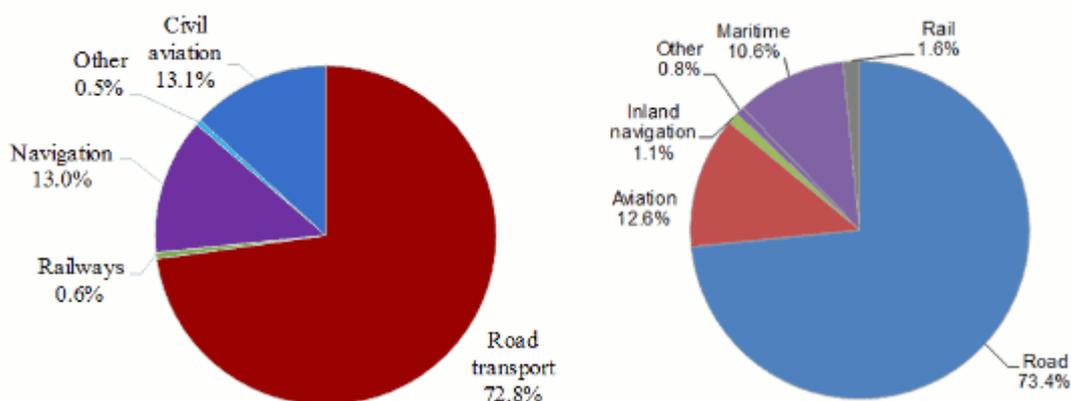


Figure 32. EU data on transport sector i) GHG emissions by mode in 2014, and ii) Share of transport energy demand by mode in 2014 (EC, 2019m)

Although anticipated road passenger vehicle electrification has recently taken off and presents one viable solution for the foreseeable future, there still remains significant uncertainties surrounding maintaining the speed of such transition due to real-world restrictions in resource (i.e. heavy metal) availability for EV battery production.

These developments, especially when set against the backdrop of an estimated requirement to lower EU's transport sector (EU-TS) GHG emissions by least 60% by 2050 (relative to 1990 figures), further implicates the continued importance of biofuel towards decarbonising the EU-TS sector at least in the short to medium term.

To this end, IEA in their transport fuel technology roadmap has identified both conventional biofuels currently in use and advanced biofuels under development for selective future application in context of other renewable transport fuel technologies, with the 4 main biofuel categories to constitute bioethanol, diesel type biofuel, biomethane, hydrogen and other biofuel types (Figure 33).

The roadmap also identified biogas and first to second generation biofuels to constitute a viable short to medium term solution, with hydrogen, synthetic and novel biofuels to constitute an important medium to longer term transport biofuel solution.

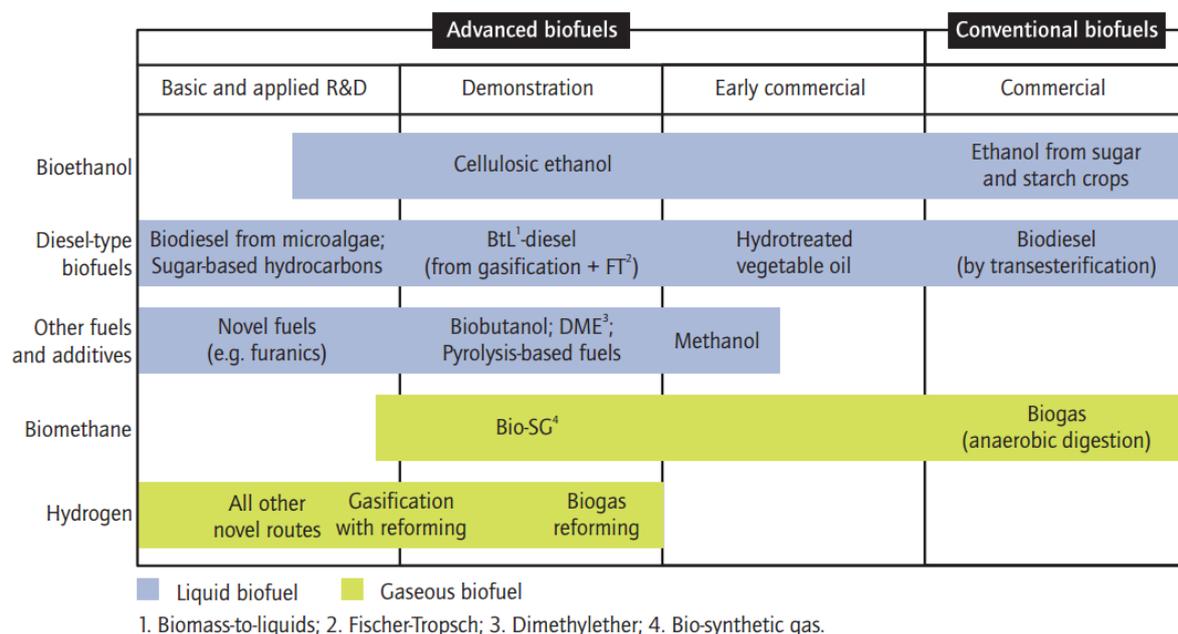


Figure 33. Fuel development status of main biofuel technologies (IEA, 2011)

These clean transport fuel adoption strategies that fall under the EU's broader European Strategy for Low-Emission Mobility (ESLEM), which identified 2 additional priority areas of increasing transport system efficiency and a transition towards zero-emission vehicles. The strategy also implicates the importance of city and local authorities in driving this change, under the specific transposed transport strategies of each EU Member States (MS).

The urgency with which these 3 priority areas need to be achieved is reflected by the significant mechanism and funding support which the EU TS received to-date, with the Investment Plan for Europe to play a very important role through projects currently pending or in progress under European Fund for Strategic Investment (EFSI) (EIB, 2019).

Consequently, significant additional funding that amounted to €70bn for transport under the ESIF were also made available, including €39bn for supporting transition towards low-emission mobility and €12 for low-carbon and sustainable urban mobility on top of €6.4bn funding from Horizon 2020 set aside for low-carbon mobility projects (EC, 2019m) (Figure 34).

EU funding for transport sector decarbonisation	European Fund for Strategic Investment (EFSI)
	European Structural and Investment funds (ESIF)
	€39bn for transition to low-carbon mobility
	Horizon 2020 (Research Framework 8) funding
	€ 6.4bn for low-carbon mobility projects

Figure 34. Major EU investments for decarbonisation the EU's transport sector

2.4 Theme 3 – UK as a key European nation for tackling Climate

The UK represents one of the most unique and important nation within the European economy for distinct reasons of contribution, ambition and change. These are respectively portrayed by UK's longstanding major contribution towards European economy and share of overall GHG emissions (2nd largest overall) (Table 10), highly ambitious GHG reduction targets and the advent of Brexit.

Table 10. Total GHG emissions by country (including international aviation, indirect CO₂ and excluding LULUCF), 1990-2017 (EU, 2018)

(Million tonnes of CO₂ equivalents)

	1990	1995	2000	2005	2010	2015	2017	Share in EU-28*
EU-28	5 722.9	5 397.8	5 287.2	5 362.0	4 917.5	4 470.3	4 483.1	100.0%
Belgium	149.7	157.6	154.5	148.9	137.1	121.6	119.4	2.7%
Bulgaria	102.6	75.5	59.8	64.5	61.1	62.2	62.1	1.4%
Czechia	199.8	158.7	151.1	149.5	141.7	129.5	130.5	2.9%
Denmark	72.1	80.1	73.2	68.8	65.5	50.8	50.8	1.1%
Germany	1 263.2	1 138.1	1 064.7	1 016.5	967.0	931.8	936.0	20.9%
Estonia	40.5	20.3	17.4	19.3	21.3	18.3	21.1	0.5%
Ireland	56.5	60.3	70.3	72.0	63.4	61.7	63.8	1.4%
Greece	105.6	111.8	128.9	138.9	121.0	98.2	98.9	2.2%
Spain	293.3	335.3	397.1	452.6	370.1	351.8	357.3	8.0%
France	556.6	553.8	567.0	570.7	528.0	477.3	482.0	10.8%
Croatia	32.4	23.2	26.1	30.3	28.4	24.6	25.5	0.6%
Italy	522.1	538.3	562.1	589.2	514.7	443.7	439.0	9.8%
Cyprus	6.4	7.9	9.2	10.2	10.3	9.1	10.0	0.2%
Latvia	26.5	13.0	10.6	11.6	12.7	11.6	11.8	0.3%
Lithuania	48.6	22.5	19.6	23.0	20.9	20.5	20.7	0.5%
Luxembourg	13.1	10.7	10.6	14.3	13.4	11.6	11.9	0.3%
Hungary	94.2	75.9	73.9	76.2	65.7	61.3	64.5	1.4%
Malta	2.3	3.0	3.1	3.2	3.2	2.5	2.6	0.1%
Netherlands	226.4	239.3	229.8	225.8	224.1	207.5	205.8	4.6%
Austria	79.6	80.9	82.1	94.5	86.8	81.0	84.5	1.9%
Poland	475.0	445.7	396.3	404.3	413.1	392.3	416.3	9.3%
Portugal	60.8	70.8	84.3	88.1	71.7	71.1	74.6	1.7%
Romania	248.9	187.8	143.6	151.7	124.4	117.2	114.8	2.6%
Slovenia	18.7	18.8	19.1	20.6	19.7	16.9	17.5	0.4%
Slovakia	73.4	53.3	49.2	51.3	46.4	41.8	43.5	1.0%
Finland	72.3	72.8	71.3	71.2	77.4	57.2	57.5	1.3%
Sweden	72.7	74.7	70.4	68.6	66.4	55.7	55.5	1.2%
United Kingdom	809.9	767.6	741.9	726.2	642.1	541.5	505.4	11.3%
Iceland	3.8	3.7	4.4	4.4	5.2	5.4	5.9	0.1%
Lichtenstein	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.0%
Norway	51.9	51.8	55.7	56.3	56.8	56.1	54.4	1.2%
Switzerland	56.7	56.1	57.2	58.3	58.5	52.9	52.6	1.2%
Turkey	219.8	248.4	300.5	340.6	404.6	483.4	537.4	12.0%

*Share in EU-28 total in year 2017

Source: European Environment Agency (online data code: env_air_gge)

These 3 notable developments are by no means completely disconnected and is indicative of the disruptive changes which the UK is driving on all fronts. Herein an optimistic outlook would lie in the emerging opportunities in climate change arising from renewed opportunities for UK

to drive disruptions across its key domestic energy sectors without significant restrictions imposed by to existing EU regulations and rules.

2.4.1 UK historical efforts against climate change

Historically, UK's effort against climate change was first formalized under the 2008 Climate Change Act (CCA) as part of EU's climate action efforts. This led to establishments of a series of legally binding short to long term GHG emission and related reduction targets (see Table 12) that constitutes EU's endeavour to achieve the long term milestones of over 80% GHG reduction (relative to 1995 levels) by 2050.

To this end, renewable energy (RE) technology research, deployment and generation is universally cited by international bodies and scientific reports to be key towards achieving the set targets, the importance of which is reflected by RE share of consumption targets by the UK and other EU MS (Table 11Table 10Figure 10).

Table 11. UK GHG climate change strategy with GHG reduction and renewable energy share targets in comparison with EU GHG reduction targets and equivalent MtCO_{2e} carbon budget

Target timeline	Short term - 2020	Short-Medium term - 2025	Medium Term - 2030	Long term - 2050
Initiative Name	Climate & Energy Package	Interim targets (no associated initiative)	Climate & Energy Framework	Climate & Energy Roadmap
GHG emission reduction (relative to 1990 levels)	20% UK wide (CCC, 2016) 42% for Scotland (CCC, 2016)	51%	57% (The Guardian, 2016)	80% (CCC, 2016)
Renewable Energy share	15% (Parliament, 2018)	Data not available	Data not available	Data not available
EU GHG reduction targets vs. 1990 baseline emissions	20%	No data	40%	80-95%
Equivalent MtCO _{2e} value	2,544	1,950	1,725	No data
Carbon budget set out	3 rd Carbon Budget (2018-2022)	4 th Carbon Budget (2023-2027)	5 th Carbon Budget (2028-2032)	N/A

Source: (Committee on Climate Change, 2017; Gov.UK, 2008; The Guardian, 2016); Green = legally binding

2.4.2 UK's climate change targets as stipulated by its Climate Action Plan (CAP) and the impact of Brexit

The UK's climate change targets, as briefly alluded to earlier exhibits ambitious mid-term GHG reduction milestones (51%, 57% and 78% by 2025, 2030 and 2035 respectively). This though currently coincides with a relatively less certain medium to long term RE deployment target, owing to mixture of technological, business, economic and political (climate change news, 2018) uncertainties.

It however remains a question of the differences in the broader strategic outlook between UK and EU following Brexit, which will inevitably trigger certain changes such as those in relation

to EU funding allocations and collaborations to pave way for limitations and emerging opportunities for UK's future CAP.

In summary, these developments to-date embodies UK's strong foundation and now, autonomous capability to tackle climate change (independent of EU mandates) as it focuses on emerging new opportunities for growth and progression in renewable energy deployment. Here the key to success will likely reply on concerted investment and deployment efforts through adopting an integrated technological, economic, social and environmental approach to reflect the multi-dimensional issue of tackling climate change.

2.4.3 UK's domestic strategy towards climate change

To this end, the UK formalized a number of forthcoming climate change mitigation strategies in their integrated reports on climate change, with two notable examples being the draft 2018 NECP (DBEIS, 2019) and the UK national adaptation programme (UK NAP) (DEFRA, 2018). Notably, the UK NAP adopts an integrated approach to tackle climate change by stipulating key focus on the multidimensional criteria of natural environment, infrastructure, people and the built environment alongside business and industry.

An added element would be the UK's devolved approach towards tackling climate change and other environmental sustainability targets, whereby Local Authorities are given significant independent authority and responsibility address relevant local issues, i.e. of waste, emissions, transport, etc.

Here it is also important to note the overview of solutions in context of targeting these sectors presented here constitutes a grossly simplified view of the real world, where fundamental importance is also applied in other sectors with direct and indirect connections to Renewable Energy Sector (RES) and High Emission Sector (HES). Namely, these include factors both included or beyond those elucidated in the UK NAP report (Figure 35), i.e. education, energy efficiency, material sciences and environmental sectors, all which contributes to the overall rate of development RES, HES and other contributory sectors to climate change mitigation as part of an interconnected system. However, given the specific focus on the literature review, a line is drawn in focusing on RES and HES for adding focus.

2.4.4 UK's Renewable Energy Sector (RES) and High Emission Sectors (HES)

Traditionally, these HES sectors include UK's industry, transport, residential, business and power sectors according to categorizations by major research and government organisations such as the CarbonBrief and DECC (Department of Energy and Climate Change). Relevant findings to-date suggested significant annual reductions in emission across all HES apart from the transport sector (TS) through a combination of measures involving improving energy efficiency, reducing energy use and RE adoption (see Figure 35 and Figure 36).

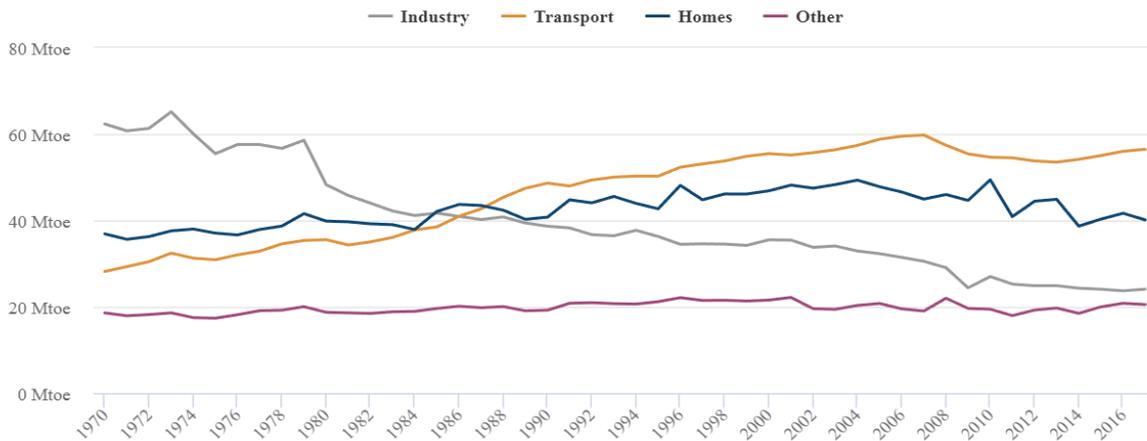


Figure 35. UK energy use by sector (Mtoe), 1970-2017 (Carbon Brief, 2016)

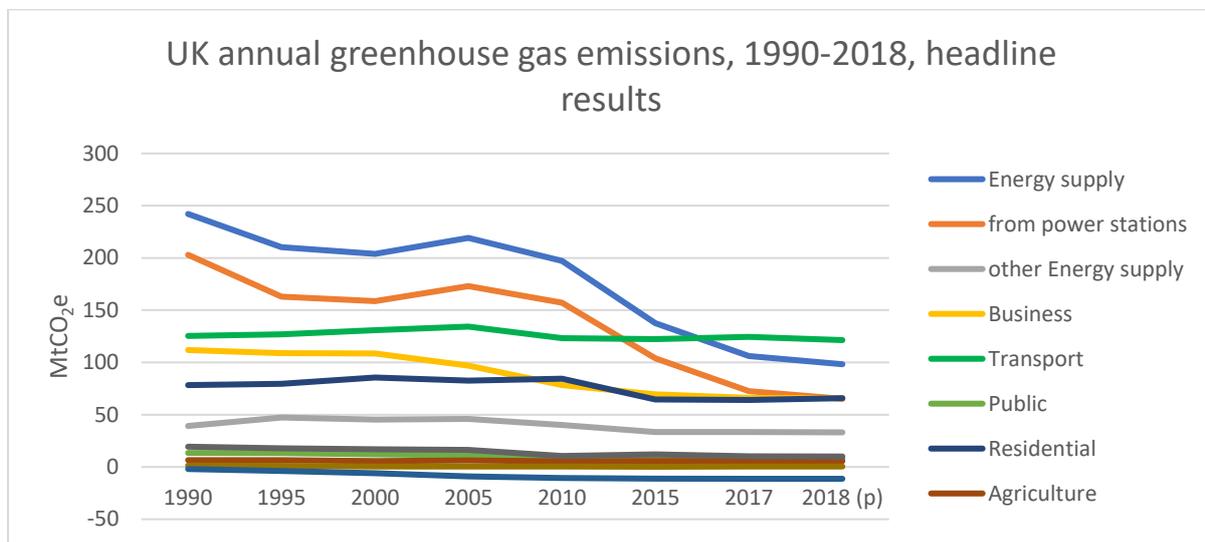


Figure 36. UK annual greenhouse gas emissions, 1990-2018, headline results (with 2018 results being provisional) (DECC, 2019)

These trends mirrors that of EU's own HES emission trends, which emphasises the reality of greater challenges associated with decarbonising the transport sector relative to other HES. Herein road transport (RT) emission vastly exceeds all other transport modalities (approximately 75%) given the sheer dominance of RT activity relative to flight, rail and sea transportation, with passenger car and taxis contributing the greatest emission component followed by HDVs and vans.

An interesting trend however also sees flight transport emission to have significantly increased over the past 2 and half decades against plateauing of RT emissions due to increase in domestic and international aviation activities (Figure 37).

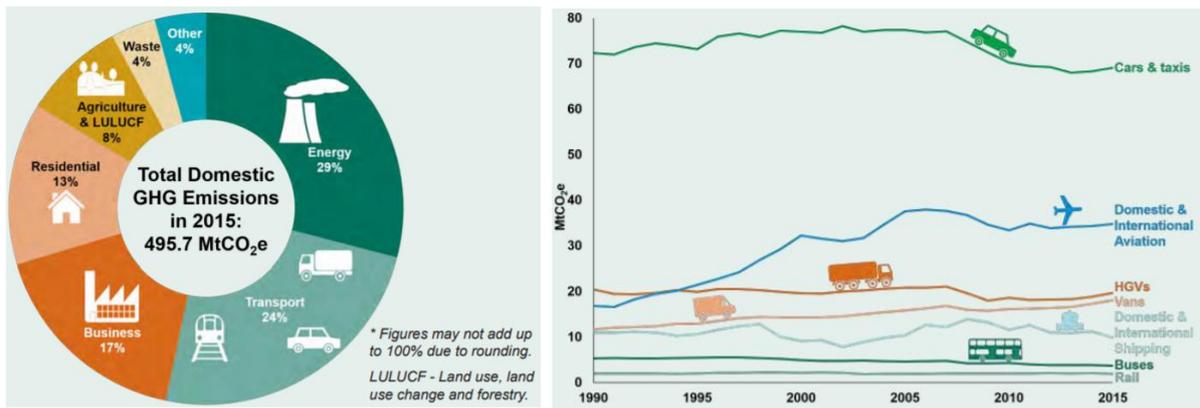


Figure 37. UK Domestic Green House Gas (GHG) emission overview i) 2015 data for TS emission as % relative to other HES (left), ii) total emission of each transport modality within TS (right)

Both freight (HGVs and vans) and passenger (cars, vans and taxis) transport presented constitute UK's RT sector, the latter has seen significant growth within the past 2 and half decades. The data driven observation of stabilizing GHG emission across all RT transport sector modalities over the same period further indicates slower rate of GHG emission mitigation technology adoption and deployment for road freight transport (RFT) relative to (RPT) road passenger transport (Figure 38).

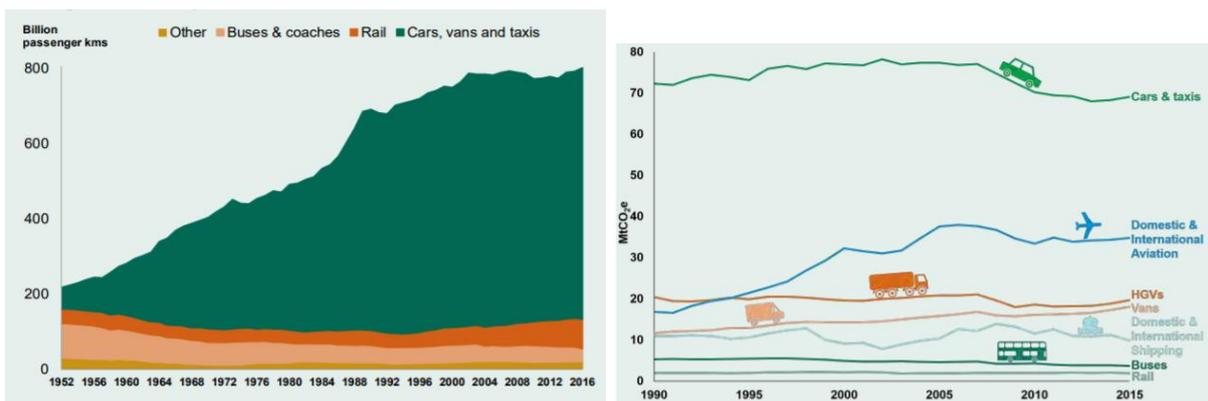


Figure 38. UK road vehicle activity (Left) vs. total GHG emissions (right) by road transport modality between 1990 and 2016.

Whilst key solutions of adopting greater alternative transport fuel and reduction of overall TS activity have been identified for mitigating TS emissions, real world implementation prove to much more difficult given the high investment costs and business risks involved. This is especially true against the backdrop of strong competitions from conventionally fuel vehicles against other barriers such as existing infrastructure availability and social acceptance associated with adoption of novel alternatively fuelled transport, i.e. electric vehicles (EV). Consequently, for swift technology transition to occur, this 'lock-in effect' and 'chicken and egg conundrum' but be addressed and overcome, which to-date it has to some extent through significant investments in EV primarily within the road passenger transport industry.

To-date, it is generally accepted that UK must at least maintain if not accelerate its renewable energy transition across its entire transport and other HES if it is to achieve its ambitious long term GHG emission reduction targets of at least 80% by 2050 (Ekins et al., 2013).

2.4.5 UK and EU strategies towards addressing the issue of Transport Sector (TS) decarbonisation

Similar to aforementioned EU's climate action strategy, UK's decarbonisation strategy also revolves around strong governmental, institutional and private funding alongside policy incentive support to overcome the 'lock-in effect' (LIE) and 'chicken and egg conundrum' (CAEC) of conventional fuel use.

The deployed strategy centres on improving existing (i.e., conventional fuel emission) technologies alongside executing R&D and gradual deployment of ATF technologies, vehicle and infrastructure. For UK's transport sector, the focus shifts specifically on simultaneous advancements in fuel technology and propulsion technologies in addition to the logistics of their integration through existing or newly built infrastructure (EC, 2013, 2016b).

The UK's technology transition roadmap within the road transport sector is underpinned advancements in vehicle gasification and electrification infrastructure and technology through combination of strong public and private investment support. These includes rapid expansion of anaerobic digestion plant facilities within the past 2 decades, and current investment focus on deployment of biomethane or EV refuel stations alongside innovations in battery electric battery, electric population and biomethane propulsion technology.

Here an often overlooked low hanging fruit of TS decarbonisation would be deployment of biomethane refuel stations and heavy duty vehicle (HDV) fleets that could more effectively utilize existing biomethane generation capacity to replace fossil fuel use. Such deployments to-date had only occurred at fragmented local fleet level, which realizes very limited economic and environmental benefits arising from economies of scale. The ideal progression would be to develop a national network of refuel infrastructure for biomethane HDV to ensure universal fuel availability for increasing fleet population utilizing biomethane propulsion technologies.

2.5 Theme 4: UK renewable energy development in context of energy flow to key sectors

UK's renewable energy landscape has seen strong upward growth in their share of total energy consumption since 2010, with bioenergy, wind, solar and hydro energy to constitute main contributors of such growth in replacing conventional fossil fuel use (Figure 39).

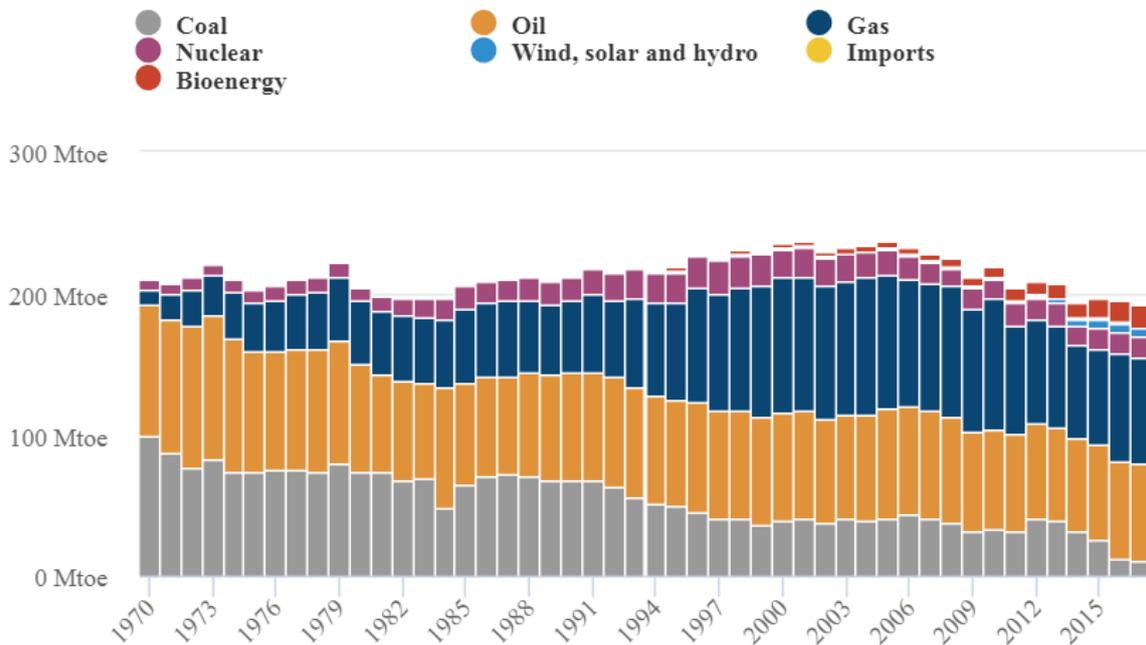


Figure 39. UK primary energy use by source, millions of Tonnes of oil equivalent (Mtoe), 1970-2017 (Carbon Brief, 2016)

The growth in bioenergy more specifically, had been a rapid increase as total share of energy consumption since around 2010, with together with increases in consumption growth of other renewable alternatives, demonstrates a strong optimistic outlook for the future of decarbonising UK's high emission sectors.

2.5.1 UK electricity generation by source

An overview of UK's RE landscape focusing on electricity generation also indicates significant greater share of RE dominance, with total RE electricity generation to have almost doubled from 14.9% in 2013 to 27.9% in 2017 (Figure 40). These increases are likely attributed to strong growth in the production capacity across all RE sectors, with wind and biomass derived energy to constitute the top 2 contributors (Figure 41).

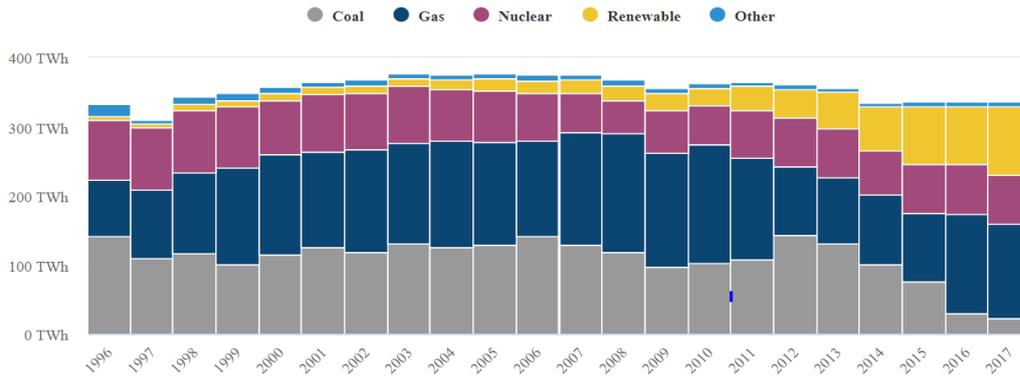


Figure 40. UK Renewable electricity generation from 1996 to 2017 (carbonbrief, 2018)

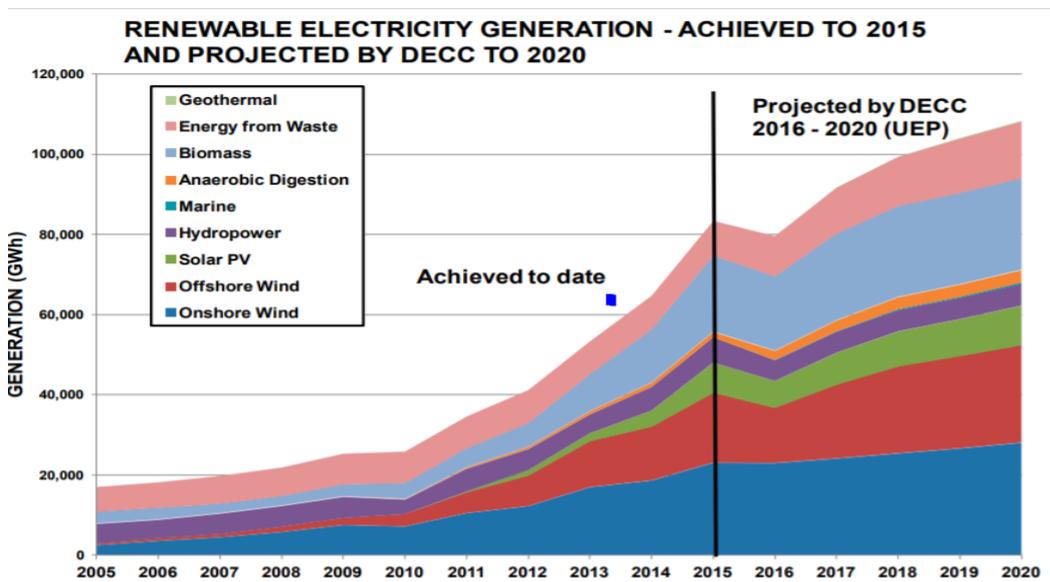


Figure 41. UK Renewable generation data and projections by the DECC from 2005 to 2020 for each Renewable Energy category (UK Renewable Energy Association, 2016)

Interestingly, there exist significant discrepancies in the magnitude of sector specific energy production relative to their total installed capacity as likely indicator of the degree of their intermittency or estimated 'down time'.

The latter shows prominence of solar PV alongside wind energy in terms of capacity for RE generation (see Figure 42). Here the data driven trend illustrates a much greater RE generation contribution to installed capacity ratio for RE derived from AD plant biomass compared to other RE types primarily attributed to the non-intermittent nature of AD-biomass generation. Conversely, solar energy demonstrated greatest levels of intermittency where installed capacity falls far below actual generation arising presumably from limited access to sunshine at sites of installation (Figure 42 and Figure 43).

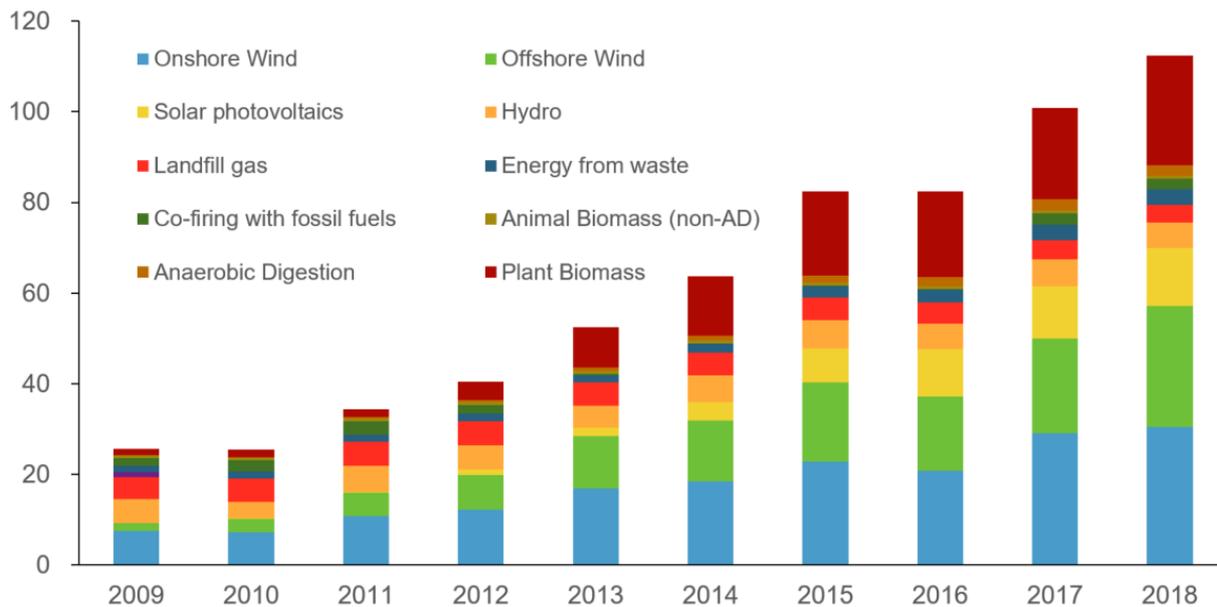


Figure 42. Renewable energy generated from each UK RES from 2009-2018 expressed in units of TWh (UK.GOV, 2019)

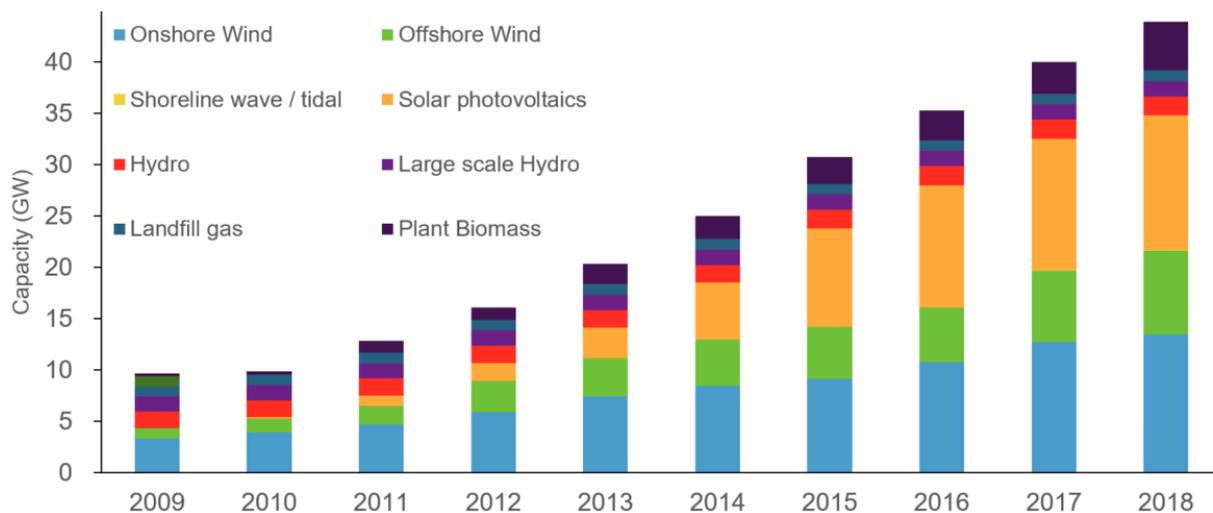


Figure 43. UK Renewable energy generation capacity for each RES from 2009-2018 expressed in units of TWh (UK.GOV, 2019)

In line with these findings, data on UK's progression from past to present in its overall renewable and non-renewable energy mix also indicates gradual albeit noticeable shifts from fossil fuel to RE use. The shift to date however arises from replacement of fossil coal and petroleum usage to greater bioenergy and renewable electricity generation across all domestic HES sectors.

Forthcoming future shifts in energy mix will increasingly replace fossil petroleum and coal fuel application with increasing share of renewable and nuclear energy. One scenario estimation highlights near complete replacement of coal and petroleum fuel with majority of energy demand to derive from gaseous and renewable sources.

Herein TS fuel being a potential exception (as fossil petroleum could constitute part of all of liquid fuels). Herein, routes towards TS decarbonisation through ATF deployment (of biofuels and renewable electric power) becomes a critical area of focus in determining the magnitude of petroleum energy demand, with an inverse relationship between these two energy sources (see Figure 44).

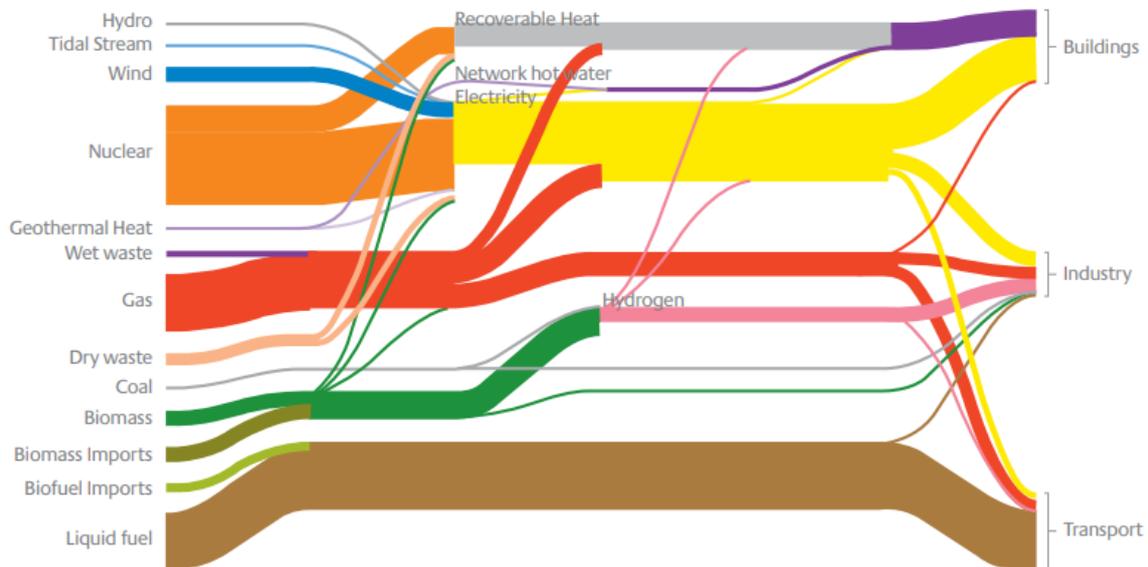


Figure 44. Estimation of bioenergy contribution to overall energy mix in 2020 to 2050 for building, industry and transport industries, electricity generation from all renewable energy sources and nuclear shown in yellow can be applied to UK's transport sector should electrification of road vehicles become mainstream.

Also of strong relevance, is the increasing opportunity for electrification of both road passenger and freight transport, which consequently brings other RE sectors of renewable electricity production into context and will likely shift the dynamics of UK's overall renewable energy production routes for TS consumption.

2.5.2 Concluding themes of focus for future of transport sector decarbonisation

These collective trends in UK's renewable energy consumption and electricity generation in context of overall past, present and future energy mix projections indicate strong barriers to, and consequently business and research opportunities for TS decarbonisation.

Several key themes, namely, alternative transport fuels (ATF) in form bioenergy and renewable electricity generation, opportunities from waste, barriers towards deployment and implementation alongside policy incentive and other support had proven to be crucial in their relative contribution to potential solutions moving forward and will be sequentially elaborated in following parts of the literature review.

2.6 Theme 5: Emerging opportunities in bioenergy application (as biomethane and electricity) for decarbonising the transport sector (TS)

2.6.1 Bioenergy as a versatile fuel source for GHG emission mitigation

The field of bioenergy is by no means a novel concept but is one that is taking off significantly since within the past 2 decades attributed to scientific and international community's recognition of its pivotal role towards tackling climate change (i.e. those by IPCC, as mentioned in theme 1 of the literature review).

The exclusive qualities of bioenergy as a renewable source which other energy lack arises from its versatility of a fuel source and it being the most viable alternative fuel option to conventional transport fuels, as eluded to at the end of theme 2 of the literature review (see Figure 45).

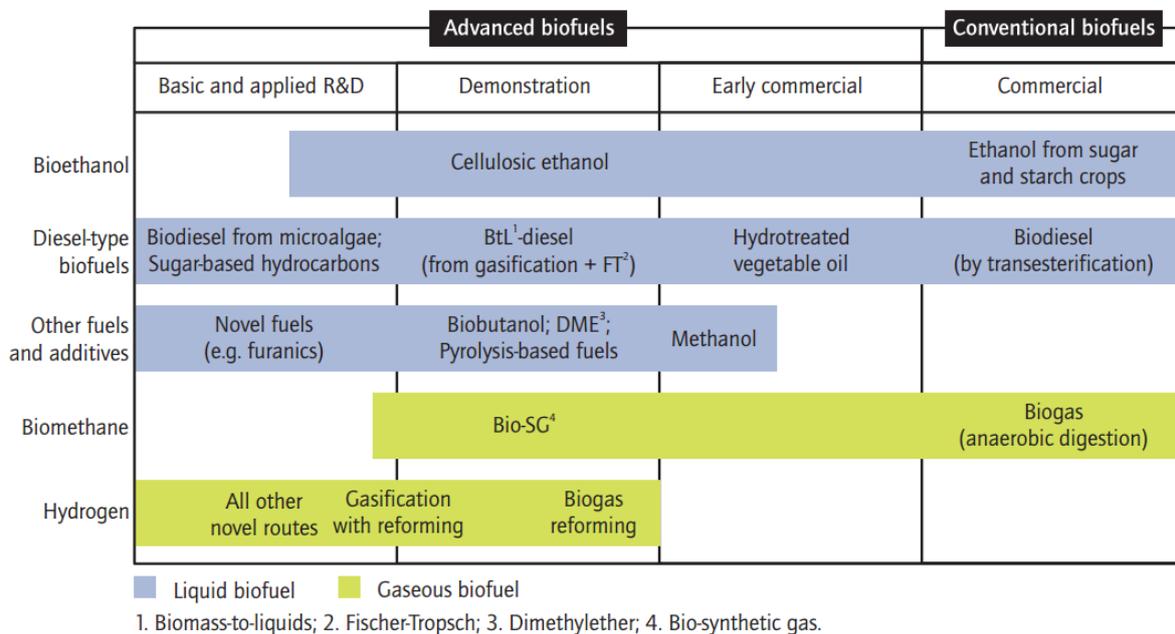


Figure 45. Fuel development status of main biofuel technologies (IEA, 2011)

Beyond this, bioenergy was also shown to constitute an important part of the overall renewable energy mix capable of enabling significant sectoral wide emission reductions across sectors beyond TS, as evidenced by data in theme 3 of the literature review above. This is further reflected by key trends demonstrating faster rate of growth in the application of bioenergy for primary energy use and renewable electricity generation relative to overall conventional and renewable energy mix (CarbonBrief, 2018; UK.GOV, 2019; UK Renewable Energy Association, 2016).

2.6.2 Forthcoming development and potential of bioenergy at the UK level

With the forthcoming decades to anticipate a continuation of growth within UK's bioenergy industry, the implications will likely entail widespread application of bioenergy across all HES in conjunction with other renewable energy sources, with variable contribution to each sector.

This is further reflected by an real-world future scenario comes from ETI 2050 projection, which sees UK bioenergy production to contribute greatly to hydrogen fuel formation for industry use (ETI, 2015) and beyond.

The projects are also closely linked with the changing dynamics of focus in biomass application between present leading into the long-term future (2050) across all HES to ensure an orderly transitional process of decarbonisation (Figure 46).

Between now and 2050, the current uses of biomass in the UK need to change:

	Most effective use today	2020s and 2030s	By 2050
 Bioeconomy	Wood in construction	Wood in construction, potentially other long-lived bio-based products (within circular economy)	
 Buildings	Biomethane, local district heating schemes and some efficient biomass boilers in rural areas		Only very limited additional use for buildings heat: niche uses in e.g. district heat and hybrid heat pumps
 Industry		Biomass use for processes with potential future BECCS applications	BECCS in industry alongside other low-carbon solutions
 Power	Ongoing use in power sector in line with existing commitments or small scale uses	Demonstration and roll out of BECCS to make H ₂ and/or power	Biomass used for H ₂ production or power with CCS
 Transport	Liquid biofuels increasingly made from waste and lignocellulosic feedstocks	Liquid biofuel transitioning from surface transport to aviation, within limits and with CCS	Up to 10% aviation biofuel production with CCS

Maximising abatement means using biomass to sequester carbon wherever possible (opportunities to do this will increase over time)

Figure 46. Hierarchy of best use for sustainable biomass resources between now and 2050. Source: Figure 2 in Biomass in a low-carbon economy, CCC 2018. (CarbonBrief, 2018)

Interestingly, much of such changes implicate an ultimate transition to adoption of carbon capture storage (CCS) technology and hydrogen fuel for the widespread applications in the industry, power and transport sector.

These developments are in good agreement with the longer term potential of bioenergy as iterated by IPCC in 5th assessment report (see theme 1) (IPCC, 2014), which also emphasized the importance of transition to hydrogen fuel and CCS (as BECCS, or Bioenergy with CCS) for achieving the greatest GHG mitigation levels by 2050 and beyond.

2.6.3 Bioenergy feedstock – a broad overview

An equally important element to adoption of BECCS would be the choice of biomass feedstock, which plays an important role in determining the baseline environmental and economical trade-offs involved in bioenergy generation. More specifically, such choices must address the conventional concerns surrounding land-use change, indirect environmental emissions and impacts alongside associated production or processing costs.

Presently the UK sources its biomass either through domestic production or imports, with the main categories contributing to bulk of UK's bioenergy generation being from energy crops (i.e. Willow and Miscanthus) and wood derived feedstocks alongside landfill gas.

Another recent trend is the popularization of bioenergy generation via anaerobic digestion and from waste derived feedstocks over the past decade, both which possess longer-term potential for further expansion, as will be eluded to in later section of this literature review on UK's 'Emerging opportunities in bioenergy application' (see theme 5) (Figure 47).

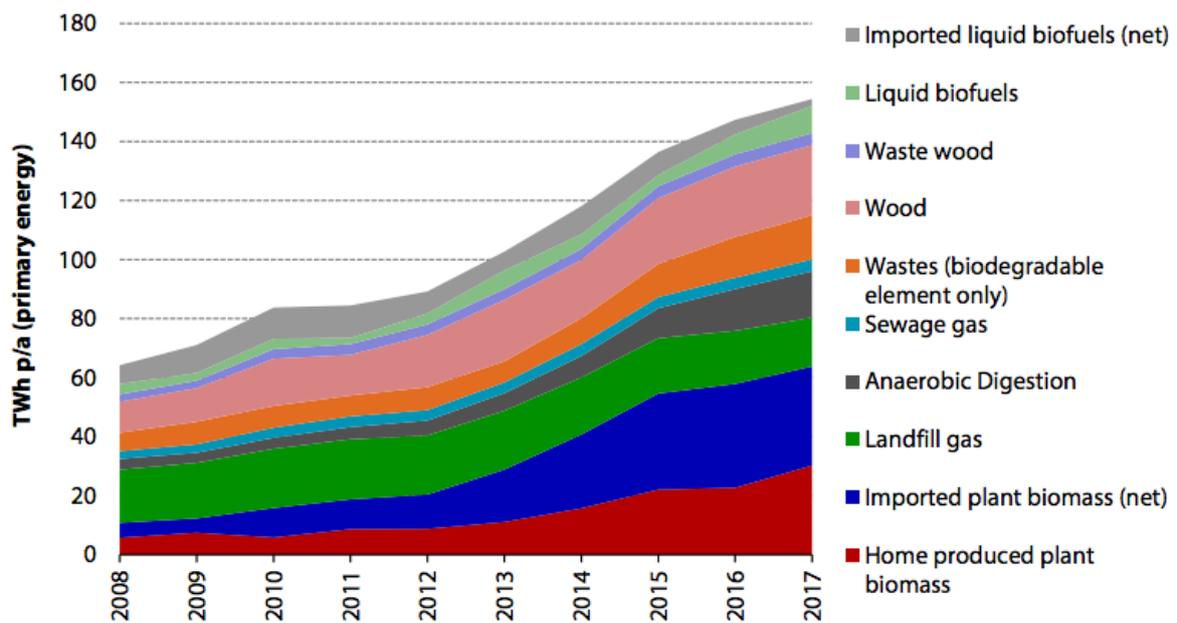


Figure 47. Bioenergy supply in the UK between 2008 and 2017, terawatt hours per year of primary energy (TWh/yr). Plant biomass includes straw, energy crops, short rotation forestry and wood pellets. Source: Figure 1.4 in Biomass in a low-carbon economy, CCC 2018, based on Department for Business, Energy and Industrial Strategy figures (CarbonBrief, 2018)

Moving forward, a number of projections have been made with regard to UK's changing bioenergy landscape in the future, with one such recent report to estimate strong growth of perennial energy crops and to a lesser extent, agricultural residues to constitute key increases in UK's future bioenergy potential (Figure 48).

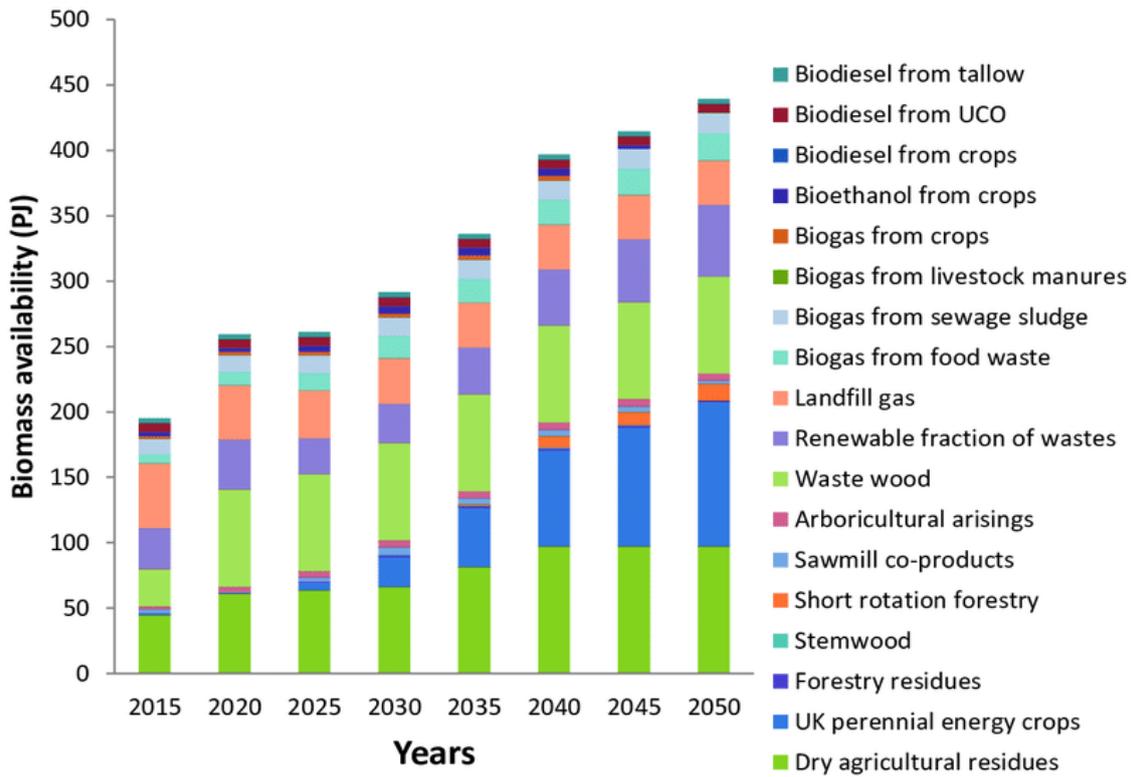


Figure 48. Projected UK biomass and waste availability between 2020 and 2050 (Natalie Gomez, 2017)

Whilst these current and anticipated future developments in bioenergy generation shows signs of promise in strong growth which infuses optimism, one key issue remains to be a lack of more sustainable means of biomass procurement. This is mainly attributed to potential scope for extra emissions and environmental degradation from land use changes and biomass imports, i.e., perennial energy crops and other plant biomass during the bioenergy generation process.

2.7 Theme 6: Barriers and opportunities surrounding implementing food waste to Transport Biomethane Conversion (FWtTBC) pathway

In comparison to use of conventional fossil fuels, alternative effective solutions exist which hinges on a strategic shift towards waste derived bioenergy generation for reasons of better economic practicality and environmental sustainability. Potential avenues here include use of wood and food waste amongst all biomass waste sources as easily categorizable and treatable waste feedstocks, with prior proof of concept has been demonstrated by existing best recycling practices from countries.

2.7.1 A mini-case study in the Swedish system of generation revenue from waste

A gold standard example of an adequate business model involves Sweden’s environmentally and financially sustainable FW disposal method, where decades of infrastructure investment alongside public acclimatization of good recycling practices has led to high levels of household FW (HHFW) recycling in AD plants for renewable energy and ‘green’ revenue generation whilst simultaneously minimizing waste and environmental pollution (Figure 49).

Biological treatment of household waste 1975–2017

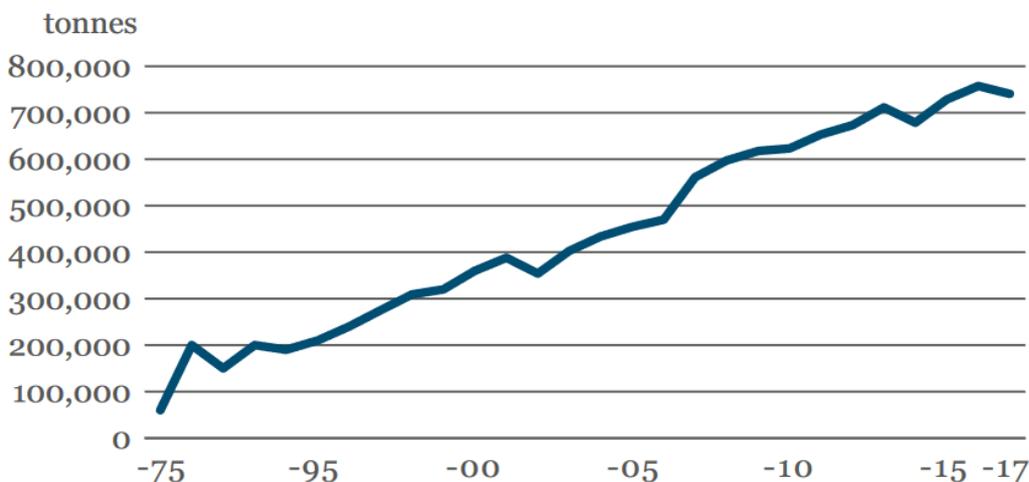
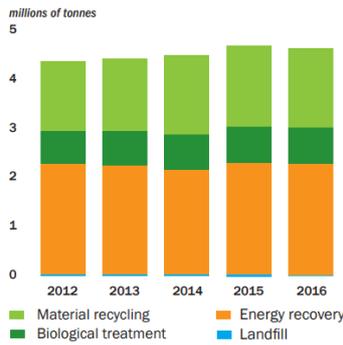


Figure 49. Biological treatment of household food waste from 1975-2017 (Avfall Sverige, 2013)

The legacy of infrastructure and good practice has also paved way for high rates of sustainable waste treatment methods to displace landfill disposal across all waste streams beyond household FW, which greatly contributed to a near waste-free economy of the Sweden seen today.

Namely, these alternative waste treatment methods include anaerobic digestion of household FW with other biological wastes eligible for anaerobic digestion, alongside material recycling and energy recovery of remaining wastes (Figure 50).

WASTE TREND 2017



OVERVIEW 1975-2016

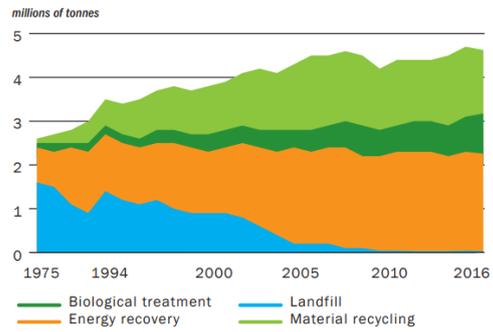


Figure 50. Sweden Waste recycling statistics. Left: from 2012, Right: From 1975 to 2016.

This recycling and business model has to-date led to an extremely strong waste to energy generation sector that saw a conversion rate of over 50% household waste to energy, with ambitious forthcoming targets of 40%, 63% and 75% AD-based HHFW recycling by 2020, 2030 and 2040, respectively (Naturvardsverket.se, 2019; Sweden.se, 2019) (Figure 51).

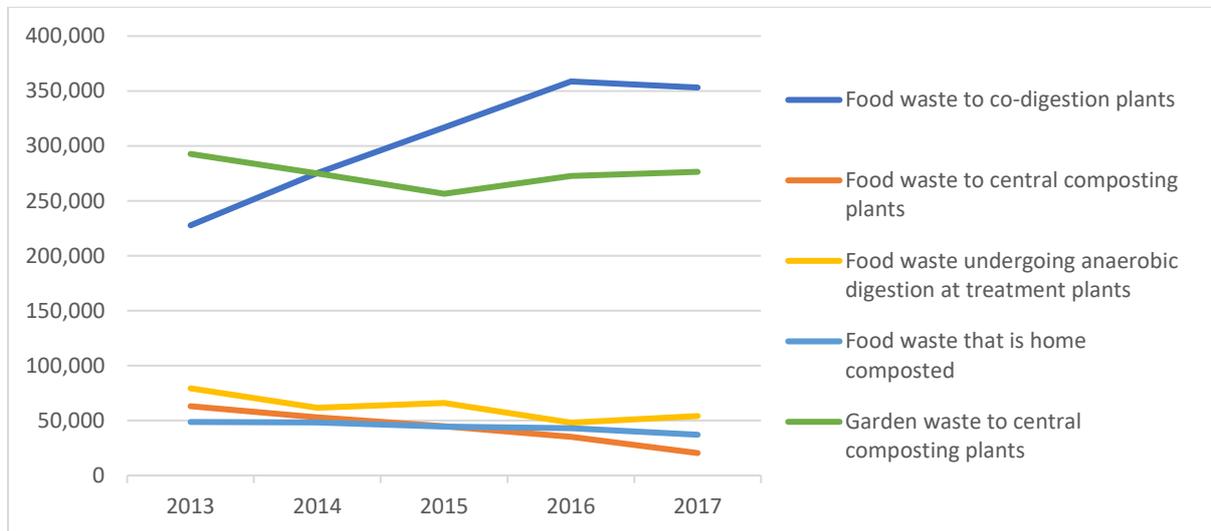


Figure 51. Biological treatment methods of household Food waste in Sweden from 2013 to 2017 (Avfall Sverige, 2013)

These FW recycling quantities constitutes over a quarter of all anaerobic digestion feedstock inputs used energy generation, which has seen an impressive growth of 72% (from 567,630 MWH to 975,680 MWH) between 2013 and 2017, most which are attributed to increase in vehicle gas generation (Avfall Sverige, 2013) (Figure 52).

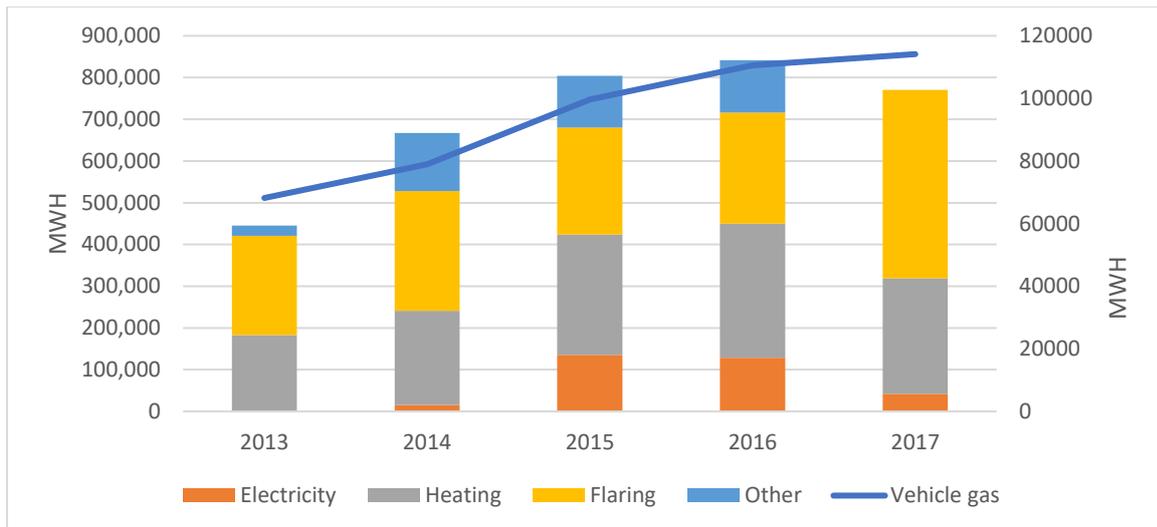


Figure 52. Sweden AD energy generation from biological waste, values in the left vertical axis represents vehicle gas, with values on the right vertical axis represents electricity, heating, flaring and other

The end outcomes consequently translate to significant financial, energy and environmental benefits on an annual basis, the importance of which will only increasing in the forthcoming decades due to enhanced emphasis on climate change and sustainability on a national and global level.

2.7.2 UK opportunity in and barriers to Food waste recycling – a general overview

The UK by contrast, possess significantly greater quantities of food waste discarded on an annual basis, which translates to significant avoidable GHG emissions and cost incurred for both household from procurement and local authorities from lost opportunities in waste to energy generation (Figure 53).



Figure 53. UK annual food waste figures for production, breakdown by type, revenue lost and CO₂ impact (GDS Infographics, 2019)

This is further exacerbated by the reality of a significant number of local authorities (estimated to be 50% in 2015) (Parliament.uk, 2017) still do not undertake dedicated (or segregated) FW recycling services for further biological treatment, as reflected by a 50% recycling rate of all UK Household FW (HHFW) by 2015 (Figure 54). The trend however does portray strong optimism from a near 3-fold increase in HHFW collection from 2008 to 2015, presumably

arising from increasing government focus to push forward local authority FW recycling schemes (Figure 54).

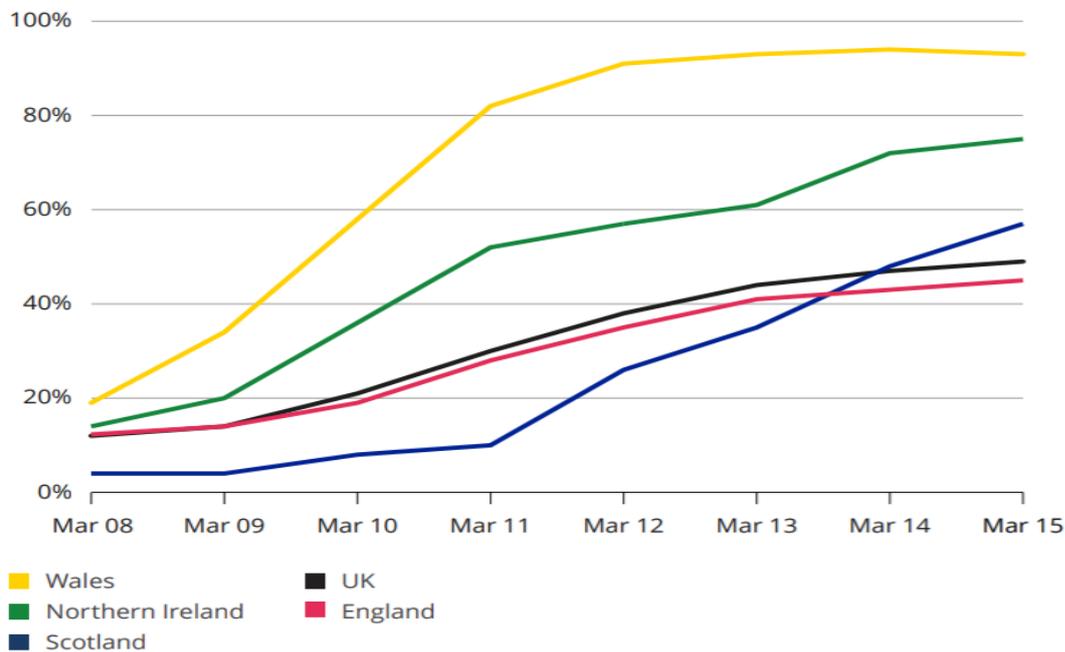


Figure 54. Percentage (%) of Households with a food waste collection (separate or mixed with garden), 2008/2008 to 2014/15 (WRAP, 2015a).

The question remains however as to the processing, treatment and/or disposal methods of the collected FW, in which recycling via the AD route constitutes by far the most desirable option favoured by both government and research organizations (i.e. WRAP) over other conventional alternatives such as recovery from incineration or direct landfill (Eunomia, 2016; Parliament.uk, 2017).

Key rationale for this is multi-fold, and centres on the optimal balance of return on investment (financial, energy, emission) and sustainability (emission and waste reduction) which AD-based FW recycling provides, which outstrips comparative benefits to all other FW post-collection treatment methods.

2.7.3 Barriers to UK food waste (FW) recycling and implications

This consequently implies that a significant proportion of FW being disposed as mixed waste which often undergo other less desirable routes of energy recovery (i.e. incineration) or landfilled (GDS Infographics, 2019), instead of undergoing recycling via AD. These often occur in key vulnerable local authority regions with little to no prior recycling scheme implementation and a lack of budget for participation in new FW recycling trials or schemes.

Critical barriers to this stems from the aforementioned lock-in effect and chicken and egg conundrum. To elaborate, many such non-participating local authorities possess a lack of infrastructure and established good practices alongside diminishing funding.

The latter is attributed largely to recent sharp steep central government funding cuts which significantly hampered investment confidence and elevated financial risk towards investments

in new AD-based FW recycling trials and schemes. Here the end outcomes constitute a vicious cycle of lock-in of these local authority regions to status-quo FW collection and disposal practices (Figure 55).

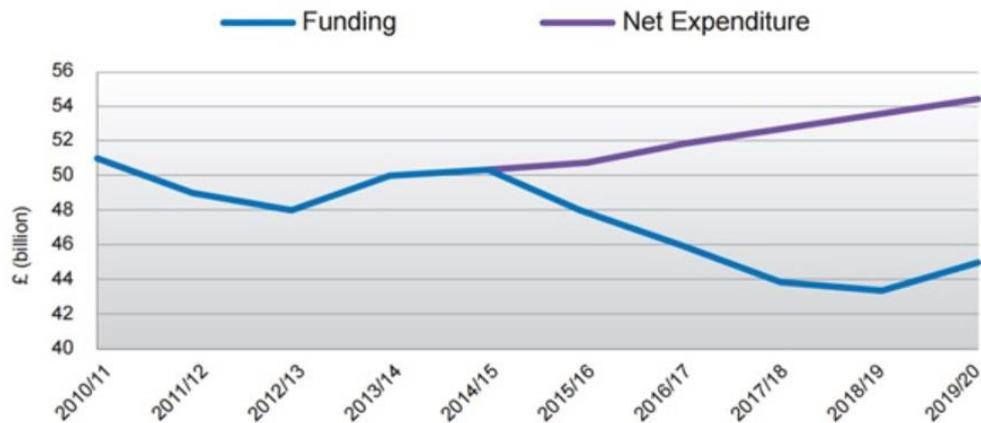


Figure 55. Local Authority income vs. expenditure between 2010 to present year (2018) and beyond (latter being estimations) (Local Government Association, 2015)

The Chicken and Egg conundrum lies in the area of financial investment and data or insight acquisition, which are critical for successful implementation of FW recycling trial and schemes (Figure 56).

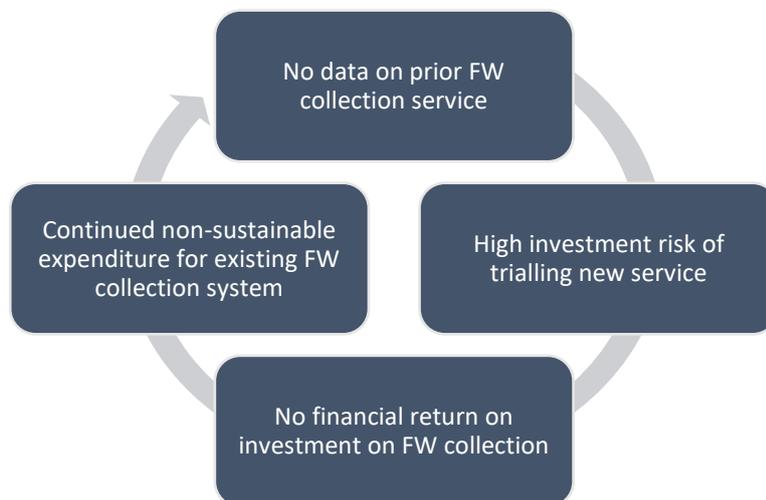


Figure 56. Chicken and egg conundrum on implementing FW recycling schemes (for transport energy conversion)

The current situation thus implicitly indicates a dangerous risk of legacy lock-in of UK's insufficient bio-waste recycling trend characterized by unsustainable business model where much funding is currently spent on maintaining non-recycling-based disposal services (with

growing waste quantities to be disposed annually) as opposed to being recouped from investments in waste recycling (i.e., bio-waste-to-bioenergy conversion). This is symptomatic of a systemic inadequacy or failure characterized by downward spiral of events, namely greater funding pressure for non-financially sustainable disposal of wastes overtime.

2.7.4 Overview of government support for sustainable FW to Transport Biomethane Conversion pathway

The risk of further perpetuating the systemic inadequacies for the deploying the FW to Transport Biomethane Conversion (FWtTBC) pathway as mentioned above have to-date been partially addressed by several key government strategies which encompasses financial incentives alongside measures to drive better organizational governance and social change.

These strategies collectively adopt an integrated top-down and bottom-up approach respectively through provision of tariff incentives alongside multi-level funding for projects and public schemes to drive public support of the FWtTBC pathway (Figure 57).

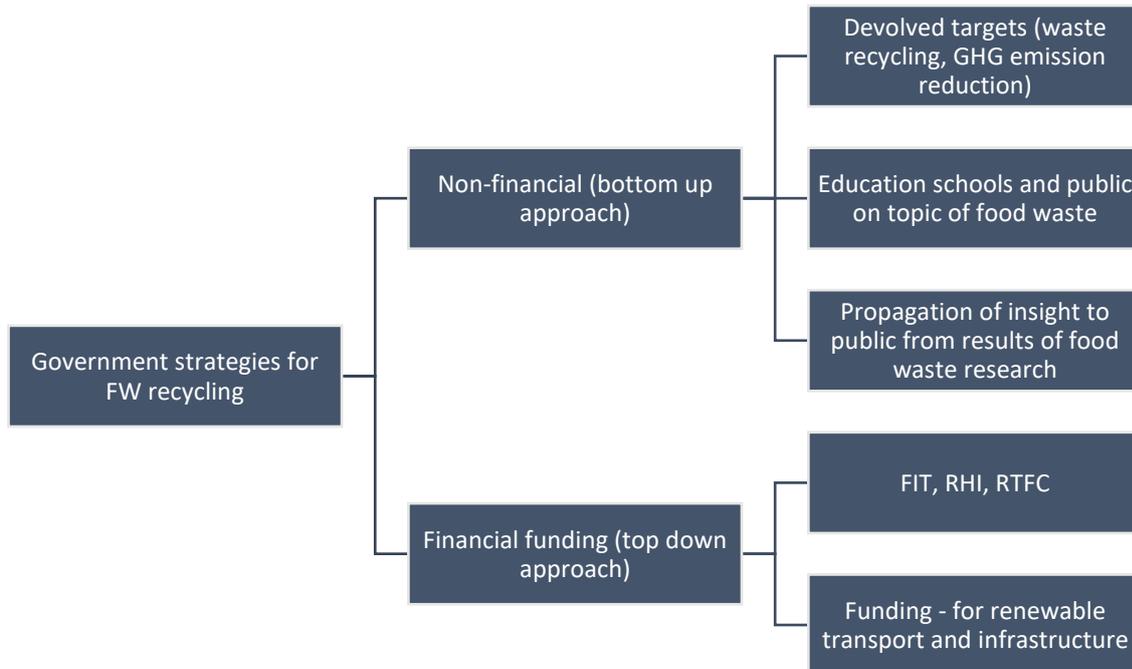


Figure 57. Summary of government strategy driving FW recycling for transport energy production

These strategies are collectively implemented within a devolved governance setting since 2016 via implementation of the UK devolution act (GOV.UK, 2017) that bestowed each local authority with greater power in managing their own FWtTBC strategies and climate change targets without forceful compliance to national targets. To this end, the EU's Waste hierarchy framework (EC, 2016c) is ubiquitously adopted for excellence of practice for waste management with prevention and disposal constituting highest and lowest disposal routes, respectively (Figure 58).

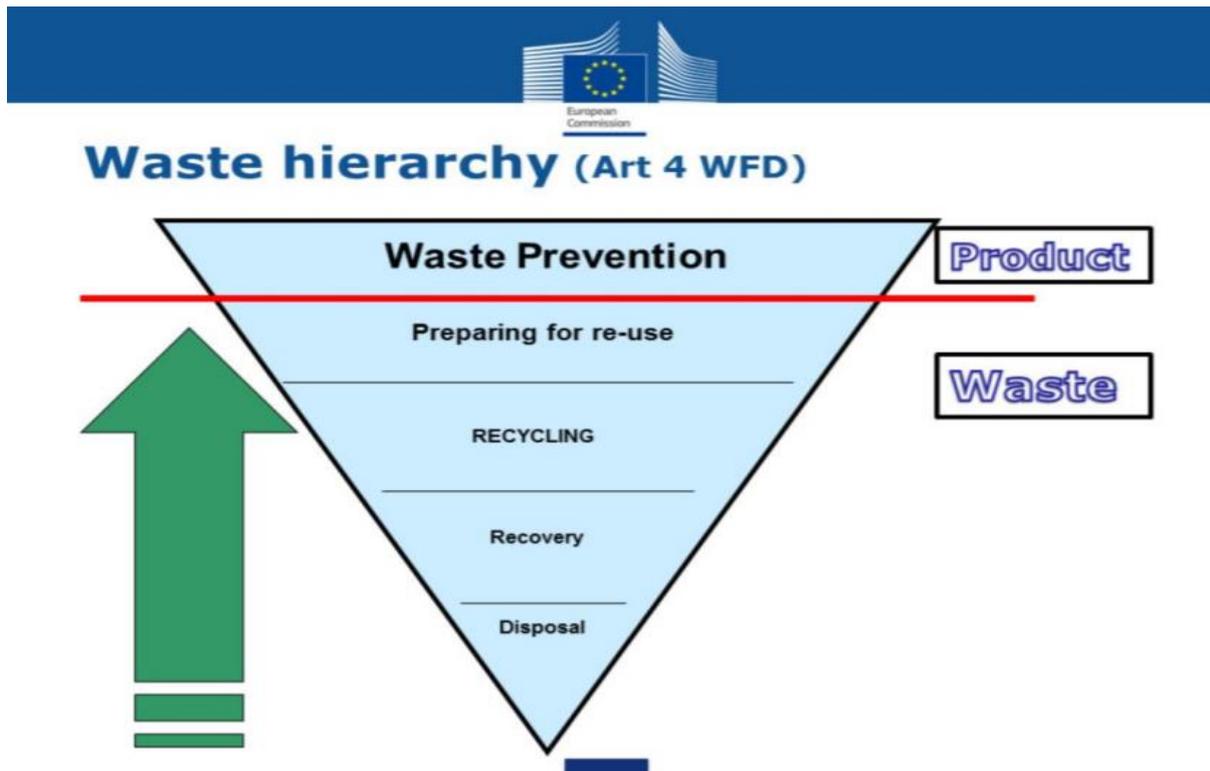


Figure 58. Summary of official Waste Hierarchy, with prevention constituting the greatest priority and disposal the lowest priority (Technical University of Denmark, 2006).

These targets are further presented as part of each Local Authorities' Sustainable Energy Action Plan (SEAP), (Aberdeen Council, 2016; Birmingham Council, 2005; Edinburgh Council, 2015), which detail their vision and strategic goal and action towards achieving specific environmental targets.

These include but does not exclude the trio of targets, namely, GHG emission mitigation, waste reduction and waste-to-landfill reduction targets stipulated by UK's environmental legislation (Table 12), itself transposed from EU's own environmental directives.

Table 12. Summary of environmental legislations and targets on the national level, all of which transposed down to the Local Authority (LA) level, with specific % targets differing between different LA

Driving Legislation/Directive (year of implementation)	Origin	Abbreviation	Transposed to UK national level
GHG Emissions directive	EU	ED	Reduce 2020, 2030 and 2050 emissions by 20% (42% - Scotland), 57% and 80% respectively (UK, with exceptions in markets).
Waste Framework Directive (2008) (GOV.UK, 2014b)	EU	WFD	Requires 50% and 70% (by weight) UK household waste to be recycled by 1 st January of 2020 and 2030, respectively (WalkerMorris, 2014)
Landfill Directive (2001) (Environment Agency, 2010)	EU	LD	Reduce Biodegradable Municipal Waste (BMW) going to landfill to 35% of 1995 levels by 2020; no landfilling of BMW should occur by 1 January 2025 (WalkerMorris, 2014)

Here it is worth emphasizing the importance of relative distribution of financial support towards enabling each approach, with tariff incentives and FWtTBC project funding to constitute key important drivers. To elaborate, the extra revenue generation potential from the three tariff incentives, namely Renewable transport fuel certificates (RTFC), FIT (Feed in tariffs) and renewable heat incentive (RHI) tariffs, are key in supporting both FW recycling infrastructure and alternative fuelled vehicles (AFVs) projects (Table 13).

Table 13. Comparison of RTFCs, RHI and FIT tiered incentives alongside milestone targets and key updates.

Tariff types	Rates	Milestone targets and important changes	Source
RTFCs	1.9 RTFC per kg biomethane (wastes derived) 3.8 RTFC per kg biomethane (non-waste derived) Around 12p per certificate (subject to fluctuations) or 30p per litre buyout price 2.8-5.6p per kWh (non-waste to waste derived, respectively)	Currently 4.75% minimum blend composition (of biofuel) in transport fuel, set to increase to 9.75% by 2020	(AD.com, 2018; NNFFCC, 2018)
RHI1	Historical rate range: 2.5-3.5p per kWh (trier dependent, 3 tiers) (NNFFCC, 2018) 2018 Revised rates: Tier 1: Small biogas (or biomethane) – 4.64 (or 5.60) Tier 2: Medium biogas (or biomethane) – 3.64 (or 3.29) Tier 3: Large biogas (or biomethane) - 1.36 (or 2.53)	12% for 2020 (sub-target, from all wastes with biogas from AD being a significant contributor)	(businessgreen, 2018; GOV.UK, 2018)
FIT1	1.55-1.61p per kWh 4.22-4.36p per kWh 4.45-4.60 p per kWh 1.55-4.60p per kWh (All figures applicable to 2018 rates)	0-250 kW installed capacity 250-500 kW installed capacity 500-5000 kW installed capacity Total range for 3 tier installation AD capacities	Complete closure for application by 31st March 2019 (replacement scheme confirmation pending). (yougen, 2018)

¹Tariffs applicable to AD plant CHP operations.

This in turn is anticipated to be complemented by increasing adoption of AFVs through greater public understanding and support of the issue of clean transport fuel in context of climate change, which necessitates funding in FW research for attaining relevant data and dissemination of any insights derived by specialist organizations such as WRAP.

2.7.5 Overview of industry support for sustainable FW recycling and reduction

Beyond government support, the UK industry is also proactive serving an increasing role in driving UK FW reduction alongside recycling through specific actions taken by the food and AD industry, respectively.

2.7.5.1 Overview of food industry

More specifically, developments in UK's food industry is mainly underpinned by the Courtauld commitment which aims to encourage food industry players, i.e. food producers, manufacturers and distributors to reduce Food Waste through joint collaborative efforts. The commitment is embodied by 3 progressive phases to-date (WRAP, 2018a), that addresses a different aspect in enabling incrementally greater levels of FW reduction that encompasses

efforts across the entire supply chain from production to end distribution for enabling a circular economy (Figure 59).

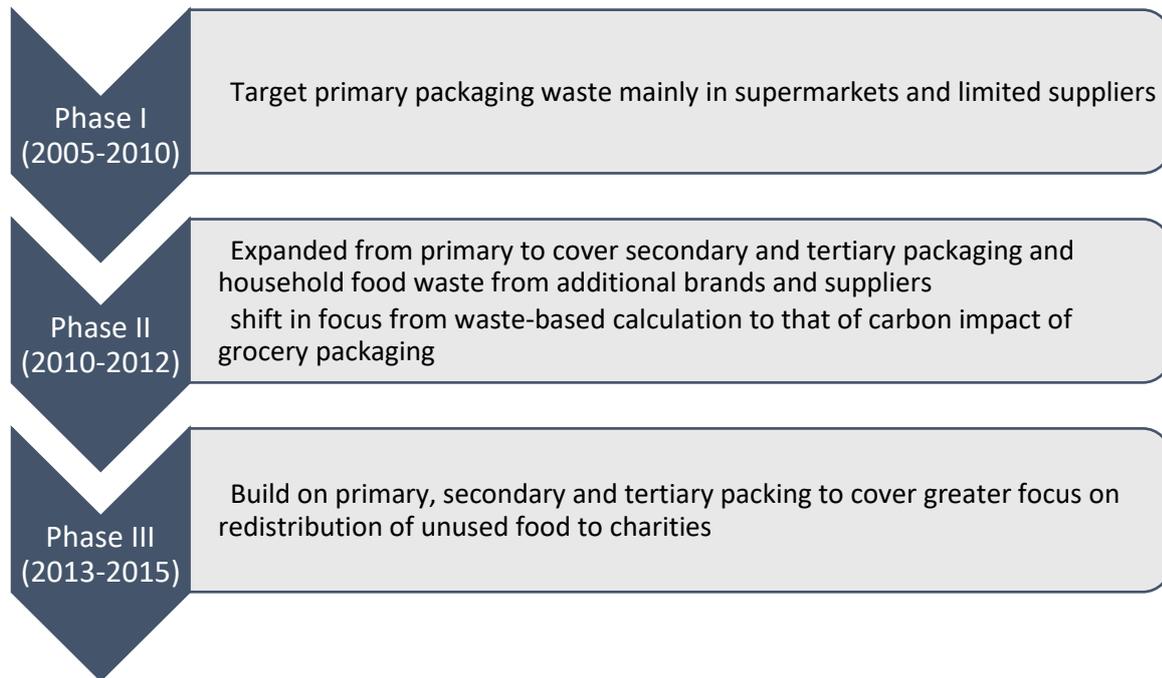


Figure 59. Three phases of the Courtauld agreement and their respective focuses

These 3 stepwise Courtauld agreement phases subsequently set the foundation for launch of the Courtauld 2025 commitment, in March 2016, with aims to reduce Food waste by 20% in 2025 against 2007 levels through a continuation and intensification of reduction efforts across different key players and parts of the supply chain. Collectively, these progressive phases of the Courtauld commitment signifies rapid expansion of UK’s food industry effort towards addressing the issue of FW through multi-stakeholder collaboration efforts (Figure 60).

2.7.5.2. Overview of UK-AD industry

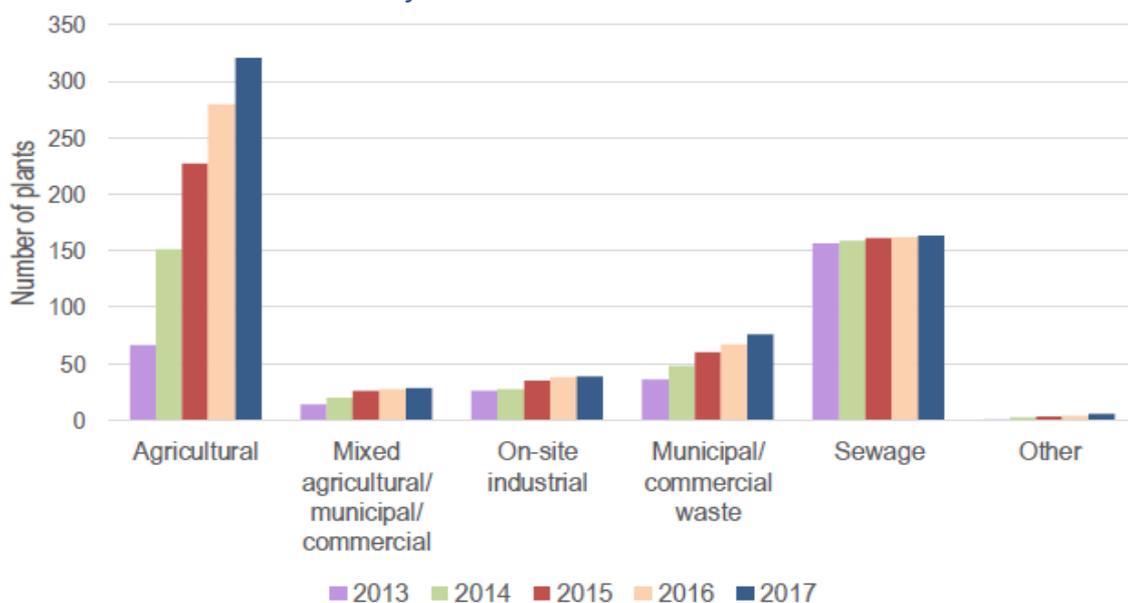


Figure 60. Accumulative number of UK AD plant by feedstock from 2013 to 2017 (ADBA, 2018)

Likewise, the AD industry has also undergone significant expansion efforts over the past decade which saw sharp increases in AD plant constructions for accommodating anticipated increase in demand of various biomass feedstock types. Herein the greatest increase is in the construction of agricultural and municipal commercial waste plants (by 500% and 100% respectively) in which food waste constitutes an important waste feedstock alongside dedicated biomass crops (ADBA, 2018).

The UK has also seen a stark increase in the number of AD biogas plants from 2011-2013 to 2014, which is surpassed only by Germany and Sweden, and indicates a growing demand for biogas as an alternative and versatile energy source. These are inextricably linked to the accumulative effects from the introduction of the aforementioned tariff incentives of RTFC, FIT and RHI (Energy saving trust, 2019) in 2005, 2010 and 2015 respectively (Union & States, 2020) (Figure 61).

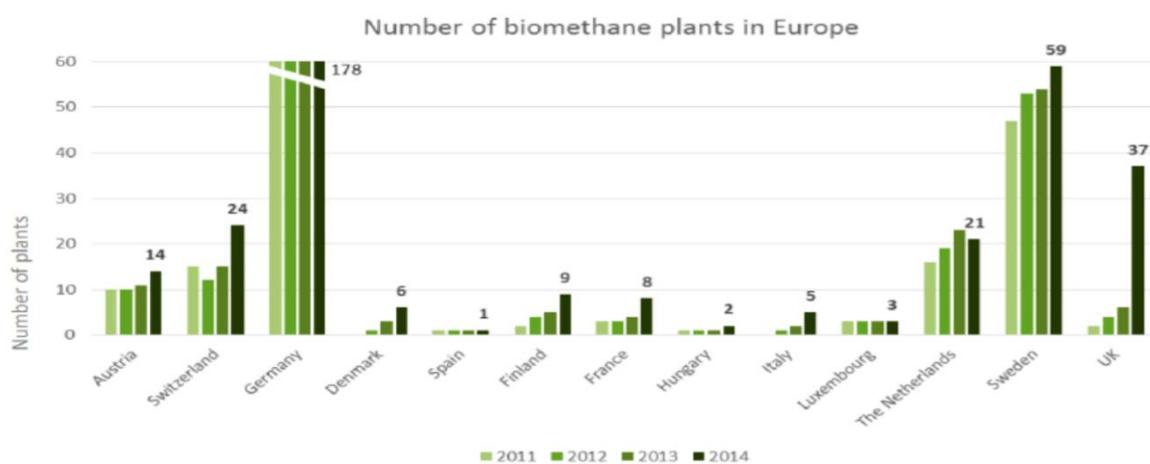


Figure 61. Biomethane plants by country and year, between 2011 and 2014

To-date, UK possess AD plants distributed across various regions and cities, which totals an estimated 648 plants by summer 2019 up from 100 in 2013, representing an increase of 600% over 6 years (anaerobic-digestion.com, 2019).

A graphical overview of AD plant by type also demonstrated near equal establishment of waste plants to agricultural plants, the majority of which are for Combined Heat and Power (CHP) generation though with significant remaining quantities tailored for combined BtG (Biogas to Grid) and CHP generation (Biogas-info, 2019) (Figure 62).

A further layer of AD plant review by site-type indicate an overwhelming majority of plants are situated on farm, commercial and industrial sites, respectively, with the remaining minority to be part of an integrated waste management system or used for demonstration purposes (Figure 63).

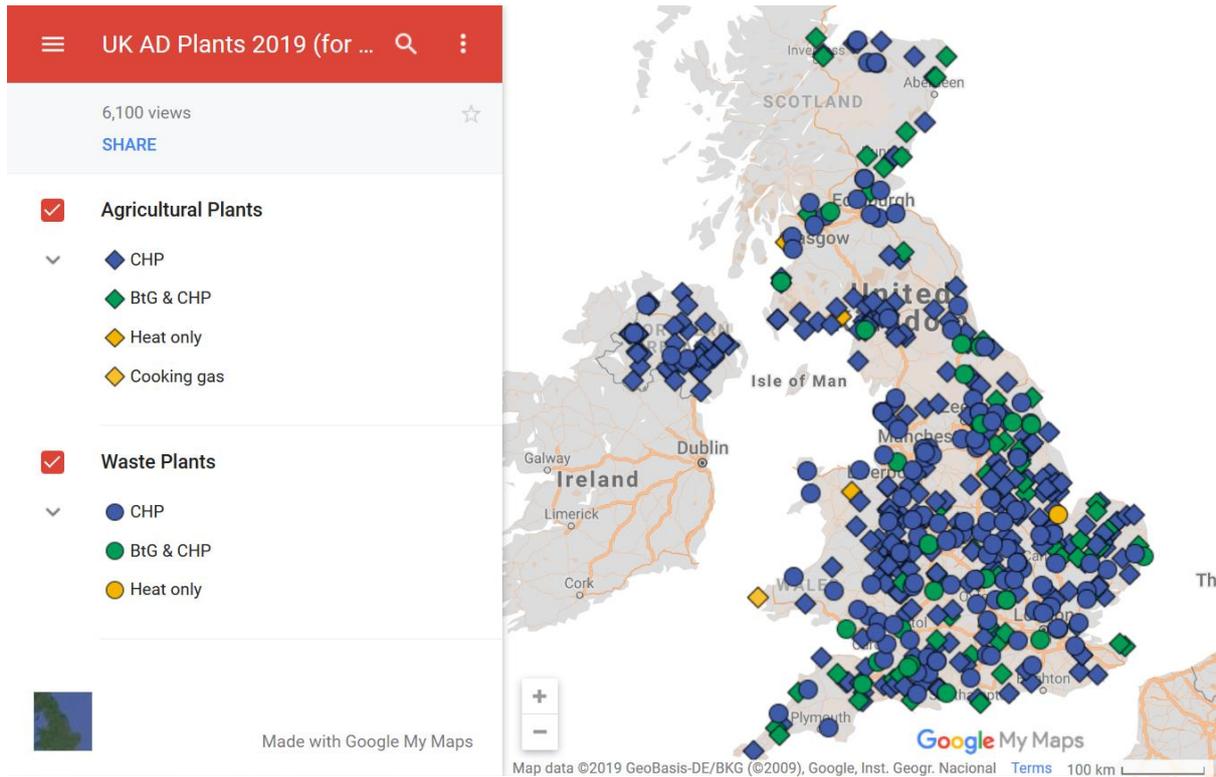


Figure 62. UK AD plant map showing locations of all AD plants with breakdown by type (Biogas-info, 2019)

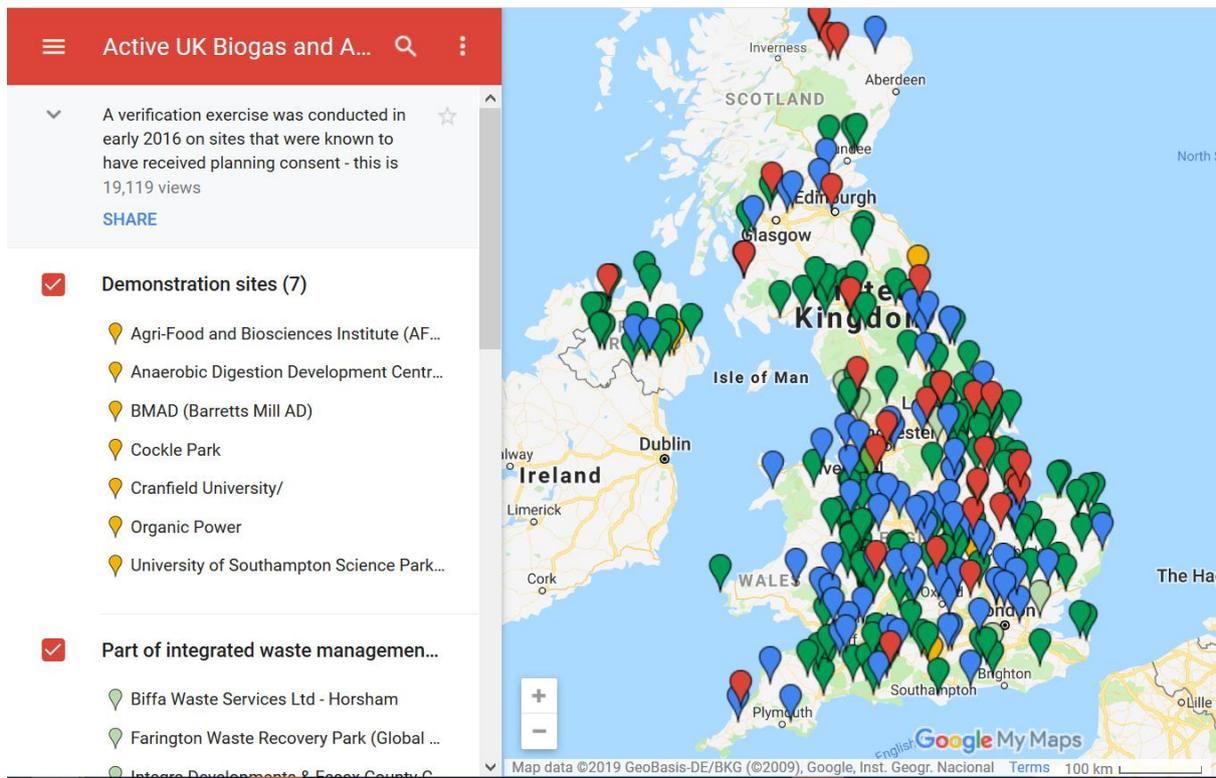


Figure 63. UK AD plant map showing locations of all AD plants with breakdown by type (WRAP, n.d.), colour coded: Green = on farm sites, blue = commercial sites, red = industrial sites, yellow = demonstrated sites, light green = part of integrated waste management system.

The extent of AD plant expansion from 2011 to-date as a measure of their absolute number and relative distribution also illustrates stark expansion across the entirety of UK, with notable increases across selected regions of (Midlands, South and North of) England, (North-East) Wales and (South of) Scotland (Figure 64).

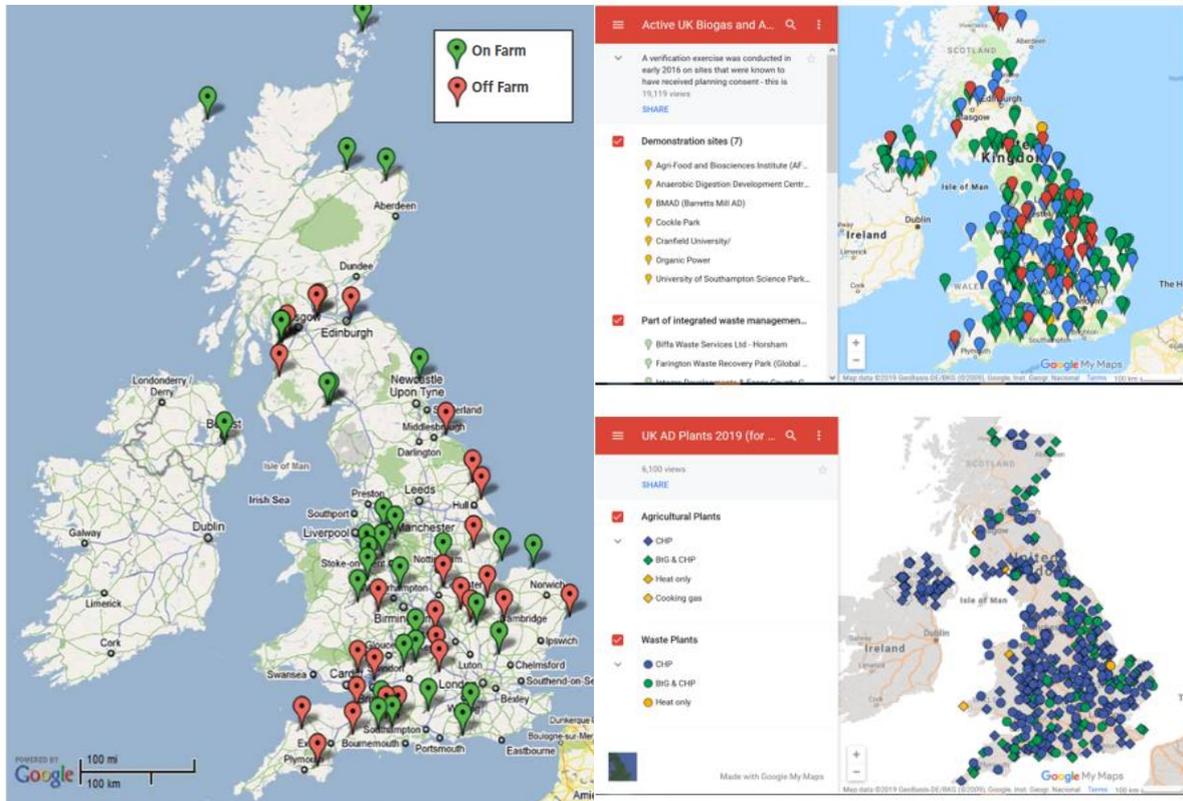


Figure 64. AD plant map of comparison (left) 2011 and right (2019) plant locations. Right top and bottom are provided by WRAP and AD-Biogas.info sources (Biogas-info, 2019; WRAP, n.d.).

Under UK's strong continued government support in form of tariff incentives to-date and state of the AD feedstock industry, the AD industry will likely exhibit continued strong growth in the decade ahead. These will likely fall into the region of AD that are suitably designed for processing dedicated biomass or waste feedstock, given UK government's focus in these dual areas of energy generation (DEFRA, 2015).

2.7.6 Key role of Local Authority (LA) in the FW recycling for biomethane and electricity generation

The collective developments of UK's expanding AD industry, devolution act and continued government financial support towards FWtTBC, have led individual LA to pursue their own FW treatment strategies under the abovementioned present tensions between strong barriers and opportunities in this area.

Interestingly, a number of LA already explored various Public Private Partnership (PPP) based schemes and business models in effort to explore this avenue for broader recycling schemes

(Birmingham Council, 2005), with successful examples includes Manchester city's recent implementation of the largest £4.2bn PPP project in solid waste management in Europe (GOV.UK, 2014a).

Another prominent example of change implicates Leeds City Council's (LCC) endeavour to simultaneously implement EV passenger car, van and RCV (refuse collection vehicle) fleet alongside city-wide FW collection scheme.

This follows a strong pivot of their original focus towards pursuing adoption of transport biomethane fuels owing to reasons of infrastructure availability. The strategy constitutes parts of a 2-year scheme that since received a £900,000 investment by LCC and £2 million investment from highway England for allowing LCC to loan a set number of EVs (totalling 70 electric vans with an undefined fleet of electric passenger cars) to local companies free of charge (Leeds.gov.uk, 2019).

The strategy thus bridges government and Local Authority funding with a dedicated scheme to drive strong adoption of EV by business overtime, with the key driver being demonstration of significant benefits of such adoption compared to use of conventional vehicles through provision and analysis of the EV telemetry data. These developments demonstrate the critical importance of relevant data and insight in shaping organizational decision making towards technological transition and change.

2.7.7 Summarizing views on current and forthcoming state of FW recycling for implementation of the FWtTBC pathway

The above overview of barriers and opportunities in FW recycling in context of recent policy and AD industry developments indicates potential for strong future development of FWtTBC pathway. To this end, the acquisition of data and derived insight for inspiring investment confidence likely constitutes a key solution for overcoming the lock-in effect and chicken and egg conundrum that has to-date significantly hampered FW recycling across many UK local authorities.

Integrated modelling of food waste and other relevant outputs (i.e. revenue, energy and GHG savings) often constitutes an applicable strategy for attaining the necessary insight needed, although most literature review to-date has revealed a absence in adoption in these modelling techniques. Most such literature do focuses one specific field connected to the FWtTBC pathway deployment, such as food waste collection method and quantification of FW outputs, or revenue generation of existing food waste potential.

The next section aims to summarize relevant studies in connection to the central theme of this PhD research on modelling trade-offs associated with deployment of the FWtTBC pathway within suitable city regions.

2.8 Theme 7 - Overview of other research to-date on the Food Waste to Transport Biomethane Conversion (FWtTBC) pathway with respect to relevance, methods and outcomes

2.8.1 Overview of FW research to-date

To-date, the field of research on Food waste recycling for biomethane generation via the FWtTBC pathway largely focuses on specific pathway components with a lack of sufficient integration for real-world application.

The caveat arises from the traditional siloed research approach often adopted in academia, which often address only one pathway component in depth whilst lacking sufficient breadth of research coverage on other pathway components, with the latter being fundamentally important for establishing key insights to model trade-off benefits attainable from the FWtTBC pathway (see Figure 65).

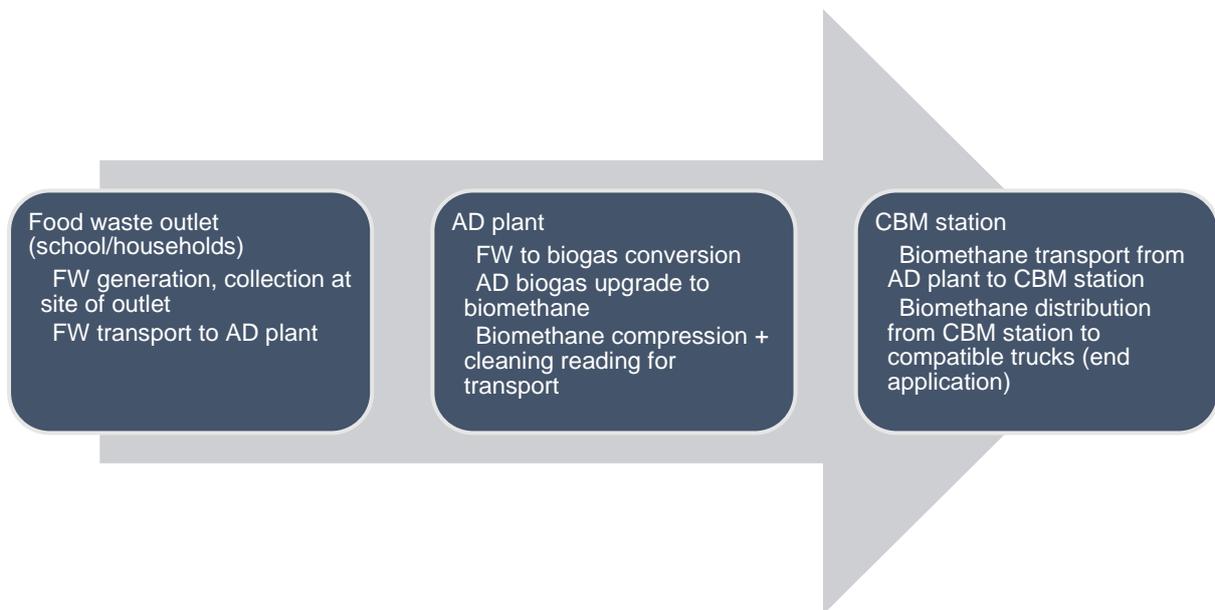


Figure 65. Overview of FWtTBC pathway components, with main and specific focus areas

To elaborate, whilst some studies focus specifically on estimating food waste output potential from relevant outlets such as schools (Saccares et al., 2014; WRAP, 2011) and households (WRAP, 2009b), others aim to evaluate the energy potential (A. Mtz. Viturtia, 1994) and economics of food waste to biogas or biomethane conversion (Andrić et al., 2017; Navaratnasamy, M., 2008; Thi et al., 2016).

There also exist a number of high-level technology specific (IEA, 2011) or techno-economic studies focusing on the AD and transport component of the FWtTBC pathway, in relation to biomethane and associated revenue generation potential on a total UK level (Ricardo-AEA, 2014, 2015). Herein the dimensions and impacts of market pricings and tariffs in governing financial feasibility and return on investment are also elucidated in relation to initial project investments.

The remaining studies possess specific focuses on either environmental emission via life cycle analysis of biomethane (Hitchcock & Lane, 2008; Opatokun et al., 2017) or Unused cooking oil (UCO) biodiesel fuel (Li et al., 2014) via various LCA methodologies and scopes of coverage.

To this end, the Low carbon truck and infrastructure trial of 2016 (Atkins-Cennex, 2016) constitutes an exemplary study on emission reduction potential of clean bioenergy replacement (biomethane, UCO) specifically in Heavy Duty Vehicles (HGV) (Table 14).

Table 14. Summary of types of studies, their relevant field of coverage and steps towards integration

Research area	Research focus	Data input output	References
Food waste (FW)	FW Collection and quantification	Kg school or household FW collected	(WRAP, 2011, 2017)
Anaerobic digestion (AD) and Biomethane	Techno-economical analysis	£/energy or fuel yield produced relative to technology investment	(Achinas et al., 2017; Andrić et al., 2017; Navaratnasamy, M., 2008)
	Energy potential analysis	Electricity - MJ or KWh Biomethane – m ³	(Islam et al., 2012; Opatokun et al., 2017; Thi et al., 2016)
Biomethane	Life cycle emission analysis	CO2 emission reduction (on % basis)	(Atkins; Cennex, 2015; Hitchcock & Lane, 2008)

2.8.2 Emerging opportunities in research on FW to clean transport energy (FWtTBC) pathway

Given proof of sufficient public data and information availability on each component of the FWtTBC pathway (

Figure 66), the emerging opportunity arises in the aggregation and integrated analysis of these available data to give to sufficient depth for real-world application.

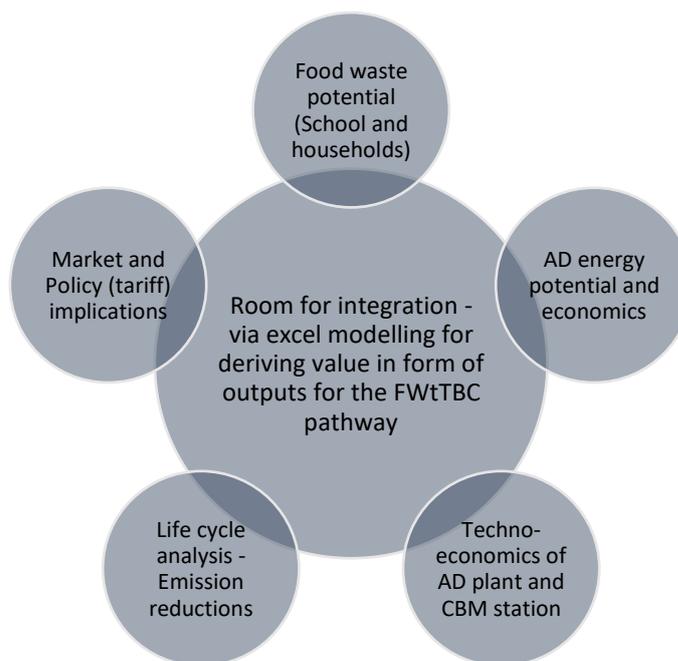


Figure 66. Research focus on FWtTBC pathway

2.8.3 Modelling techniques chosen for integration

Herein adoption of case-study based modelling approach is critical for deriving insights in key areas (

Figure 66) needed for establishing sufficient business and investment confidence needed to overcome conventional barriers (of lock-in effect and chicken and egg conundrum) towards implementing the FWtTBC pathway.

Historically a number of modelling techniques have been developed in academia to match various scales and breadth of coverage. A prime example of this includes overview of modelling types for traffic networking modelling, as illustrated in Figure 67 and further elaborated in Table 15 (Linton et al., 2015).

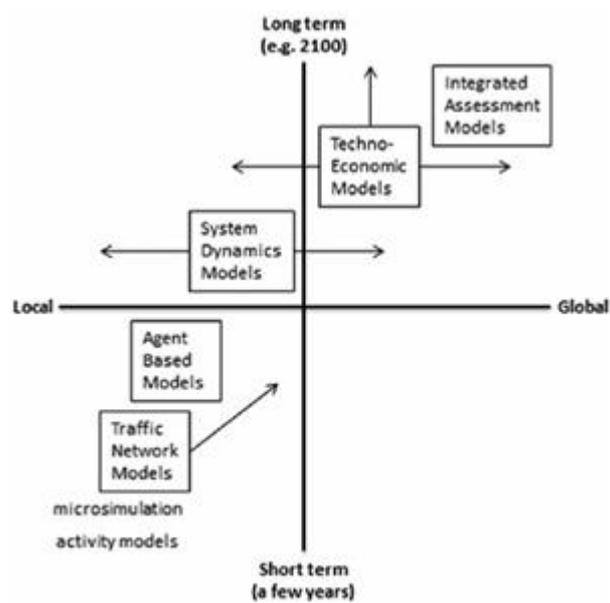


Figure 67. Spatial and temporal scales for transport modelling approaches considered

Table 15. Summary of modelling approaches considered with specific examples and additional description

Modelling approach	Example packages/studies	Elements of transport system captured	Underlying concepts
Traffic network models – microsimulation	Dracula	Vehicle movement in predefined traffic network	
	VISSIM	Total data across network (i.e. emissions, delays, travel time).	
Behavioural models	Stern and Richardson process-oriented framework	Individual decision making travel choices	
Agent based modelling	MATISM	Behavioural dynamics in the transport system	
System dynamics	ASTRA	Interactions and feedbacks mechanisms	Built on CLD and stock and flow relationships
	MARS		
Techno-economic models	Roadmap	Large-scale dynamics of transport system (via social economic changes)	Use socio-economic characteristics and forecast changes to estimate transport demand and emission projections
	World Energy Project System Plus (WEPS+)		Roadmap: run over 5-year time steps from 2000 to 2015.
IAMs	Global Change Assessment Model (GCAM)	Large scale modelling of economy and environment with transport submodule – capture tech change and environmental impact driven by social economic factors	Run in steps of 15 years from 2005 to 2095 to achieve equilibrium in regional markets in each time-step.

Interestingly, the cross-application of such models to the field of FW research is very limited in all but systems dynamics, techno-economic and IAM models, which possess key elements of feedback and medium to long term prediction of multiple key metrics needed for modelling the FWtTBC pathway. In full evaluation however, even these 3 modelling possess significant caveats for all intents and purposes of this research.

Namely they include lack of capacity to capture full spectrums of key metrics for this study, which extend beyond just the techno-economics into other focus areas (Figure 68) in addition to having a lack of versatility embodied by the simple user interface required to enable any quick and easy adjustments by most average users in response to changing real-world circumstances.

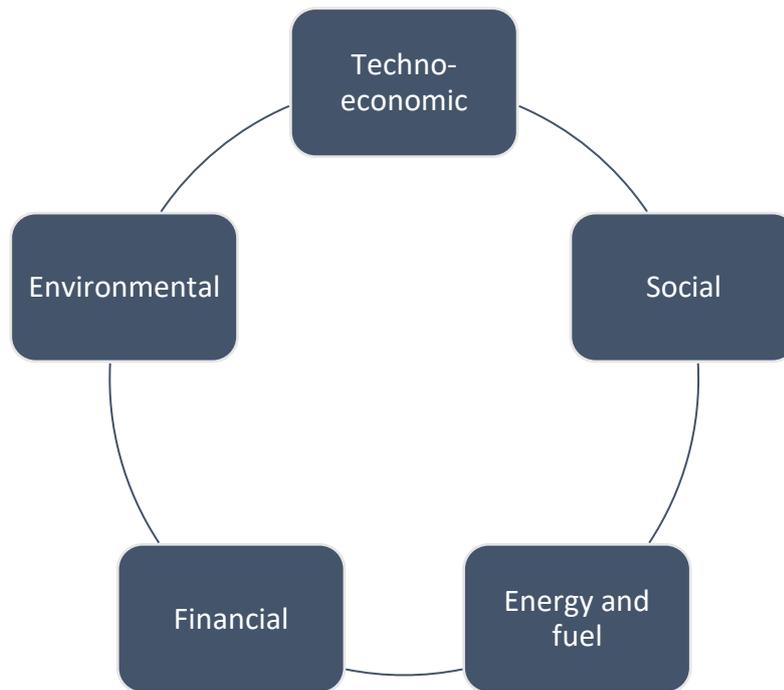


Figure 68. Modelling focus area for evaluating trade-offs pertaining to the FWtTBC pathway

In consideration of the factors above, Excel modelling is chosen to be the most suitable modelling methodology given its ability to function as a highly versatile and modular modelling with good usability to provide unrivalled capability for universal application and quick adjustments (of both model structure and inputs) on-demand (Figure 69 Table 72).

Versatility	Modularity	Usability
Excellent for producing graphs and tables for use in reports and visualising results	New metrics can be easily added and removed to adapt modelling	Ease to use for most employees - for changing, adding and removing metrics on-demand

Figure 69. Advantages of utilizing Excel as modelling approach

2.8.4 Key areas of focus for maximizing real-world representation of modelling outputs

To ensure strong real-world representation and applicability of the modelling outcomes (Table 16), careful selection of appropriate methodological approach for acquisition of accurate and reliable data for subsequent processing and analysis using key assumptions is key.

Table 16. Quantitative and qualitative outcomes

	Quantitative ¹	Qualitative ²
1	Food waste (tonne)	Policy
2	Energy (MJ)	Business
3	Fuel (m ³ or L)	Research field
4	Revenue (£)	Local council strategy
5	GHG or CO ₂ reduction (% or tonne)	Social
6	Return on investment (of 2-5)	Techno-economic

¹All expressed in term of annual potential, thus unit/year, ²All expressed in form of recommendations for each specified area

To elaborate, a simplified Excel representation for carrying out calculation of qualitative outputs is highlighted in Figure 70 below, and is further expanded in the methodology section with the full series of equations listed.



Figure 70. Simplified Excel template calculations for deriving quantitative outputs, with full equations elaborated in the methodology section

2.8.5 Summarizing views

The adoption of the abovementioned integrated research method is critical for establishing integrated perspectives and insights required to address both challenge and emerging opportunities associated with deployment of the FWtTBC pathway as part of UK’s broader climate action effort.

The next and final theme aims to emphasise on the importance of each integrated focus area, namely, social, techno-economics, environmental, finance and policy, and their individual as well as collective importance for enabling the FWtTBC pathway as part of an integrated system. The theme also elucidates the wider role of excel modelling to derive key insights in form of quantitative trade-offs between relevant focus areas, pertaining to the FWtTBC pathway, i.e. financials, energy and fuel, emissions, through aggregation and integrated analysis of available data, which constitutes the core contribution of this PhD study.

2.9 Theme 8 – Overview of emerging research on the FWtTBC pathway from a whole systems and wider - impact perspective

2.9.1 Knock-on effects and feedback loops characteristic of system level studies on the FWtTBC pathway

Beyond the current research's inter-disciplinarily focus on elucidating novel insights in form of cost-benefit trade-off pertaining to the FWtTBC pathway through use of Excel modelling of publicly available data, the phenomenon of knock-on (or butterfly effect) also critically underpins an additional area of insight and novelty characteristic of system level studies.

These effects are also known as feedback loops, which refers to the effect that occurs when the output of a system becomes the input of the same system (SOAS, 2019). Herein, the two components of the feedback include financial revenue and clean transport energy generation arising from FWtTBC pathway deployment.

A parallel example to illustrating this involves the feedback loops concerning eggs, chickens and road crossings, which demonstrates the concept of positive and negative feedback as well as equilibrium. To elaborate, the case of positive feedback would manifest under the conditions of greater return on both energy and financial investment made throughout the entire FWtTBC pathway (as indicated by mutually reinforcing effects of chickens and eggs) (Figure 71).

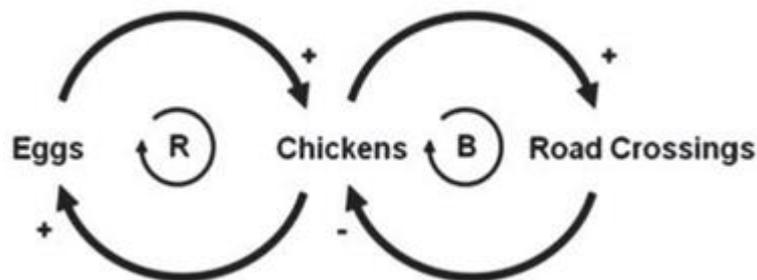


Figure 71. Chicken, Egg and Road Crossings causal loop diagram (Shepherd, 2014)

2.9.2 Knock-on effects and feedback loops pertaining to the FWtTBC pathway in real-world context

One of key real-world factors affecting this includes strict consideration of additional factors beyond financial and energy metrics and their respective interactions. Here additional quantifiable metrics captured by the excel modelling must also include energy output, emission savings and food waste reductions, all in context of specific policies and regulatory measures, i.e. tariff incentives and waste to landfill tax.

In modelling these above elements using excel, this thesis aims to increase both knowledge and insight surrounding perceived opportunities and previously unknown barriers currently hampering the FWtTBC pathway. Here, the key effects include interactions between individual social, techno-economics, environmental, energy and fuel, finance and policy components,

the collective dynamics of which affects the barriers and opportunities pertaining to the FWtTBC pathway (Figure 72).

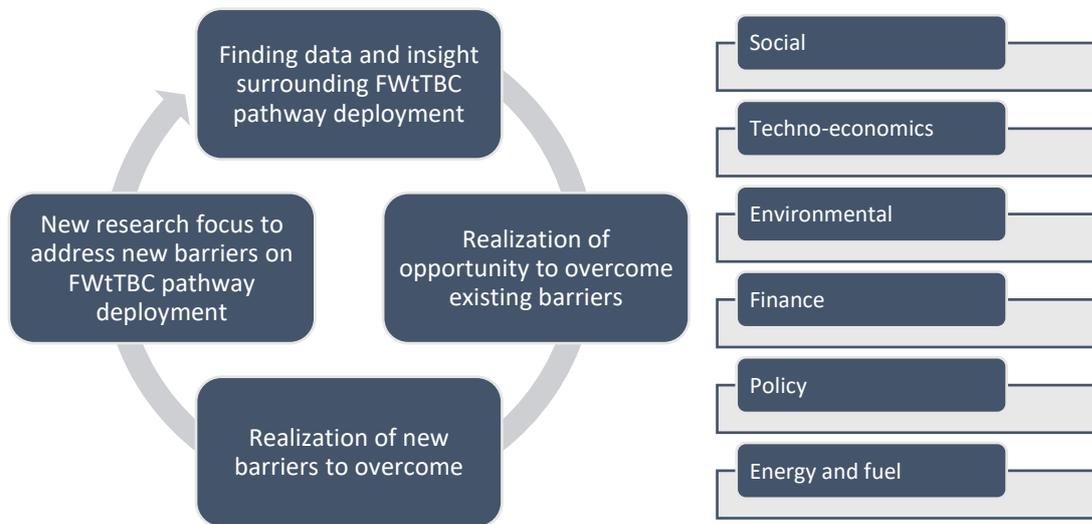


Figure 72. (Left) Research evolution in relation to feedbacks between insight, opportunity and barriers encapsulated by the Chicken and egg feedback loop shown in Figure 74, in context of the quantitative parameters (and relevant publicly available data) used in the excel modelling process (right) for providing insight.

Key examples of feedback effects involve how financial investments and GHG emission could both shape and be shaped by new policy implementations, and how they in turn could affect energy and fuel generation in form of transport biomethane alongside social benefits, i.e. greater social acceptance and participation of household FW recycling.

2.9.3 Conclusions and Summaries of literature review of themes 1 to 8 with respective to evolution of research on the FWtTBC pathway.

The above 8 literature review themes present a strong case for this research to establish a novel modelling approach to investigate cost-benefit trade-off attainable from deployment of the FWtTBC pathway, with it being an overlooked emerging opportunity at the present time. To this end, excel modelling approach is chosen for conducting system level modelling of key metrics that constitute strong drivers of pathway deployment.

More specifically, these metrics includes financial returns on investment (considering revenue and cost), renewable energy or fuel generation in addition to GHG emissions and waste reduction potential, which strongly serves the interests of key enablers of FWtTBC pathway deployment, i.e. UK government and potential private or public investors.

It is hoped for such outcomes in form of data, insight and policy recommendations to support any component of the FWtTBC pathway that proves to be most challenging depending on the local challenges under which they are implemented to overcome the aforementioned lock-in and chicken and egg effect that presently significant restricts its deployment, i.e. FW collection,

FW recycling via local AD plant operations, or transport biomethane fuel delivery via refuel station operations.

The next chapter will focus on elucidating critical methodological precursors required for establishing a novel, integrated methodology that applies Excel modelling with whole-systems analysis and is capable of elucidating all anticipated findings and outcomes arising from FWtTBC pathway components as mentioned above.

Chapter 3. Methodology Precursor: Assessment of methodological design criteria, boundary conditions and process components

This chapter outlines key context and rationale behind the establishment of a novel methodological approach to address key research aims and objectives as summarized in Figure 73 below (see Chapter 1.7 for full details).

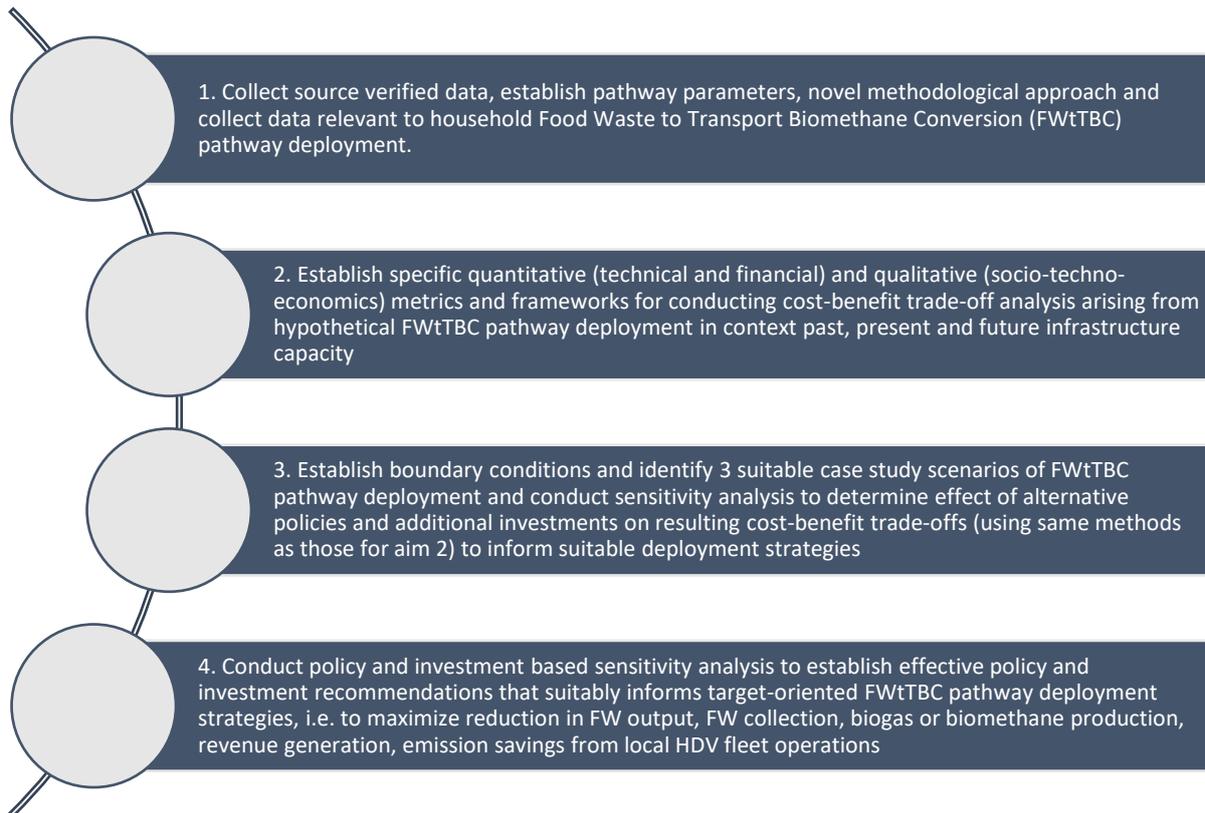


Figure 73. Summary of research aims and objectives, summarized from full aims and objectives present in Chapter 1.8 (Aims and Objectives)

This is due mainly to unconventional and explorative nature of the present research, which ambitiously endeavours to explore cost-benefit trade-off arising from FWtTBC pathway deployment using a highly interdisciplinary approach that considers dynamic interactions between critical pathway components (i.e. technical, social, policy and financial) under different real-world deployment scenarios. By contrast, many existing relevant research are often conventional which utilizes established methodologies and focuses only on a single pathway component in greater depth (see Figure 74).

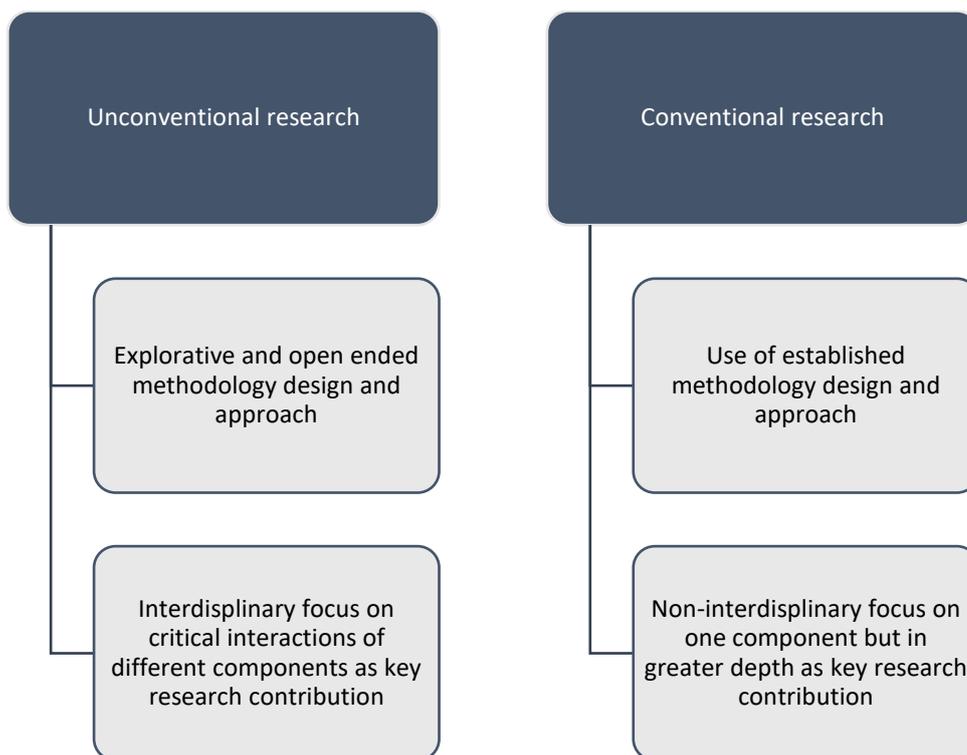


Figure 74. Key difference in focus and approach between unconventional and conventional research approaches

This is further evidenced by findings from significant preparatory work in form of reviewing existing research literature pertaining to relevant FWtTBC pathway components and consulting relevant online specialist website and databases, which outlined many research focusing solely on one specific discipline area. Any relevant data and findings are consequently isolated within each respective discipline, thus limiting extent of insight they are able to contribute (see Table 17 and Table 18).

Table 17. Relevant research pertaining to FW component of FWtTBC pathway deployment, with outputs being isolated and thus unable to cross-communicate with each other to provide additional insight

Pathway component	Conventional Research focus (with one research focusing on individual bullet point component only)
Food waste*	<ul style="list-style-type: none"> • Food waste output (household and/or commercial) • Food waste collection (quantity and/or estimated cost) • Food waste characterisation (category and/or chemical composition)

*FW pertains mainly to household food waste, but also those from other applicable sources, i.e. commercial food waste

Table 18. Relevant research pertaining to AD and Refuel station component of FWtTBC pathway deployment, with outputs being isolated and thus unable to cross-communicate with each other to provide additional insight

Pathway component	Conventional Research focus (with one research focusing on individual bullet point component only)
Anaerobic digestion	<ul style="list-style-type: none"> • Food waste to biogas conversion yield: <ul style="list-style-type: none"> • Using different food waste types differing in compositions • Using different testing methods (in lab or actual AD plant) • Changing AD operational conditions • Biogas to biomethane conversion yield using different conversion technologies
Refuel station	<ul style="list-style-type: none"> • Emission profile of HDV using conventional vs. biomethane as main fuel

To this end, this research endeavours to establish a novel methodological approach by adapting and subsequently integrating a number of key existing scientific methods outlined in **Error! Reference source not found.** and Table 19 below, to confer additional value in form of derived research findings and insights, which can not be achieved by using any individual methodology alone (see Chapter 4 for full details).

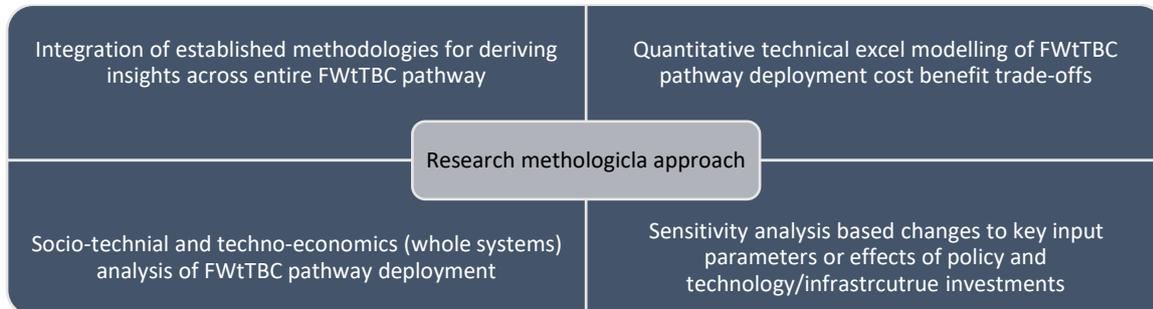


Figure 75. Summary of existing research methodologies

Table 19. Interconnecting research disciplines which to-date constitute sole focus of most existing ‘conventional’ academic research pertaining to the FWtTBC pathway (or any sub-pathway components), all of which are included by the present research on establishing trade-off benefits arising from FWtTBC pathway deployment and recommendations on suitable alternative deployment strategies

No.	Research discipline	Description
1	Methodological design across each FWtTBC pathway component	Specific Methodology focusing solely on <ul style="list-style-type: none"> • Food waste collection • Food waste to biogas or biomethane conversion • Biogas upgrading to biomethane • Transport emission savings through displacement of conventional fuel with biomethane
2	Quantitative technical excel modelling and analysis	Specific models focusing only on <ul style="list-style-type: none"> • On food waste collection operations only • On anaerobic digestion of food waste operations only • On transport emission savings only
3	Social technical and techno-economics analysis	Specific whole systems analysis focusing only on <ul style="list-style-type: none"> • Social-technical analysis of select FWtTBC pathway components • Techno-economic analysis of select pathway components (mainly AD operations based on existing models found)
4	Sensitivity analysis	Sensitivity analysis on specific FWtTBC pathway related components, such as: <ul style="list-style-type: none"> • Any specific input parameters, i.e. FW output, FW biomethane yield • Effects of changes to relevant policies • Effects of investments on relevant infrastructure or novel technology

*All disciplines are laid out in context of FWtTBC pathway components and case study scenario implementation, with latter also being omitted from most conventional research

Here it is also worth emphasising that the design of this methodological approach involves an explorative process based predominantly on a variety of preparatory work conducted in the first year of research, which includes:

1. Extensive literature and research paper reviews
2. Assessment of available facility and researcher’s supervisory team expertise
3. External consultations with local city council members and relevant businesses

The next chapter will outline individual methodologies used and their collective integration in greater technical detail for addressing aforementioned research aims and objectives (see Figure 73 for summary or Chapter 1.8 for full details).

Chapter 4. Methodological design approach and methodology

4.1 Chapter overview

This chapter outlines the design of a novel comprehensive methodological approach that can be effectively implemented to establish key findings capable of addressing all research aims and objectives (see Table 20).

This is in part due to there being a lack of existing literature that focuses specifically on the integration of all components that constitute the Food Waste to Transport Biomethane Conversion (FWtTBC) pathway, but with ample literature focusing on each individual pathway components, as observed by the researcher whilst conducting literature review.

Consequently, key engineering elements, metrics and processes must be established using the novel methodology (see below) for setting a precedent in this field of interdisciplinary whole-system based research, which scope for cross-application across other suitable waste to energy conversion pathways and possibly beyond.

Table 20. Summary of section findings in context of specified aims and objectives set out by the research (please see Chapter 5 – Results and findings for details on fulfilment of the remaining research aims and objectives).

Aim	Objectives	Description outline	Covered by Chapter 4 (Methodology) (Y/N) / Relevant chapter	Covered by Chapter 5 (Results and Findings) (Y/N) / Relevant chapter
1		Source verified data collection		
	1.1	Establish key pathway data metrics	Y / 4.2	
	1.2	Establish novel methodology for data collection	Y / 4.3	
	1.3	Conduct data collection for all identified parameters		Y / 5.2, 5.3 & 5.4
2		Establish high level pathway deployment metrics		
	2.1	Evaluate household food waste collection data		Y / 5.2
	2.2	Establish operational process diagrams	Y / 4.2	
	2.3	Establish whole systems analysis metrics	Y / 4.4	
3		Establish detailed case study scenario elements		
	3.1	Establish boundary conditions and parameters	Y / 4.2	
	3.2	Establish cost-benefit trade-offs analysis of all metrics from FWtTBC pathway deployment		Y / 5.2, 5.3 & 5.4
	3.3	Conduct sensitivity analysis in relation to Obj 3.2		Y / 5.2, 5.3 & 5.4
4		Conduct whole-systems analysis with target oriented focus on policy, investment, barriers		
	4.1	Maximize reduction in FW output		Y / 5.5
	4.2	Maximize key financial return on investment		Y / 5.5
	4.3	Maximise emissions savings potential		Y / 5.5

The overall methodology design process adopts a systematic ground-up design approach to evaluate the design of each methodological component with respect to (i) what can be suitably implemented within known time and resource limitations, (ii) their individual suitability for addressing each relevant aim and objective, and (iii) how they fit within overall context of other methodological components.

Consequently, it is worth noting that this give rises to a much longer methodology chapter than what be seen from a conventional PhD research, which typically outlines pre-established methodologies with some level of adaptation (to contrary of ground up novel design) as it includes important elements of

- (i) Design considerations,
- (ii) Consequential actions taken and key design decisions made,

- (iii) Most suitable methodology adopted out of all possible implementation methodologies for elucidating key research results and findings.

To this end, the methodological design process and finalized methodological approach also constitutes a unique area of research finding and original research contribution per se, given its originality of its design (see Table 21).

Table 21. Summary of methodological design component and process pertaining to the present research methodology against conventional research methodology

No.	Methodological design process	Present research methodology	Conventional research methodology
1	Establish methodological design process for several methodological components across different disciplines (across the FWtTBC pathway for this research)	Yes	No (pre-established)
2	Establish and implement assessment criteria and evaluation frameworks for each methodological component to determine most suitable choice of methodology for use from a list of existing options	Yes	No (pre-established)
3	Elaborate on specific details surrounding implementation of chosen methodology for attaining results and findings	Yes	Yes

The finalized methodological approach involves establishing critical boundary criteria that underpin (i) FWtTBC pathway deployment under real-world case study scenarios, (ii) specific FWtTBC pathway components of interest, (iii) corresponding operational processes outlining flow of key pathway input-output metrics alongside relevant computational equations, (iv) suitable data collection method, (v) excel model design, and (vi) modelling (quantitative and whole-systems) data analysis for elucidating cost-benefit trade-off attainable from pathway deployment under relevant real-world scenarios.

Post-analytical outcomes will be subsequently adopted to inform effective policy and investment measures (and recommendations) for supporting FWtTBC pathway deployment alongside suitable FWtTBC pathway deployment strategies in context of relevant stakeholders (see Figure 76).

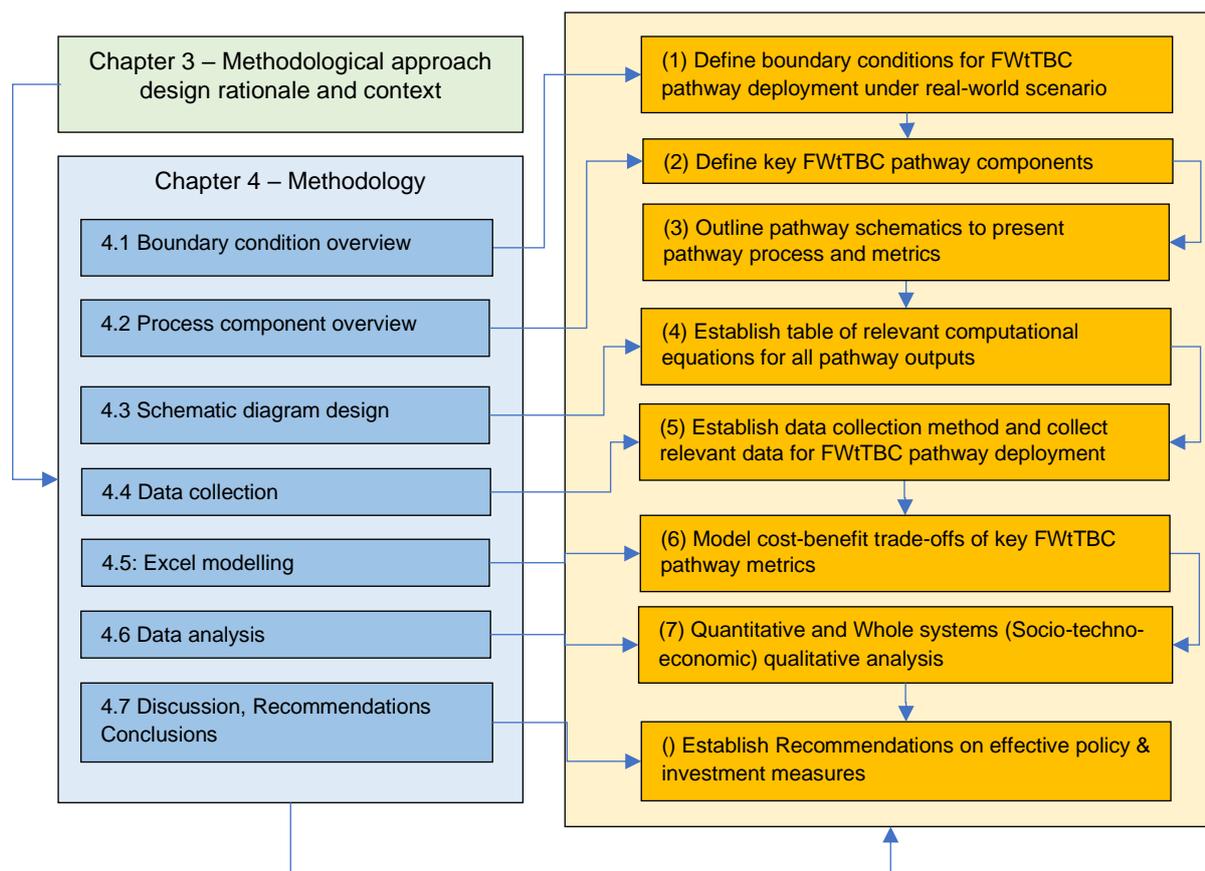


Figure 76. Process schematic overview of research methodology with respect to thesis section and chapter. M and F represent Methodology and Findings, respectively.

Functional role of each methodological component is further outlined in Table 22 below.

Table 22. All methodological components, descriptions and their prerequisite methodology criteria

	Methodological component	Functional role	Prerequisite for which methodology
1	Pathway boundary condition	Establish boundary conditions that define FWtTBC pathway deployment under real world case study scenarios in line with research aims and objectives	Excel modelling
2	Pathway process overview	Overview main components of FWtTBC pathway deployment	Schematic diagram design
3	Schematic diagram design	Visually illustrate FWtTBC pathway operational process components alongside corresponding flow of key input-output metrics and equation calculations	Data collection
4	Data collection	Collection of relevant data specified by operational process schematic diagrams outlined by the FWtTBC pathway	Excel modelling
5	Excel modelling	Modelling of collected quantitative data from available body of online literature, informed by methodological component 1-4	Data analysis
6	Data analysis	Quantitative analysis of outputs of excel modelling and whole systems socio-techno-economic analysis of FWtTBC pathway deployment (with input of quantitative and qualitative data)	Discussion recommendations & conclusions
7	Discussions, recommendations and conclusions	Outline implications of analytical results alongside effective policy and investments strategies that could further optimize FWtTBC pathway deployment in context of cost-benefit trade-offs	N/A

The next section outlines full details on the design of each individual methodology components in systematic order (see Figure 86), with specific cross-references made to illustrate how their individual design is informed by or informs the design of relevant previous and subsequent methodologies (outlined in Table 22) and their collective integration within the full methodological approach.

4.2 Methodology 1 – Establishing real-world scenario deployment boundary conditions

4.2.1 Scenario deployment criteria overview

This section outlines key criteria that underpins the establishment of real-world deployment scenarios for the FWtTBC pathway, which includes choice of technology used throughout the deployment process, alongside suitable geographical and time duration of such deployments (see Figure 77).

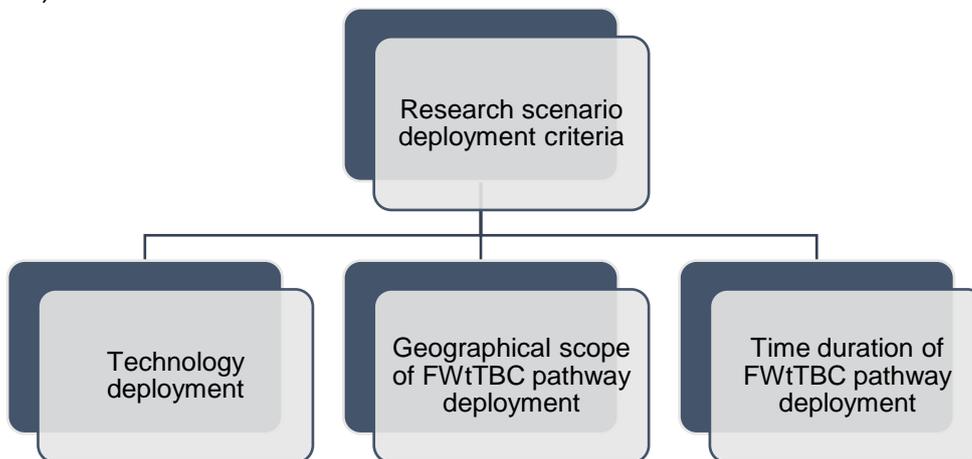


Figure 77. Summary of research boundary criteria for FWtTBC pathway deployment

These 3 criteria are key for informing the design and input of the remaining methodological components (i.e. to help inform technical metric-energy conversion factors, process operations and operational logistics) required to enable modelling of cost-benefit trade-off of FWtTBC pathway deployments for identifying effective deployment strategies under targeted policy and investment support (see Chapter 1.8 aims and objectives for details).

A detailed elaboration on the choice of technology for pathway deployment and deployment boundary conditions is outlined respectively below support by relevant rationale and contextual information (see Chapter 4.2.2 - 4.2.5 below).

4.2.2 Technology development

The deployment of FWtTBC pathway is achieved through the synergistic application of many different technologies involved in the logistical operations and technical conversion process, i.e. of material to fuel and useful energy outputs. Of these, critical technologies implicated in key operational processes that commands significant potential to substantially affect cost-

benefit trade-off arising from FWtTBC pathway deployment should be evaluated to ensure the suitable technology is chosen for effective deployment.

Within the scope of aims and objectives outlined by this research, these mainly include technology implicated in food waste to biogas conversion, biogas to biomethane upgrade (or food waste to biomethane conversion, if these two processes are counted as a single step, as done in some literatures) and biogas or biomethane to energy conversion technologies, i.e. as transport fuel or for Combined Heat and Power (see Figure 78).



Figure 78. Summary of technology considered for deployment of the FWtTBC pathway

These processes respectively constitute conversion process of material to energy and energy to useful outputs that will be systematically elaborated in two separate sections below.

4.2.2.1 Food waste to biogas or biomethane conversion technology deployment

To-date there exist a number of alternative technologies that possess strong transport biofuel production capabilities, i.e. pyrolysis, gasification and anaerobic or aerobic fermentation, with the deployment of each alternative technology also implicates varying cost-benefit trade-off and process operations that constitute necessary inputs for the design of downstream methodologies. Consequently, all available food waste to biogas and biomethane conversion technologies are assessed (see Figure 78, 1 & 2) using a technological feasibility roadmap for their overall suitability for deployment within the context of FWtTBC pathway deployment (see Figure 79).

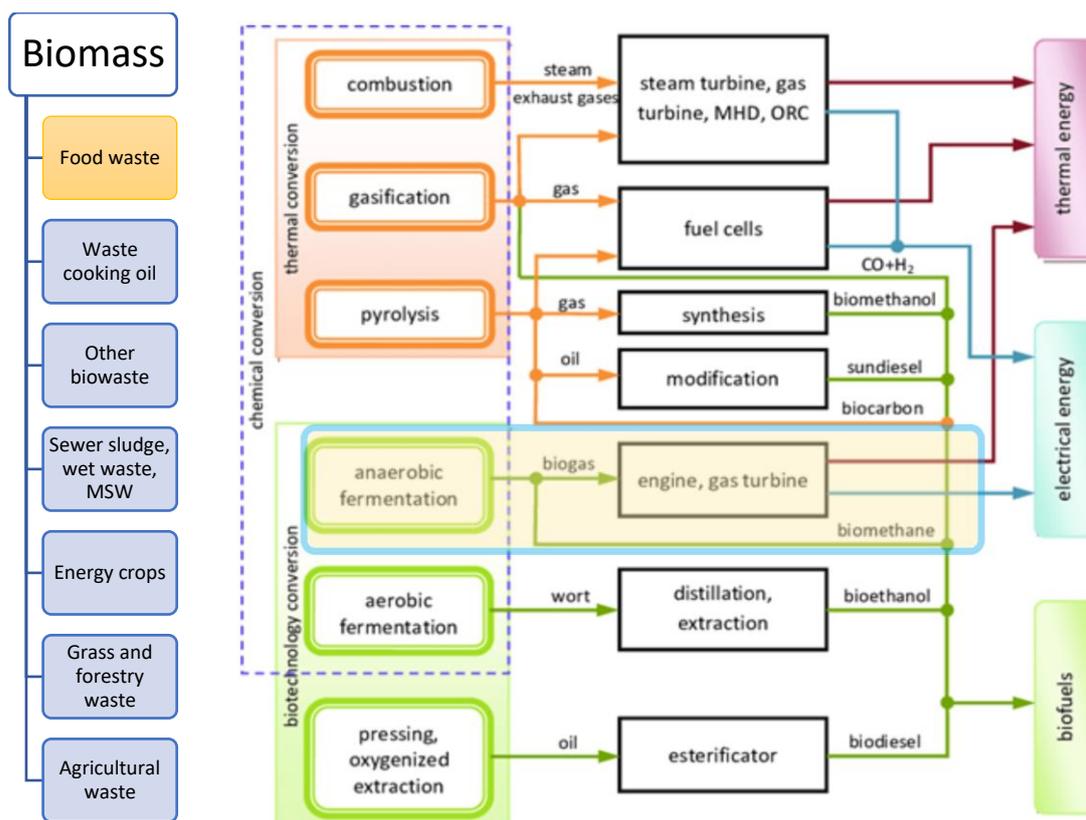


Figure 79. Technological feasibility roadmap of biomass mass to energy and fuel conversion pathways, with yellow highlighted areas demonstration viable research pathway (pertaining to the food waste to transport biomethane conversion pathway)

This initial assessment indicated that anaerobic fermentation process appears be the only feasible technological pathway for the production biogas and biomethane. This assessment also elucidates several competing biomass to transport biofuel conversion pathways that falls beyond the scope of this research but are nonetheless important for contributing to the overall bioenergy industry.

As part of a broader technology assessment, all biofuel conversion technologies are further evaluated from an integrated technical, infrastructure and sustainability standpoint, using 5 specific criteria to help determine suitability of their deployment for general transport biofuel production (not limited to biomethane) (see Table 23).

Table 23. Select criteria used for broad technological assessment

No.	Criteria name	Description
1	Feedstock availability	Relative suitability of food waste vs. other waste as a primary feedstock
2	Process sustainability	Based on Waste framework of prevention, re-use, re-cycling, recovery and disposal
3	Infrastructure readiness	Based on total UK commercial plants with large scale production capabilities
4	Future deployment potential	Based on degree of novelty of emerging technology for large scale deployment in the future
5	Fuel versatility	Based on if output fuel can be used for multiple purposes (as outlined in the technology readiness map)

Assessment outcomes collectively highlights the use of anaerobic fermentation technology to be most suitable for FWtTBC pathway deployment, owing to strong feedstock compatibility, infrastructure readiness and versatility of the output fuel. Other alternative technological options by contrast, possess relatively shortfalls in one or more aforementioned criteria, and are suitable for conversion of other bio-wastes or require more time to ensure broad infrastructure readiness see (Table 24 and Table 25).

Table 24. Summary details on deployment suitability for food waste to transport biofuel conversion for each technology type

Process	Details
1 Combustion	<ul style="list-style-type: none"> Wet organic waste, i.e. food waste not the most suitable feedstock Emission pollution concerns from combustion Output energy directly non-utilizable as transport fuel Infrastructure readily available but above factors render them for use using FW not ideal
2 Gasification	<ul style="list-style-type: none"> Wet organic waste, i.e. food waste not the most suitable feedstock Emerging technology that may require more R&D to optimize operations Lack of readily available infrastructure and industry not yet mature Output energy versatile and can be used for transport or non-transport applications High foreseeable cost of future R&D and development Process operations highly sustainable for generating renewable energy Infrastructure not readily available and above factors render them for use using FW not ideal
3 Pyrolysis	
4 Anaerobic fermentation	<ul style="list-style-type: none"> Food waste ideal feedstock, either per se or with other organic waste (as a mix). Process operations highly sustainable for generating digestate and renewable energy Output energy most suitable for use as biomethane transport fuel (or alternatively as CHP) Established technology and Infrastructure that is readily available for rapid upscale and cost-effective deployment Contains relatively strong continued future deployment potential due to all of the above
5 Aerobic fermentation	<ul style="list-style-type: none"> More ideal feedstock available than food waste, i.e. liquid waste contains sugar compounds All other criteria similar to that of AD industry outlined above (with exception of output energy being bioethanol instead that is suitable for mixing with ethanol for use in transport)
6 Pressing, Oxygenated extraction	<ul style="list-style-type: none"> More ideal feedstock available than food waste, i.e. Waste Cooking Oil All other criteria similar to that of AD industry outlined above (with exception of output energy being biodiesel instead that is suitable for mixing with diesel for use in transport)

Table 25. Broader technology assessment of all biomasses to biofuel conversion technologies

Technology	Feedstock compatibility	Process Sustainability	Infrastructure readiness	Future deployment potential	Fuel versatility	Overall Suitability
1 Combustion	Weak	Weak	Strong	Weak	Moderate	10
2 Gasification	Weak	Strong	Weak	Strong	Strong	11
3 Pyrolysis	Weak	Strong	Weak	Strong	Strong	11
4 Anaerobic fermentation	Strong	Strong	Strong	Moderate	Strong	14
5 Aerobic fermentation	Moderate	Strong	Strong	Weak	Weak	10
6 Pressing, Oxygenated extraction	Moderate	Strong	Strong	Weak	Weak	11

¹Weak (Red), Moderate (Yellow) and Strong (Green) respectively represent scores of 1, 2, and 3 respectively, with total score indicating relative suitability of each technology for food waste to biofuel conversion.

²Full details are outlined in Table 24 above in context of present industry and technology development in 2022

This is predominately due to UK's rich history of anaerobic digestion industry development (technology that carries out anaerobic fermentation) which has to-date led to the establishment of a mature industry capable of achieving large scale recycling of organic wastes, of which food wastes constitutes a significant component.

Effective utilization of UK's AD infrastructure capacity for FWtTBC pathway deployment consequently also eliminates many critical challenges, i.e. of logistical operations, insufficient infrastructure capacity or technology readiness and high cost of deployment, which are more commonly faced by deployment of emerging technologies.

Other emerging technologies such as pyrolysis and gasification by contrast will also likely play an increasingly important role (pending infrastructure upscale and technological advancements) in the generation of other bioenergy types from other waste or dedicated biomass feedstock, such as sunflower seed husks and almond shells.

4.2.2.2. Transport Biomethane and Conventional Transport fuel combustion technology

For technologies involved in the distribution and utilization of useful biogas and biomethane energy output, technological deployment surrounding transport fuel refuelling station infrastructure and HDV transport type or propulsion technology are considered in context of the 4 key criteria of (i) HDV transport utility, (ii) infrastructure availability, (iii) environmental sustainability and (iv) financial cost-benefit trade-off (see Table 26).

Table 26. Technological deployment criteria for biogas and biomethane utilization

	HDV transport Type	HDV Propulsion technology type	Refuel stations
1	Bus	Compressed Biomethane (CBM) or Liquefied Biomethane (LBM) Engine	Compressed (CBM) or Liquid (LBM) Biomethane Station
2	Freight Truck	Electric Vehicle (EV) engine	Electric Vehicle (EV) charging station
3	Refuse vehicle	(Conventional Fuel) Diesel or Petrol engine	Conventional refuel station
4	Trade off benefits in - Emission (CO₂, NO_x, PM) and Financial Cost-benefit from use of different HDV type matched with different propulsion technology and refuelling technology		

*All individual technology elements of HDV transport type, propulsion technology and refuel station are used for establishing trade off benefits

These respectively informs types of operational logistics and corresponding useful outputs downstream of AD biofuel generation (i.e. in form of biogas or biomethane), with such findings being essential in their contribution for conducting cost-benefit trade-off analysis for deployment of the FWtTBC pathway.

For HDV transport, Busses, freight trucks are considered given significant possibility of retrofitting these transports with biomethane or electric propulsion systems for rapid and highly scalable individual vehicle or fleet deployment. These are in turn supported by existing network of Compressed Biomethane (CBM), Liquefied Biomethane (LBM) or Electric Vehicle (EV) refuelling infrastructure that are essential for carrying out transport refuelling, with corresponding emissions and refuelling costs determined by the type and other parameters (emission and fuel economy) pertaining to the specific engine type used (see Figure 80).



Figure 80. Key Infrastructure components of the FWtTBC deployment pathway, that informs methodological design of process operations section

Collectively, these technologies possess broad technological compatibility with the chosen deployment of Anaerobic Digestion (AD) technology infrastructure as outlined above and will likely see significant and rapid upscale in their adoption for the foreseeable future as UK implements increasing efforts to decarbonise its transport sector.

4.2.3 Geographical scope of FWtTBC pathway deployment

The geographical scope of FWtTBC pathway deployment outlines geographical areas of focus (or ‘boundary’) that underpins each deployment case study scenario and is in turn subjected to 4 selection criteria. These criteria concern predominately with selecting regions that possess readily available infrastructure where research results can be rapidly applicable to help promote real-world FWtTBC pathway deployment and not just by means of a theoretical exercise. To this end, researcher aim to concentrate research efforts on UK regions with the greatest potential to achieve desired cost-benefit trade-off (i.e. economic, social and environmental) arising from FWtTBC pathway deployment (see Table 27).

Table 27. Summary of geographical boundary selection criteria and rationale behind their selection in determining specific geographical regions to be included in the case study scenarios for FWtTBC pathway deployment.

	Selection Criteria	Description	Rationale
1	Infrastructure	Regions with sufficient existing availability of anaerobic digestion (AD) plant infrastructure and capacity for FWtTBC pathway deployment	To render research both scientifically/commercially relevant and applicable by targeting regions that can make readily available use of all research findings (in modelling cost-benefit analysis of and recommendations for pathway deployment)
2	Techno-Economics	Key regions where FWtTBC pathway deployment will yield further significant techno-economic benefits that is self-reinforcing i.e. in form of additional local AD and refuel station infrastructure development	To ensure research findings can contribute to a balanced repertoire of cascading and self-reinforcing benefits that can be equitably distributed to all stakeholders and participants of the FWtTBC pathway deployment process
3	Socio-economics	Key regions where pathway deployment can yield significant socio-economic benefits that are not only marginal but transformational	
4	Regional support for pathway deployment	Regions which show strong political and investment will towards FWtTBC pathway deployment	Maximize real world relevance of each case study scenario by ensuring they are in regions where deployment is a significant possibility given right information input illustrated in this research and not just a theoretical exercise

A comprehensive assessment of all UK geographical regions using the geographical boundary selection criteria helped to identify and shortlist Greater London (GL) and Northern

Powerhouse (NPH) region as 2 potential geographical regions of research interest for FWtBC pathway deployment (see Figure 81).

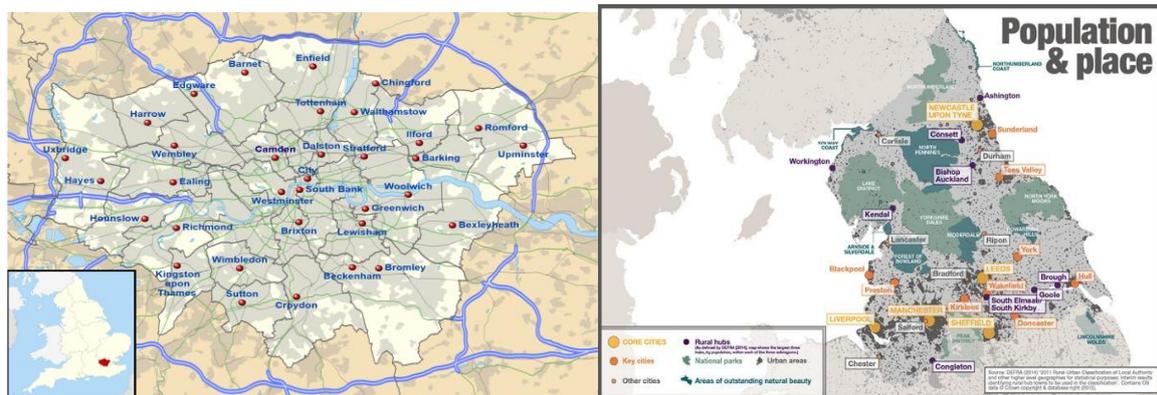


Figure 81. Geographical presentation of UK's Greater London Area (left) (Wikipedia, 2020) and Northern Power House region (CityMetric, 2016) (right)

This is predominately based on their strong economic and strategic significance for UK's future regional and national development coupled with strong infrastructure and feedstock (food waste) availability, strong demand for transport biofuel or alternative renewable energy, alongside significant techno-economical and socio-economic benefits attainable from pathway deployment (see Table 28).

Table 28. Evaluation of Greater London Area (GLA) and Northern Powerhouse (NPH) regions using 4 selection criteria for FWtBC pathway deployment

	Geographical boundary selection criteria	Greater London Area (GLA) Region	Northern Power House (NPH) Region
1	Infrastructure	1.1 Moderate AD plant infrastructure availability 1.2 AD plant being scarcely populated across London with limited capacity and scope for further cost-effective expansion	1.1 Strong AD plant infrastructure across the entire NPH region 1.2 AD plant densely populated in cluster regions and scarcely populated elsewhere, with significant capacity for cost-effective expansion
2	Techno-economics	2.1 FWtBC pathway deployment will likely yield weak to moderate effect on development of new AD (and refuelling station) infrastructure due to reasoned outlined in 1.1 and 1.2 above	2.1 FWtBC pathway deployment will likely yield strong effect on development of new AD (and refuelling station) infrastructure due to reasoned outlined in 1.1 and 1.2 above
3	Socio-economics	3.1 Regional benefits to population from FWtBC pathway deployment are marginal given lack of scalable potential for infrastructure development	3.1 Regional benefits to population from FWtBC pathway deployment are relatively stronger given strong scalable potential for infrastructure development, i.e. from increased job opportunity and equitable wealth distribution.
4	Regional support for pathway deployment	4.1 Strong from all regions to promote increased production of sustainable transport fuel and waste recycling, and in select regions for FWtBC pathway infrastructure development	4.1 Strong from all regions to promote increased production of sustainable transport fuel and waste recycling, and in select regions for FWtBC pathway infrastructure development

A more in-depth comparison for each factor between the two selection regions outlined the Northern Power House (NPH) region to be a more suitable candidate overall for conducting case scenario-based modelling of cost-benefit trade-off attainable from FWtTBC pathway deployment. Any resulting findings and post-modelling analysis will also be conducted in context of assessing how such deployments can contribute to NPH region's current developmental focus areas of hi-tech sector economy, transport & connectivity links, and renewable energy project developments (see Figure 82).

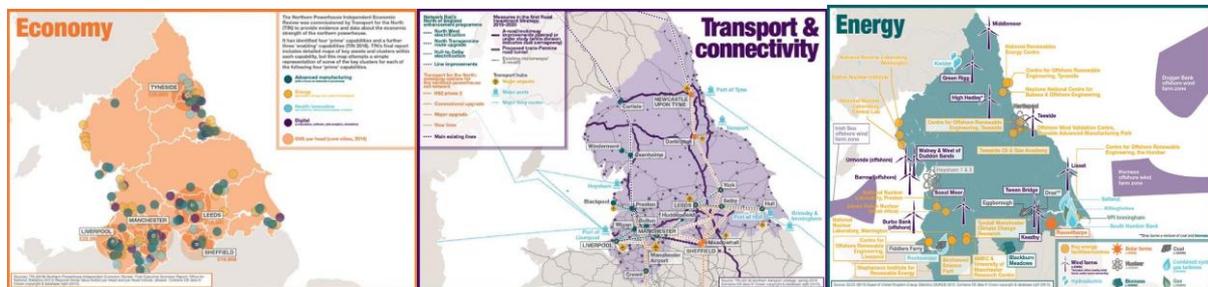


Figure 82. Northern Powerhouse cross-industry focus on key HiTECH developmental industries (left), Transport industry development of Northern Powerhouse (middle) and renewable energy development sector (right) (IPPR, 2016)

For the chosen NPH region in which FWtTBC pathway scenario-based modelling will focus on, modelling analysis from 3 different geographical scale of deployment is considered. Namely, these includes specific local, city, metropolitan county region with strong intention to undertake FWtTBC pathway deployment in the foreseeable future and where research data is sufficiently available (Table 29).

Table 29. More specifically they will focus on intra-city, city and multi-city level

No.	Geographical scope of coverage	Description
1	Local	Small scale trial regions (i.e. for Food waste collection, AD or refuelling trials) for FWtTBC pathway deployment at Leeds Rothwell region
2	City	City region of Manchester, Leeds. Liverpool, Sheffield and Newcastle
3	Metropolitan County region	Greater Manchester (Manchester), West Yorkshire (Leeds), Merseyside (Liverpool), South Yorkshire (Sheffield) and Tyne and Wear (Newcastle).

Where there exists strong rationale for the selection of any given region within the NPH for modelling analysis, the main focus on intra-city and city level region will be predominately on Rothwell and Leeds city region. This is due to strong indication of there being real actionable plans by Leeds City Council (LCC) to expand the existing food waste (FW) collection trials at Rothwell region (of 20,000 individuals, 2.5% of total Leeds population) (Populations, 2018) to the entire urban city region, which renders output of the present research both immediately relevant and valuable in assessing cost-benefits attainable should all collected FW be diverted for Anaerobic Digestion.

Where historical efforts by LCC towards establishing an AD plant in Leeds had fell through, it is hoped for any research findings to stimulate new consultations on alternative effective FWtTBC pathway deployment strategies in context of the anticipated new city-wide food waste collection scheme implementation. Where applicable, modelling analysis of remaining 4 urban city regions will also be conducted for comparative measure.

Likewise, focus on the modelling analysis of metropolitan county region will be extended across all 5 regions to determine individual total benefits attainable from FWtTBC pathway deployment across each NPH region (Table 30).

Table 30. Rationale for selecting specific geographical regions for implementing FWtTBC pathway modelling

No.	Geographical scale	Description and rationale
1	Local	Rothwell <ul style="list-style-type: none"> • Current small scale food waste collection trial deployment • Food waste collection data being available for trial duration
2	Urban City region	Leeds <ul style="list-style-type: none"> • Future planned city scale implementation of food waste collection • Previous attempts to secure AD plant facility for FWtTBC pathway deployment • Attain useful data to inform city wide food waste collection strategy, i.e. via the FWtTBC pathway
3	City region (Optional)	Inclusion of other 4 NPH city regions <ul style="list-style-type: none"> • Given adequate time and data availability (i.e. Manchester, Liverpool, Sheffield and Newcastle) • To compare against modelling analysis findings from Leeds
4	Metropolitan County Region	Inclusion of all 5 NPH regions <ul style="list-style-type: none"> • For comparative analysis of modelling outputs across all individual NPH regions • Findings can be totalled to establish modelling outputs across the entire NPH region

4.2.4 Time duration of FWtTBC pathway deployment

For each selected geographical region outlined above, a time boundary criterion is applied to restrict modelling to timeframes and milestones that are specifically relevant to UK's climate change policy targets subject to data availability (Figure 83).



Figure 83. Key research time period focus for modelling analysis in context of UK's short, medium to long term climate change targets

A few selection of specific timeframes for modelling of total cost benefit trade-off attainable from FWtTBC pathway deployment is outlined in Table 31 below, with actual timeframe used to be subject to data availability.

Table 31. Table of timeframes considering for modelling FWtTBC pathway deployment cost-benefit trade-off

	Timeframe 1	Timeframe 2	Timeframe 3	Timeframe 4
1	2010-2020	2020-2030	2030-2040	2040-2050
2	2010-2030	2020-2040	2030-2050	
3	2010-2040	2020-2050		

4	2010-2050			
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4.2.5 Pathway scenario deployment criteria summary

The FWtTBC pathway scenario deployment criteria set out outlines key factors for modelling analysis, namely the technological infrastructure and components selected for pathway deployment within specific geographical regions of the Northern Power House (NPH) regions over the selected timeframes of 2010-2050, subject to data availability (Table 32).

Table 32. Summary of FWtTBC pathway deployment criteria with descriptions

Deployment criteria	Details
Technical element	AD (anaerobic fermentation) technology and infrastructure Biomethane propulsion system (used in transport) and refuel infrastructure
Geographical element	NPH region – 4 geographical levels of focus (intra-city or local, city, metropolitan county region)
Time duration element	2010-2050 timeframe duration, with milestone points in 2020, 2030, 2035, 2045 and 2050.

These criteria are used to inform the design of all methodological components outlined in subsequent sections on defining FWtTBC pathway process and metric components, data collection, modelling, Excel modelling and whole systems analysis, as respectively highlighted in the remaining sections of this chapter.

4.3 Methodology 2 – Define FWtTBC pathway process and metric components

4.3.1 Pathway process overview

The establishment of the FWtTBC pathway process diagram outlines an integrated assessment of these 3 distinct technical pathway components of food waste, anaerobic digestion plant and transport biomethane refuel station, with specific sub-components process further outlined in Figure 84 below.

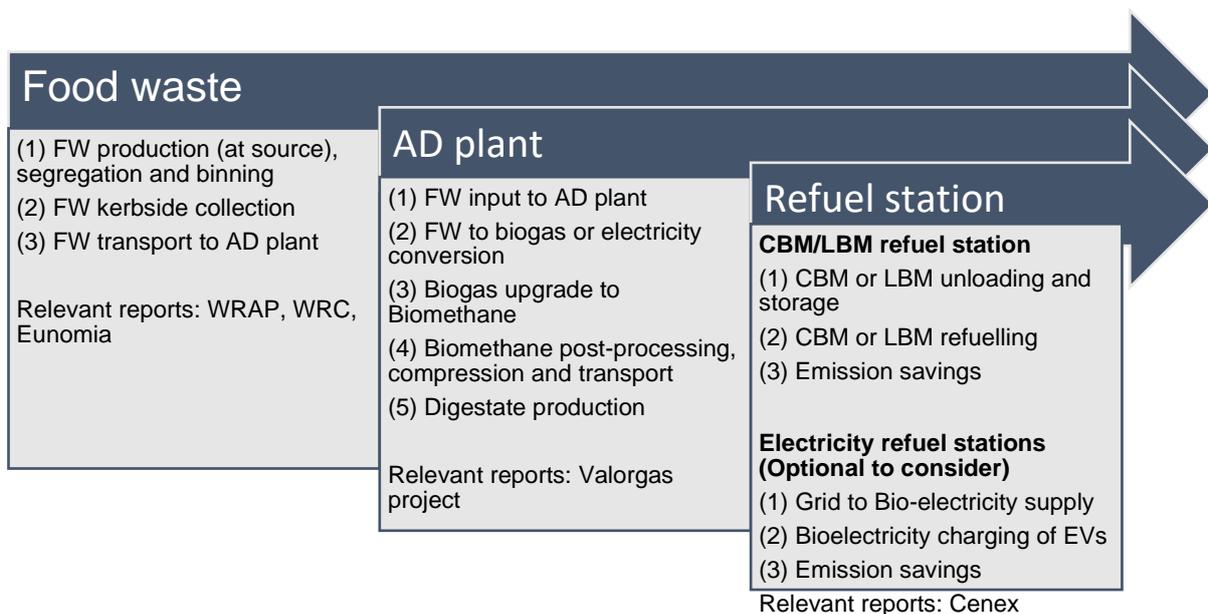


Figure 84. Food Waste to Transport Biomethane Conversion (FWtTBC) pathway process diagram (breakdown on basis of main pathway components), CBM/LBM pertain to compressed/liquified biomethane respectively.

The diagram had been adapted by drawing specific technical information and insight from key reports and studies that outlined all pathway metric and process step components, i.e. those from Waste Data Flow (Waste Data Flow, 2016), The Waste Resources Action Programme (WRAP, 2008), Water Research Centre (WRc, 2009), Eunomia (Eunomia, 2007), Valorgas Project (Valorgas, 2019) and Cenex (CENEX, 2009).

Below outlines individual basic process steps associated with the deployment of the FWtTBC pathway (see Figure 85) with expected unit of material and/or energy output.

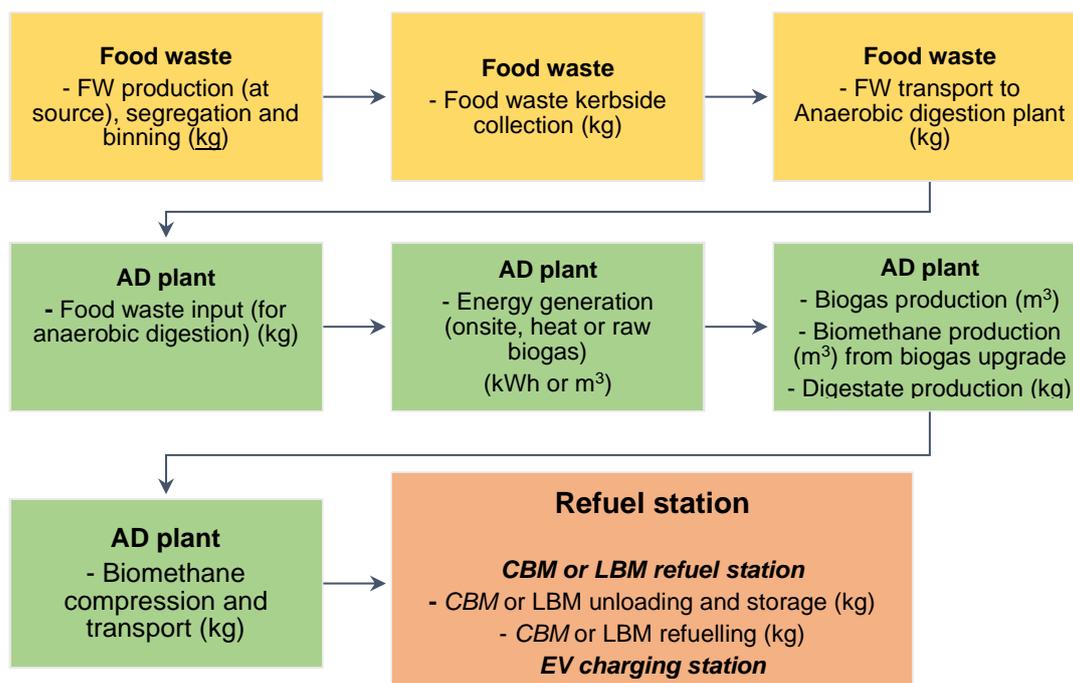


Figure 85. Food Waste to Transport Biomethane Conversion (FWtTBC) pathway process diagram (breakdown on basis of individual process steps). Units of measurement are in brackets.

4.3.2 Process diagram schematic overview

The above FWtTBC pathway process diagram is subsequently adapted to establish a series of interconnected process diagram schematics that respectively outline computational steps of all primary (mass, energy) and secondary (emission reduction and financial) metrics that constitutes novel research modelling outcomes for subsequent qualitative analysis, as illustrated in Figure 86 below.

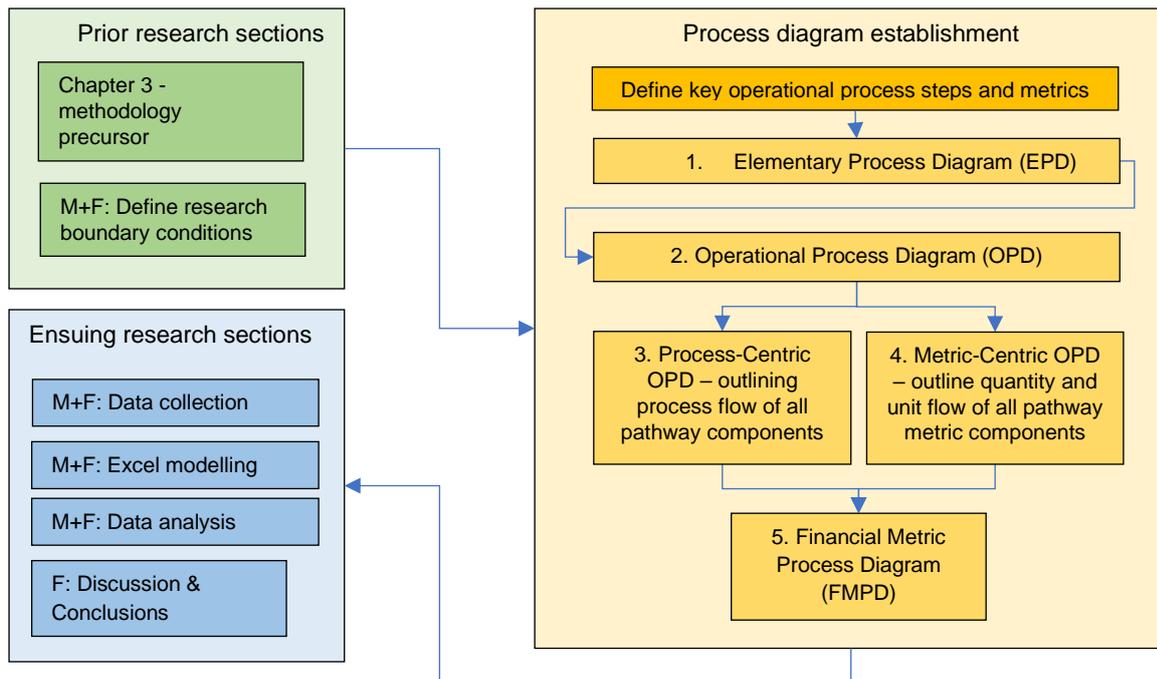


Figure 86. Process schematic overview of research methodology with respect to thesis section and chapter. M and F represent Methodology and Findings, respectively.

Summary of and references figures for each process diagram schematic is further outlined in Table 33 below, with full schematics and computational methods outline in the next section.

Table 33. Table of summary of Process schematic overview of research methodology with respect to thesis section and chapter

Process diagram type	Abbreviation	Summary of process diagram schematic
Research Methodology Process Diagram Overview	<i>RMP</i>	Process schematic overview of research methodology with respect to thesis section and chapter
Basic operational process diagram	<i>bOPD</i>	Basic process diagram illustrating flow of all basic FWtTBC pathway metrics
Operational process diagram	<i>OPD</i>	Operational process diagram illustrating process and/or quantity and unit flow of all FWtTBC pathway metric components under defined scenarios of geographical and time duration of deployment).
Advanced Operational process diagram 1	<i>aOPD-1</i>	
Advanced Operational Process Diagram 2	<i>aOPD-2</i>	
Financial (metric) process diagram	<i>FPD</i>	Process diagram on financials (cost vs revenues) metrics associated with FWtTBC pathway deployment

4.3.3 Basic operational process diagram (bOPD) and metrics overview

The Basic operational process diagram (bOPD) (Figure 87) illustrates general material-energy flows across the entire FWtTBC pathway at the most fundamental level (Figure 87) and establishes all core metrics for modelling pathway outputs.

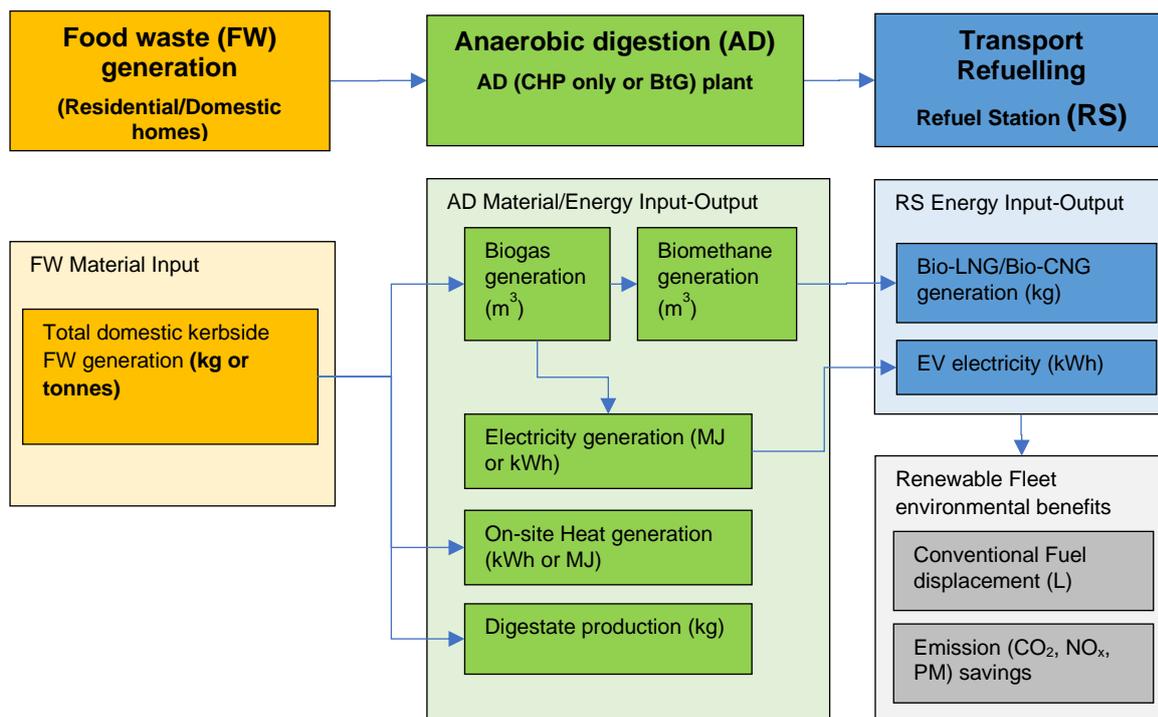


Figure 87. Elementary FWtBTC pathway process diagram illustrating all basic pathway metrics

Further details for each core metric and their respective calculation equations intended for use as part of basic Excel modelling process is presented in

Table 34 and

Table 35 below.

Table 34. FWtBTC pathway core metrics in context of FWtBTC pathway component with data metric name, abbreviations, metric units and description

Pathway component	Data Metric name	Abbreviation	Metric Units	Description
Food waste (FW)	Food waste	FW	t	Domestic residential food waste collected for input into anaerobic digester (AD) plant
Anaerobic Digestion (AD)	Biogas	BioG	m ³	Raw bio-energy output from food waste
	Biomethane	BioM	m ³	Upgraded gas product of biogas
	Bioelectricity	BioE	kWh	Bio-energy output from biogas combustion
	Digestate	D	t	Digestate output from processed FW
Refuel Station (RS)	Compressed Biomethane	BioCBM	Kg	Compressed product of biomethane for use in CNG road transport fleets
	Liquified Biomethane	BioLBM	Kg	Liquified product of biomethane for use in CNG road transport fleets
Renewable Fleet environmental benefits	Conventional Fuel displaced	CF	L	Fossil or diesel fuel displaced from use of BioCBM or BioLBM road fleet vehicles
	Carbon Dioxide (CO ₂) savings	CO ₂ S	t	Carbon dioxide savings derived from conventional fuel displacement

	Particulate matter (PM) savings	PM-S	t	Particulate matter savings derived from conventional fuel displacement
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*Weight measurements for all gases occurring in standard atmospheric conditions and temperatures

Table 35. Calculations for deriving core material-energy metric outputs

Pathway Component	Abbreviated metric name	Metric name	Units	Equation name	Equation	Abbreviations
Food waste (FW)	FW	Food waste	t	FW-E1	$\text{FW output per person (t/pp)} \times \text{Number of people (pp)} = \text{Total food waste output (t)}$ $\text{FW output per household (t/hh)} \times \text{Number of household (pp or hh)} = \text{Total food waste output (t)}$	$FW_{PP} \times PP = FW_T$ $FW_{HH} \times HH = FW_T$
Anaerobic Digestion (AD)	BioG	Biogas	m ³	AD-E1	$\text{Total FW output (t)} \times \text{FW biogas yield (m}^3\text{/t)} = \text{Total Biogas output (m}^3\text{)}$	$FW_T \times FW_{Bg} = Bg_T$
	BioM	Biomethane	m ³	AD-E2	$\text{Total FW output (t)} \times \text{FW biomethane yield (m}^3\text{/t)} = \text{Total Biomethane output (m}^3\text{)}$ $\text{Total Biogas output (m}^3\text{)} \times \text{Biomethane yield (\%)} = \text{Total Biomethane output (m}^3\text{)}$	$FW_T \times FW_{Bm} = Bm_T$ $Bg_T \times Bg_{Bm} = Bm_T$
	BioE	Bioelectricity	kWh	AD-E3	$\text{Total Biogas output (m}^3\text{)} \times \text{Biogas electricity yield (kWh/m}^3\text{)} = \text{Total electricity yield (kWh)}$	$Bg_T \times Bg_{BE} = BE_T$
	D	Digestate	t	AD-E4	$\text{Total FW output (t)} \times \text{FW digestate yield (m}^3\text{/t)} = \text{Total Digestate output (m}^3\text{)}$	$FW_T \times FW_D = D_T$
Refuel Station (RS)	BioCBM	Compressed Biomethane	Kg	RS-E1	$\text{Total Biomethane output (m}^3\text{)} \times \text{Biomethane to BioCBM compression conversion yield (kg/m}^3\text{)} = \text{BioCBM output (kg)}$	$Bm_T \times Bm_{BioCBM} = BioCBM_T$
	BioLBM	Liquified Biomethane	Kg	RS-E2	$\text{Total Biomethane output (m}^3\text{)} \times \text{Biomethane to BioLBM compression conversion yield (kg/m}^3\text{)} = \text{BioLBM output (kg)}$	$Bm_T \times Bm_{BioLBM} = BioLBM_T$
Renewable Fleet environmental benefits	CF	Conventional Fuel displaced	L	RF-E1	$\text{Total BioCBM or BioLBM used (kg)} \times \text{BioCBM or BioLBM to Conventional fuel conversion yield (L/kg or L/kWh)} = \text{Total Conventional Fuel replaced (L)}$ $\text{Total BioElectricity used (kWh)} \times \text{BioElectricity to Conventional fuel conversion yield (L/kWh)} = \text{Total Conventional Fuel replaced (L)}$	$BioCBM_T \times BioCBM_{CF} = CF_T$ $BioLBM_T \times BioLBM_{CF} = CF_T$
	CO ₂ S	Carbon Dioxide (CO ₂) savings	t	RF-E2	$\text{Total Conventional Fuel replaced} \times \text{CO}_2 \text{ savings per tonne conventional fuel replaced} = \text{Total CO}_2 \text{ savings}$	$CF_T \times CF_{CO2} = CO_{2(T)}$

4.3.4 Advanced Operational Process Diagram (OPD) and metrics overview

4.3.4.1 Advanced OPD Introduction

In establishing a concrete understanding of specific operational mechanisms surrounding the FWtTBC pathway deployment in a real-world context, the bOPD is subsequently expanded by integrating more advanced 'operational step' components and relevant 'metrics' corresponding to each step to reflect real-world material and energy flows and losses across key pathway checkpoints.

Here the aim is to conduct modelling in context of specific material-energy losses across these checkpoints using real-world or theoretical loss data to determine the extent of impact on pathway metric outputs (given the same material-energy input) and cost-benefit trade-off.

Two Advanced Operational Process Diagram is established to visually outline 2 distinct calculation methods using either high level or low level data input for computing real-world material energy flows for FWtTBC pathway deployment at different geographical and time scale (see Table 36).

Table 36. Summary of 2 advanced-OPD schematics

Process diagram reference	Description summary of key focus and components	
1	aOPD-1	Low-Level OPD (LL-OPD) is designed for input of low level data
2	aOPD-2	High-Level OPD (HL-OPD) is designed for input of high level data

*NOTE: hereafter the terms of aOPD-1 are interchangeable, as is aOPD-2.

These scenarios based geographical and time scales that outlines at 3 levels of FWtTBC pathway deployment are re-iterated using summary details in Table 38 below.

Table 37. Re-iterated summary of Geographical and operational years (based on boundary conditions set for this research, see Methodology: boundary condition section for details).

Geographical boundary	Year of operation (Time boundary)
Northern Powerhouse (NPH) region (Level 1) Leeds city region (Level 2) Intra-Leeds Rothwell region (Level 3) NPH region cities (level 1): <ul style="list-style-type: none"> Greater Manchester (Manchester) West Yorkshire (Leeds) Merseyside (Liverpool) South Yorkshire (Sheffield) Tyne and Wear (Newcastle). 	Categorization of specific timeframes of research focus: <ul style="list-style-type: none"> 2000-2020 - Rapid development of UK's AD and FW recycling industry 2030-2050 - Timeframe for achieving UK's medium and long term climate change milestones 2100 - Super Long term theoretical estimation (conditional: depending on data availability)

4.3.4.2 Advanced-OPD component diagram schematic and calculation

Each advanced OPD (aOPD-1 and aOPD-2) further expands from the basic material energy metrics outlined in the bOPD to form 4 distinct categories of data input-output to include financial and environmental cost-benefit trade-off from FWtTBC pathway deployment in context of real world process inefficiencies (see Table 38).

Table 38. Elaborations on key components of the both advanced operational process diagram (aOPD-1 and aOPD-2) for FWtTBC pathway (see Figure 100)

Component	Description	
1	Core material-energy metric	Core metric outputs outlined in bOPD (see Figure 87, Table 34 and Table 35)
2	Material-energy loss metrics	Metrics that represent real-world material-energy losses (or process inefficiencies) arising from key pathway checkpoints (i.e. transportation, storage and conversion)
3	Financial metrics	Metric outputs associated with commercialization of FWtTBC pathway deployment, i.e. taking account of revenue and costs
4	Environmental metrics	Metric outputs in form of NO _x , CO ₂ and PM savings arising from displacement of conventional fuel by biomethane

Schematics of both advanced OPD is illustrated below depicting specific data inputs and outputs.

4.3.4.3 Advanced Operational Process Diagram-1 (Low-level OPD) schematics

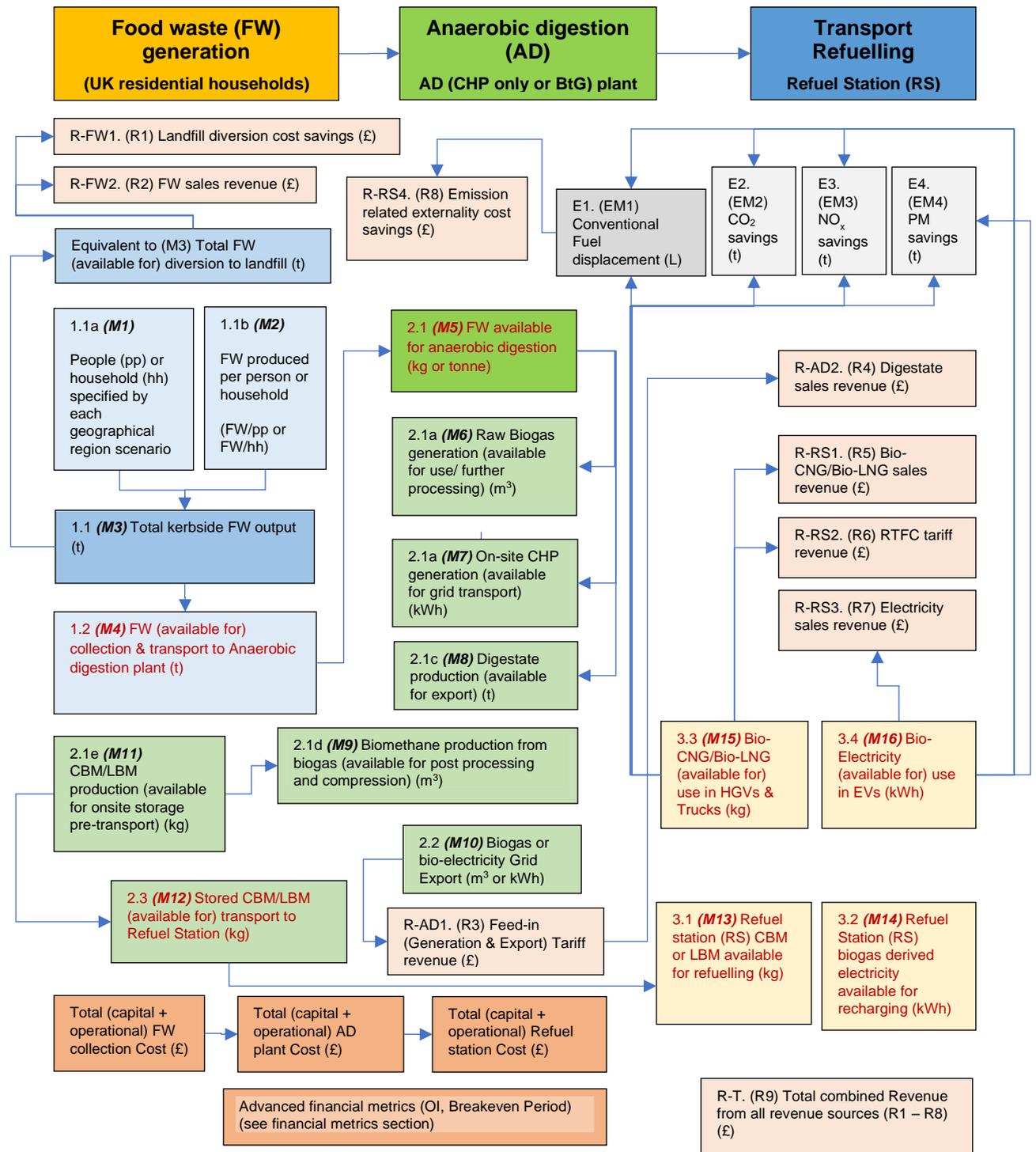


Figure 88. FWtTBC pathway process diagram illustrating physical flow of material-energy components (expressed as metrics) with corresponding revenues and emission reductions associated with pathway deployment. Black and Red font represent primary material-energy and secondary material-energy metric (accounting for real world loss) respectively. All metrics outputs are scaled to match FWtTBC pathway deployment at specified geographical regions (GR) and time durations outlined by each of the 3 case study scenarios (summarized in Table 37). Box colour scheme – Financial revenue in Orange, FW metrics in blue, AD metrics in Green, RS metrics in Yellow, Fuel and Emission metrics in Grey.

4.3.4.4 Advanced Operational Process Diagram-2 (Metric-Centric OPD)

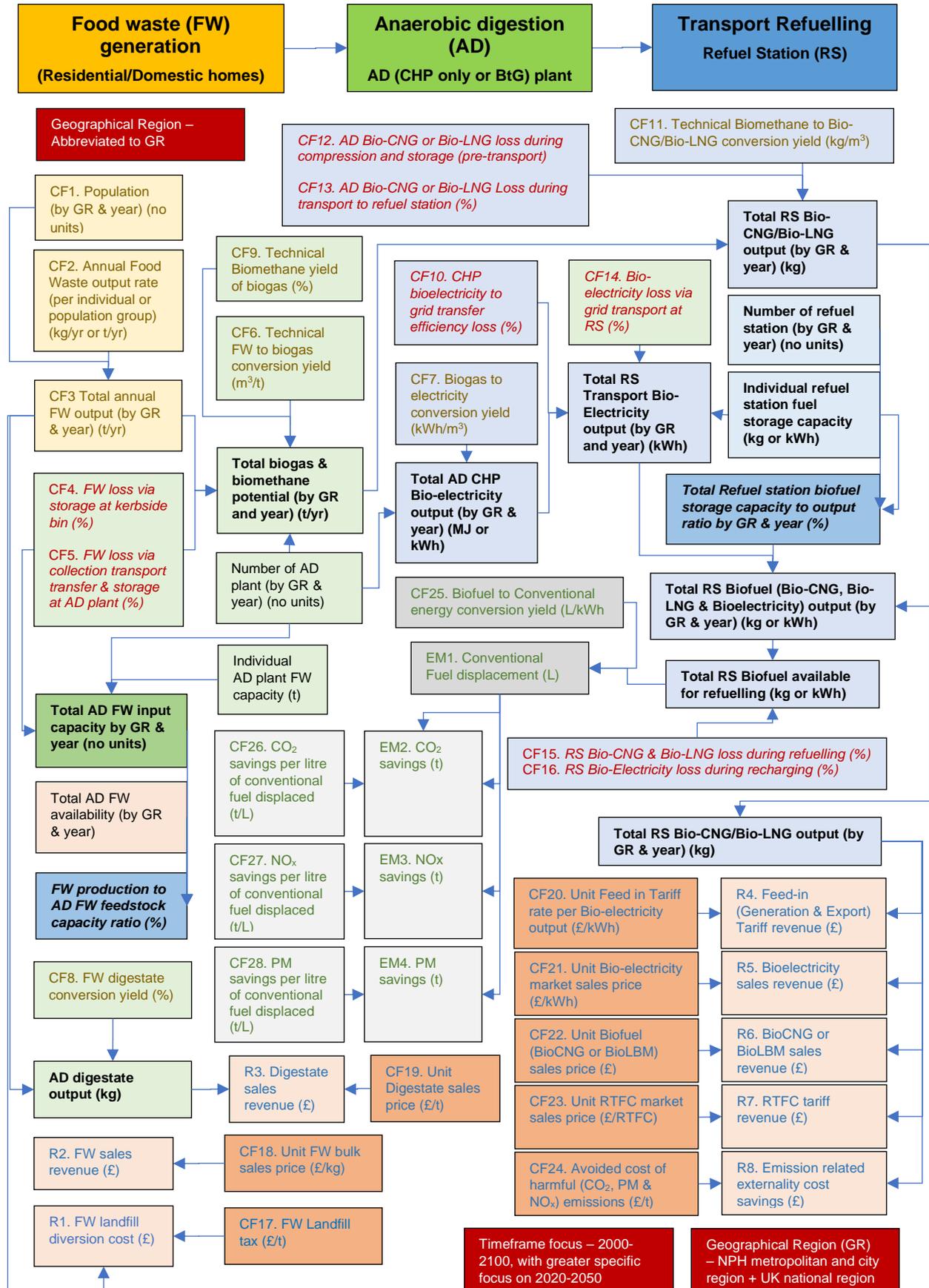


Figure 89. FWtBTC pathway process diagram on calculation of conversion factors (abbreviated to CF) and main material-energy, emissions and revenue metrics (in black bold font) based on geographical region (abbreviated to GR) and year (as summarized in red boxes). Box colour coding remain the same as Figure 102 above.

4.3.4.5 Advanced Operational Process Diagram (OPD) metrics calculation method using conversion factors

Details of calculations for all advanced operational metrics associated with FWtTBC pathway deployment that accounts for real-world material-energy conversions is outlined in Table 39 below. Here a conversion factor (CF) is applied to the calculations of all non-initial data input metrics (i.e. population size and food waste output) that takes account of real-world conversions and inefficiencies of different process steps within the FWtTBC pathway (see Table 39, Table 40 and Table 41).

Table 39. Key FWtTBC pathway material-energy metric calculations (refer to Figure 89 for context and visual flow of relevant metrics)

Pathway Component	Metric number	Metric (M) description (see left column)	Conversion factor number	Conversion factor description	Equation	Equation description
FW	M1	Population size (pp or hh)	CF1	N/A	N/A	Population size (pp or hh) = Existing population data (actual or inferred) based on geographical and time value (pp or hh)
	M2	Individual person or household FW output (kg/pp or kg/hh)	CF2	N/A	N/A	Individual person or household FW output (kg/pp or kg/hh) = Existing data (actual or inferred) for individual FW output (kg/pp or kg/hh)
	M3	Total kerbside FW (generation & binning) output (t)	CF3	N/A	$M1 \times M2 = M3$	Population size (pp or hh) \times Individual person or household FW output (kg/pp or kg/hh) = Household FW output (kg)
	M4	FW (available for collection and transport to AD station) (t)	CF4	FW loss via storage at kerbside bin (%)	$M3 \times CF4 = M4$	FW output (for collection and transport) (t) \times FW loss via collection and transport (%) = FW input (for AD plant) (t)
	M5	FW (available for input for AD plant) (t)	CF5	FW loss via collection transport transfer & storage at AD plant (%)	$M4 \times CF5 = M5$	FW output (for collection and transport) (t) \times FW loss via transfer & storage at AD plant (%) = FW input (for AD plant) (t)
AD	M6	Raw biogas generation (m ³)	CF6	FW to Biogas conversion yield (m ³ /t)	$M5 \times CF6 = M6$	FW input (for AD plant) (kg/yr) \times FW to Biogas conversion yield (m ³ /kg) = Raw biogas generation (m ³)
	M7	On-site CHP bio-electricity generation (kWh)	CF7	Biogas to bio-electricity conversion yield (kWh/m ³)	$M6 \times CF7 = M7$	Raw biogas generation (m ³) \times Biogas to electricity conversion yield (kWh/m ³) = On-site CHP generation (kWh)
	M8	Digestate production (t)	CF8	Food waste to digestate conversion yield (%)	$M5 \times CF8 = M8$	FW input (for AD plant) (t) \times Food waste to digestive conversion yield (%) = Digestate (t)
	M9	Biomethane production (m ³)	CF9	Biomethane yield of Biogas (%)	$M6 \times CF9 = M9$	Raw biogas generation (m ³) \times Biomethane yield of Biogas (%) = Biomethane production (m ³)
	M10	Grid Exported biogas electricity (kWh)	CF10	CHP bioelectricity to grid transfer efficiency loss (%)	$M7 \times CF10 = M10$	On-site CHP generation (kWh) \times CHP bioelectricity to grid transfer efficiency loss (%) = Grid Exported Bio-electricity (kWh)
RS	M11	Compressed Biofuel (BioCBM or BioLBM) (kg)	CF11	Biomethane to BioLBM or BioCBM compression conversion yield (%)	$M9 \times CF11 = M11$	Biomethane production (m ³) \times Biomethane to BioLBM or BioCBM compression conversion yield (%) = Compressed Biofuel (BioCBM or BioLBM) (kg)
	M12	AD BioCBM or BioLBM (available for transport to refuel station) (kg)	CF12	AD BioCBM or BioLBM loss during compression and storage (pre-transport)	$M11 \times CF12 = M12$	Compressed Biofuel (BioCBM or BioLBM) (kg) \times BioCBM or BioLBM loss during compression and storage (pre-transport) (%) = BioCBM or BioLBM (available for) transport to refuel station (kg)
	M13	RS BioCBM or BioLBM (available for refuelling) (kg)	CF13	AD BioCBM or BioLBM Loss during transport to and storage at refuel station (%)	$M12 \times CF13 = M13$	AD BioCBM or BioLBM (available for) transport to refuel station (kg) \times AD BioCBM or BioLBM Loss during transport to and storage in refuel station (%) = RS BioCBM and BioLBM (available for) refuelling (kg)
	M14	RS Bio-Electricity (available for refuelling) (kWh)	CF14	AD BioElectricity loss via grid transport to and storage at electric charging station (%)	$M10 \times CF14 = M14$	Grid Exported bio-electricity (kWh) \times AD Bio-electricity loss via grid transport to and storage in electric charging station (%) = RS Bio-Electricity (available for) refuelling (kWh)
	M15	BioCBM or BioLBM (available for) use in HGVs (kg)	CF15	RS BioCBM or BioLBM loss during refuelling (%)	$M13 \times CF15 = M15$	RS BioCBM and BioLBM (available for) storage (kg) \times RS BioCBM and BioLBM loss during refuelling (%) = BioCBM/BioLBM (available for) Refuelling for HGVs & Trucks (kg)
	M16	RS BioElectricity (available for) use in EVs (kWh)	CF16	RS BioElectricity loss during recharging (%)	$M14 \times CF16 = M16$	RS Bio-Electricity (available for) storage (MJ or kWh) \times RS Bio-Electricity loss during recharging (%) = Bio-Electricity (available for) Refuelling for EVs (kWh)

*Text Colour description: Loss co-efficient in red, Efficiency co-efficient in green, abbreviated or full descriptive equations involving CF in blue

Table 40. Key FWtTBC pathway revenue metric calculations (refer to Figure 89 for context and visual flow of relevant metrics)

Pathway Component	Metric number	Metric (M) description (see left column)	Conversion factor number	Conversion factor description	Equation	Equation description
Revenue	R1	Landfill diversion cost savings (£)	CF17	FW landfill tax per tonne (£/t)	$M3 \times CF17 = R1$	Total kerbside FW (generation & binning) output (kg or tonnes) \times FW landfill tax per tonne (£/t) = Landfill diversion cost savings
	R2	FW sales revenue (£)	CF18	Unit FW bulk sales price (£/kg)	$M4 \times CF18 = R2$	FW (available for) <i>collection and transport to AD station (t)</i> \times Unit FW bulk sales price (£/kg) = FW sales revenue (£)
	R3	Digestate sales revenue (£)	CF19	Unit Digestate sales price (£/t)	$M8 \times CF19 = R3$	Digestate production (t) \times Unit Digestate sales price (£/t) = Digestate sales revenue (£)
	R4	Feed-in (Generation & Export) Tariff revenue (£)	CF20	Unit Feed in Tariff rate per Bio-electricity output (£/kWh)	$M10 \times CF20 = R4$	Grid Exported biogas electricity (kWh) \times Unit Feed in Tariff rate per Bio-electricity output generation (£/kWh) = Feed-in (Generation & Export) Tariff revenue (£)
	R5	BioElectricity sales revenue (£)	CF21	Unit electricity market sales price (£/kWh)	$M14 \times CF21 = R5$	RS Bio-Electricity (available for) refuelling (kWh) \times Unit electricity market sales price (£/kWh) = Bioelectricity sales revenue (£/kWh)
	R6	BioCBM or BioLBM sales revenue (£)	CF22	Unit Biomethane (BioCBM or BioLBM) sales price (£)	$M13 \times CF22 = R6$	RS BioCBM or BioLBM (available for) refuelling (kg) \times Unit Biomethane (BioCBM or BioLBM) sales price (£) = BioCBM or BioLBM sales revenue (£)
	R7	RTFC tariff revenue (£)	CF23	Unit RTFC market sales price (£/RTFC)	$M13 \times CF23 = R7$	RS BioCBM or BioLBM (available for) refuelling (kg) \times Unit RTFC market sales price (£/kg) = RTFC tariff revenue (£)
		R8	Avoided cost of harmful (CO ₂ , PM & NO _x) emissions (£/t)	CF24		

An alternative representation of revenue calculations without use of conversion factors is outlined in Table 41 below.

Table 41. Key (primary and secondary) FWtTBC pathway financial metrics (as outlined in Figure 98) with relevant conversion factors, units and equations

Pathway Component	Metric	Metric (M) description (see left column)	Equation name	Equation	Abbreviations	Description
Food waste	R1	Landfill diversion cost savings	R-FW1	FW landfill tax per tonne (£/t) × total FW quantity diverted (t) = Total Landfill diversion cost avoided (£)	$FW_{LFT} \times FW_T = FW_{T-LFT}$ (R-FW1)	Avoided cost of paying to landfill food wastes (typically as part of general waste contaminants)
	R2	FW sales revenue	R-FW2	Unit FW bulk sales price (£/t) × total FW quantity sold (t) = Total FW sales revenue (£)	$FW_{SP} \times FW_T = FW_{T-SR}$ (R-FW2)	Extra revenue from bulk sales of FW, assume it being viewed as a valuable commodity
Anaerobic digestion	R3	Feed-in (Generation & Export) Tariff revenue (£)	R-AD1	Unit Feed in Tariff rate per Bio-electricity output generation (£/kWh) × Total Bioelectricity generated (kWh) = Total Feed-in (Generation & Export) Tariff revenue (£)	$BioE_{eFIT} \times BioE_T = BioE_{T-eFIT}$ or $BioE_{gFIT} \times BioE_T = BioE_{T-gFIT}$ (R-AD1)	Tariff Revenue from renewable electricity generation and export, former differ based on size of AD. latter fixed.
	R4	Digestate sales revenue (£)	R-AD2	Unit Digestate sales price (£/t) × Total digestate quantity sold (t) = Total Digestate sales revenue (£)	$D_{SP} \times D_T = D_{T-SR}$ (R-AD3)	Revenue from Digestate sales typically to farms and agricultural industry
Refuel station	R5	BioCBM/BioLBM sales revenue (£)	R-RS1	Unit Biomethane (BioCBM or BioLBM) sales price (£) × Total biomethane quantity (kg) = Total BioCBM/BioLBM sales revenue (£)	$BioCBM_{SP} \times BioCBM_T = BioCBM_{T-SR}$ $BioLBM_{SP} \times BioLBM_T = BioLBM_{T-SR}$ R-AD2	Revenue from sales of compressed biomethane typically for uses as transport biofuel
	R6	RTFC tariff revenue (£)	R-RS2	Unit RTFC market sales price (£/RTFC) × Total RTFC traded (no units) = Total RTFC sales revenue (£)	$RTFC_{SP} \times RTFC_T = RTFC_{T-SR}$ (R-RS1)	Revenue from sales of, or equivalent avoided cost of buying Renewable Fuel Transport Certificates (RTFC) at market price
	R7	Bio-Electricity sales revenue (£/kWh)	R-RS3	Unit electricity market sales price (£/kWh) × Total units of bio-electricity sold (kWh) = Total Bio-Electricity sales revenue (£)	$BioE_{SP} \times BioE_T = BioE_{T-SR}$ (R-RS3)	Revenues from sales of bulk electricity at market price to grid, similar to Export tariff but at different (market) price point
	R8	Emission related externality cost savings (£)	R-RS4	Avoided cost of harmful (CO ₂ , PM & NO _x) emissions (£/t) × Total Emissions avoided (t) = Total Emission related externality cost avoided (£)	$EC_{GE} \times EC_T = EC_{T-GE}$ (R-RS4) Where GE (Gas emission) = CO ₂ , PM or NO _x	Revenue from avoided environmental and health cost associated with reductions in emission of harmful gases (CO ₂ , PM & NO _x)
All	R9	Total Revenue (£) from all sources	R-T	Total (FW digestate & sales + Feed in Tariff or/and RTFC + Fuel sales) revenue (see right)	$FW_{T-LFT} + FW_{T-SR} + BioE_{T-eFIT} + BioE_{T-gFIT} + D_{T-SR} + BioCBM_{T-SR} + BioLBM_{T-SR} + RTFC_{T-SR} + BioE_{T-SR} + EC_{T-GE} = T_{R(FW+AD+RS)}$ (R-T)	Total revenue sums from the aggregation of different revenue streams above. Used for more advanced financial metrics analysis such as ROI, NPV, breakeven point analysis.

A more in-depth and complete assessment of financial cost-benefit trade-off of FWtTBC pathway deployment is outlined in the next section on advanced cost-benefit financial calculations.

Table 42. Key FWtTBC pathway fuel and emission metric calculations (refer to Figure 89 for context and visual flow of relevant metrics)

Pathway Component	Metric number	Metric (M) description (see left column)	Conversion factor number	Conversion factor description	Equation	Equation description
Fuel and emissions	EM1	Conventional Fuel displacement (L)	CF25	Biomethane to Conventional energy conversion yield (L/kWh or L/kg)	$M15 \text{ or } M16 \times CF25 = EM1$	BioCBM or BioLBM (available for) use in HGVs (kg) or RS BioElectricity (available for) use in EVs (kWh) \times Biomethane to Conventional energy conversion yield (L/kWh or L/kg) = Conventional Fuel displacement (L)
	EM2	CO ₂ savings (t)	CF26	CO ₂ savings per litre of conventional fuel displaced (t/L)	$EM1 \times CF26 = EM2$	Conventional Fuel displacement (L) \times CO ₂ savings per litre of conventional fuel displaced (t/L) = CO ₂ savings (t)
	EM3	NO _x savings (t)	CF27	NO _x savings per litre of conventional fuel displaced (t/L)	$EM1 \times CF27 = EM3$	Conventional Fuel displacement (L) \times NO _x savings per litre of conventional fuel displaced (t/L) = NO _x savings (t)
	EM4	PM savings (t)	CF28	PM savings per litre of conventional fuel displaced (t/L)	$EM1 \times CF28 = EM4$	Conventional Fuel displacement (L) \times PM savings per litre of conventional fuel displaced (t/L) = PM savings (t)

This approach also makes possible the adoption of an alternative, ‘cumulative co-efficient’ method using mainly initial data input metrics and conversion factors as outlined in the next section.

4.3.5 Design of Cumulative Co-efficient method as an alternative method of calculating all Advanced Operational Process Diagram (aOPD-1 and aOPD-2) outputs

4.3.5.1 Cumulative Co-efficient method introduction

The cumulative co-efficient method is developed to ensure calculations of all FWtTBC pathway metrics are possible when only initial data input values (of population size and food waste output) and CF values are known.

This enables greater theoretical modelling estimations of material-energy, revenue or emission outputs based on possible real-world adjustments that for example, leads to improved efficiency of material-energy conversion or reduced material-energy loss compared to the default real-world pathway deployment scenario.

4.3.5.2 Cumulative Co-efficient method equation

The method is underpinned by the cumulative co-efficient equation:

$$N \times CF1 \times CF2 \times CF3 \dots$$

Table 43. Table of calculations via the cumulative co-efficient product method

Pathway Component	Metric number	Metric (M) description (see left column)	No. of cumulative CF co-efficient (n)	Metric equations (original data input × all applicable CF co-efficients, see Table 39 for details)	Final metric output
FW	M1	Population size (pp or hh)	0	M1	
	M2	Individual person or household FW output (kg/pp or kg/hh)	0	M2	
	M3	Total kerbside FW (generation & binning) output (t)	0	M1 × M2	
	M4	FW (available for collection and transport to AD station) (t)	1	M1 × M2 × CF4	=M4
	M5	FW (available for input for AD plant) (t)	2	M1 × M2 × CF4 × CF5	=M5
AD	M6	Raw biogas generation (m ³)	3	M1 × M2 × CF4 × CF5 × CF6	=M6
	M7	On-site CHP bio-electricity generation (kWh)	4	M1 × M2 × CF4 × CF5 × CF6 × CF7	=M7
	M8	Digestate production (t)	3	M1 × M2 × CF4 × CF5 × CF8	=M8
	M9	Biomethane production (m ³)	4	M1 × M2 × CF4 × CF5 × CF6 × CF9	=M9
	M10	Grid Exported biogas electricity (kWh)	4	M1 × M2 × CF4 × CF5 × CF6 × CF7 × CF10	=M10
RS	M11	Compressed Biomethane (BioCBM or BioLBM) (kg)	5	M1 × M2 × CF4 × CF5 × CF6 × CF9 × CF11	=M11
	M12	AD BioCBM or BioLBM (available for) transport to refuel station (kg)	6	M1 × M2 × CF4 × CF5 × CF6 × CF9 × CF11 × CF12	=M12
	M13	RS BioCBM or BioLBM (available for) refuelling (kg)	7	M1 × M2 × CF4 × CF5 × CF6 × CF9 × CF11 × CF12 × CF13	=M13
	M14	RS Bio-Electricity (available for) refuelling (kWh)	6	M1 × M2 × CF4 × CF5 × CF6 × CF7 × CF10 × CF14	=M14
	M15	BioCBM or BioLBM (available for) use in HGVs (kg)	8	M1 × M2 × CF4 × CF5 × CF6 × CF9 × CF11 × CF12 × CF13 × CF15	=M15
	M16	RS BioElectricity (available for) use in EVs (kWh)	7	M1 × M2 × CF4 × CF5 × CF6 × CF7 × CF10 × CF14 × CF16	=M16

Where N represents original (food waste) data input and that values of all participating CF (conversion factors) is known in

Table 43 outlines all calculations for each metric based on the cumulative co-efficient equation using abbreviated metric and conversion factors in Table 39 above.

Below outlines a table of theoretical cumulative material-energy losses applicable to the modelled non-loss outputs, which demonstrates high sensitivity of outputs in material, energy, financial or emissions to the cumulative inefficiencies arising from multiple operational processes within the FWtTBC pathway (see Table 44, compare results of last column).

Table 44. Table of coefficient values used for calculating loss metrics specified in the operational process diagram (OPD)

Output efficiency as a result of cumulative co-efficient losses, presented as $(CF_x)^n$ where x represent number of co-efficient in use, which is reflected in the n (power) value								
Co-efficient loss for each Conversion Factor (CF)	$(CF_x)^1$	$(CF_x)^2$	$(CF_x)^3$	$(CF_x)^4$	$(CF_x)^5$	$(CF_x)^6$	$(CF_x)^7$	$(CF_x)^8$
0.5%	99.50%	99.00%	98.51%	98.01%	97.52%	97.04%	96.55%	96.07%
1%	99.00%	98.01%	97.03%	96.06%	95.10%	94.15%	93.21%	92.27%
1.5%	98.50%	97.02%	95.57%	94.13%	92.72%	91.33%	89.96%	88.61%
2%	98.00%	96.04%	94.12%	92.24%	90.39%	88.58%	86.81%	85.08%
2.5%	97.50%	95.06%	92.69%	90.37%	88.11%	85.91%	83.76%	81.67%
3%	97.00%	94.09%	91.27%	88.53%	85.87%	83.30%	80.80%	78.37%
3.5%	96.50%	93.12%	89.86%	86.72%	83.68%	80.75%	77.93%	75.20%
4%	96.00%	92.16%	88.47%	84.93%	81.54%	78.28%	75.14%	72.14%
4.5%	95.50%	91.20%	87.10%	83.18%	79.44%	75.86%	72.45%	69.19%
5%	95.00%	90.25%	85.74%	81.45%	77.38%	73.51%	69.83%	66.34%
5.5%	94.50%	89.30%	84.39%	79.75%	75.36%	71.22%	67.30%	63.60%
6%	94.00%	88.36%	83.06%	78.07%	73.39%	68.99%	64.85%	60.96%
6.5%	93.50%	87.42%	81.74%	76.43%	71.46%	66.81%	62.47%	58.41%
7%	93.00%	86.49%	80.44%	74.81%	69.57%	64.70%	60.17%	55.96%
7.5%	92.50%	85.56%	79.15%	73.21%	67.72%	62.64%	57.94%	53.60%
8%	92.00%	84.64%	77.87%	71.64%	65.91%	60.64%	55.78%	51.32%
8.5%	91.50%	83.72%	76.61%	70.09%	64.14%	58.68%	53.70%	49.13%
9%	91.00%	82.81%	75.36%	68.57%	62.40%	56.79%	51.68%	47.03%
9.5%	90.50%	81.90%	74.12%	67.08%	60.71%	54.94%	49.72%	45.00%
10.00%	90.00%	81.00%	72.90%	65.61%	59.05%	53.14%	47.83%	43.05%

4.3.6 Advanced financial cost-benefit trade-off calculation method for FWtTBC pathway deployment

4.3.6.1 Advanced FW-OPD introduction

To help determine financial cost benefits attainable from FWtTBC pathway deployment in further detail beyond revenue calculations, a process diagram illustrating financial metrics that also takes account of logistical processes of FW collection is established and outlined in Figure 90 below.

4.3.6.2 Advanced FW-OPD introduction schematic and metrics overview

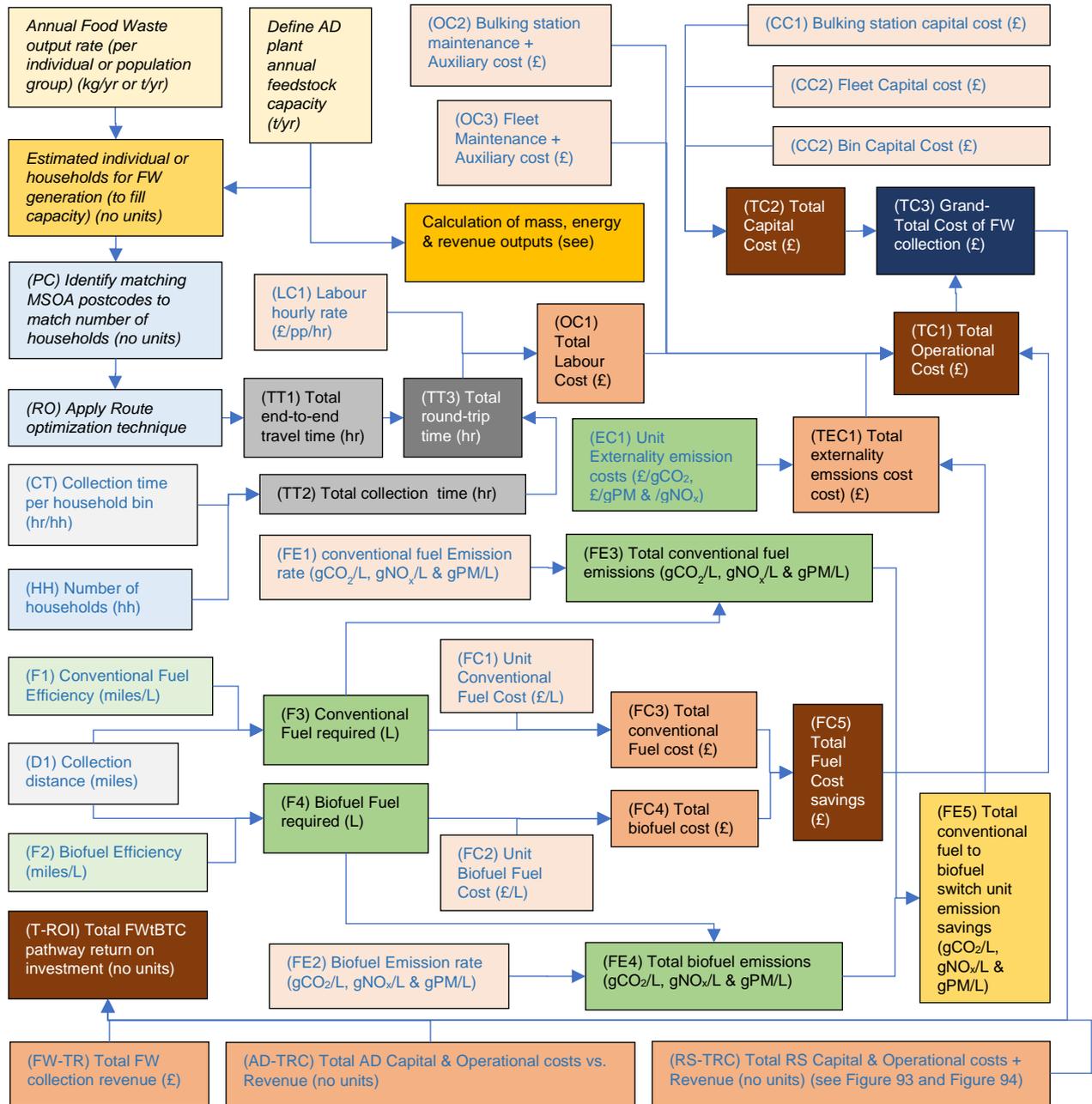


Figure 90. Food waste collection Operational Process Diagram (FWC-OPD) schematic for calculating financial cost-benefit trade-offs of FWtBTC pathway with including of more specific costs associated with food waste collection at local deployment scale.

This added level of process intricacy enables more precise cost and revenues associated with FW collection to be made based on changes to detailed physical operational steps that are omitted in previous OPDs. This enables assessment of alternative FW collection deployment strategies that could yield different levels of financial cost-benefit returns at a more detailed level.

Table 45 and Table 46 below outlines dual components of metric values alongside set of established equations used for calculation of key operational and financial components as illustrated in the FW collection OPD above.

Table 45. FW-OPD Metrics with description of potential data sources required for calculation of these metrics as per Figure 104

Metric type	Metric	Metric Abbreviations	Units (abbreviated units)	Potential Data Source
Collection Household, time and distance	Number of households	HH	No units	MSOA postcode data used for specifying number of households intended for target for FW collection
	Collection time per household	CT	Minutes (min)	Case specific real-world individual household collection data time recorded for household FW collection process
	Collection Distance	CD	Miles	Mapping tool with travel distance measurement
	Total end-to-end travel time	TT1	Hour (Hr)	Mapping tool with estimated travel time calculation
Fuel & emissions	Biomethane efficiency	F1	Miles/Litre (miles/L)	(Individual or Fleet) Collection vehicle biofuel (BioCBM, BioLBM or Bioelectricity) efficiency rating
	Conventional Fuel efficiency	F2	Miles/Litre (miles/L)	(Individual or Fleet) Collection vehicle conventional fuel efficiency rating
	Biomethane Emission rate	FE1	Grams Carbon dioxide/Litre (gCO ₂ /L);	(Individual or Fleet) Collection vehicle biofuel emission rates for carbon dioxide, nitrous oxide and particulate matter.
	Conventional fuel Emission rate	FE2	Grams Nitrous oxide/Litre (gNO _x /L)	(Individual or Fleet) Collection vehicle conventional fuel emission rates for carbon dioxide, nitrous oxide and particulate matter.
	Unit externality emission costs) (£/gCO ₂ & £/gNO _x)	EC1	Grams particulate matter/Litre (gPM/L)	(Individual or Fleet) Collection vehicle total emission for carbon dioxide, nitrous oxide and particulate matter.
Cost (FW component)	Labour hourly rate	LC1	£	Average market value labour rate of FW collection vehicle driver and co-driver (or assistant)
	Bulking station maintenance + Auxiliary cost	OC2	£	Operational cost for bulking station for FW drop-off (if applicable)
	Fleet Maintenance + Auxiliary cost	OC3	£	Operational cost for fleet maintenance and additional associated operational costs
	Bulking station capital cost	CC1	£	Capital cost for bulking station for FW drop-off (if applicable)
	Fleet capital cost	CC2	£	Capital cost for FW collection vehicle fleet
	Bin capital cost	CC3	£	Capital cost for FW bins
Cost (Other)	AD cost vs revenue	AD-TRC	£	Calculation of total AD Capital and operational costs + Revenue (£) (see Figure 93 and Figure 94)
	Refuel Station cost vs revenue	RD-TRC	£	Calculation of total RS Capital and operational costs + Revenue (£) (see Figure 93 and Figure 94)
FW revenue	Total FW collection revenue (£)	FW-TR	£	Total revenue from total FW sales (if applicable) and avoided landfill tax of FW to landfill disposal

Table 46. FW collection OPD Equations outlining key material-energy and revenue metrics for FW collection process in context of collection time, distance, logistics and fleet route optimization

Component	Metric	Metric (M)	Equation	Abbreviations
Time	TT2	Total collection time (hr)	Collection time per household bin (hr) × Number of Households (no units) = Total time required for collection (hr)	CT × HH = T2
	TT3	Total round-trip time (hr)	Total end-to-end travel time (hr) + Total collection time (hr) = Total round-trip time (hr)	TT1 + TT2 = TT3
	F3	Conventional Fuel required (L)	Collection distance (miles) / Conventional Fuel efficiency (miles/L) = Conventional Fuel required (L)	CD / F1 = F3
	F4	Biomethane Fuel required (L)	Collection distance (miles) / Biomethane efficiency (miles/L) = Biofuel required (L)	D1 / F2 = F4
	FE3	Total conventional fuel emissions (gCO ₂ /L, gNO _x /L & gPM/L)	Conventional fuel required (L) × Conventional fuel Emission rate (gCO ₂ /L, gNO _x /L & gPM/L) = Total conventional fuel emissions (gCO ₂ /L, gNO _x /L & gPM/L)	F3 × FE1 = FE3
	FE4	Total biofuel emissions (gCO ₂ /L, gNO _x /L & gPM/L)	Biofuel Fuel required (L) × Biofuel Emission rate (gCO ₂ /L, gNO _x /L & gPM/L) = Total biofuel emissions (gCO ₂ /L, gNO _x /L & gPM/L)	F4 × FE2 = FE4
	FE5	Total fuel emission savings (£)	Total conventional fuel emissions (gCO ₂ /L, gNO _x /L & gPM/L) - Total biofuel emissions (gCO ₂ /L, gNO _x /L & gPM/L) = Total conventional fuel to biofuel switch unit emission savings (gCO ₂ /L, gNO _x /L & gPM/L)	FE3 - FE4 = FE5
	TEC1	Total Externality emission costs (£)	Unit externality emission costs (£/gCO ₂ , £/gPM & £/gNO _x) × Difference in Emissions (gCO ₂ & gNO _x & gPM) = Total Externality emission costs (£)	EC 1 × FE5 = TEC1
	FC3	Total conventional fuel cost (£)	Conventional Fuel required (L) × Unit Conventional Fuel Cost (£/L) = Total conventional fuel cost (£)	F3 × FC1 = FC3
	FC4	Total biofuel cost (£)	Biofuel required (L) × Unit Biofuel Cost (£/L) = Total biofuel cost (£)	F4 × FC2 = FC4
	FC5	Total fuel cost savings (£)	Total biofuel cost (£) - Total conventional fuel cost (£) = Total fuel cost savings (£)	FC4 - FC3 = FC5
	OC1	Total labour cost (£)	Labour hourly rate (£/pp/hr) × (TT3) Total round-trip time (hr) = Total labour cost (£)	LC1 × TT3 = OC1
	TC1	Total operational cost (£)	Fuel cost savings (£) + Total labour costs (£) + Total externality emission cost (£) + Bulking station maintenance + auxiliary cost (£) + Fleet maintenance + auxiliary cost (£) = Total operational cost (£)	FC5 + OC1 + TEC1 + OC2 + OC3 = TC1
	TC2	Total capital cost (£)	Bulking station capital cost (£) + Fleet capital cost (£) + Bin capital cost (£) = Total capital cost (£)	CC1 + CC2 + CC3 = TC2
	TC3	Grand Total cost of FW collection (£)	Total operational cost (£) + Total capital cost (£) = Total cost of FW collection (£)	TC1 + TC2 = TC3
	T-ROI	Total FWtBTC pathway return on investment (no units)	[Total FW collection revenue (£) / Total Cost of FW collection (£)] + Total AD Capital and operational costs vs. Revenue (no unit) + Total RS Capital and operational costs vs. Revenue (no units) = Total FWtBTC pathway return on investment (no units)	[FW-TR / TC3] + AD-TRC + RS-TRC = T-ROI

Note: Blue fonts equates to units whose data value are derived directly from either experiment or existing literature data

The next section illustrates integration of the above financial calculation method with AD (anaerobic digestion) and RS (refuel station) related costs and revenues to enable a full, integrated assessment of financial trade-off benefits associated with deployment of the entire FWtBTC pathway at scale.

Considerations were also made to adopt a similar approach for anaerobic digestion (AD) operations and refuelling station (RS) operations, but this was ultimately rejected given lack of access to suitable and relevant data.

4.3.7 Financial Process diagram schematics and metrics overview

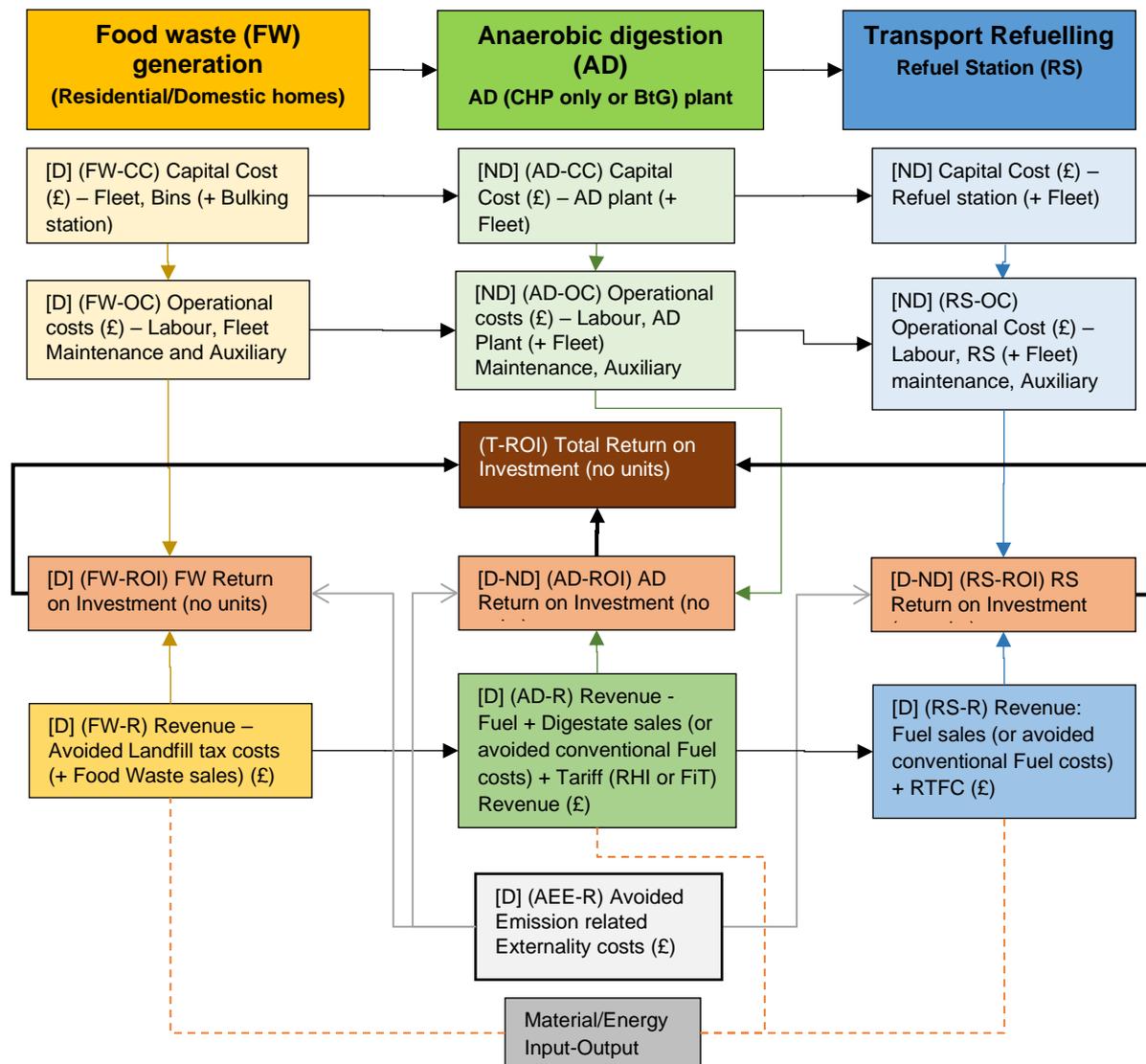


Figure 91. Financial Process diagram (FPD) of cost vs revenues associated with FWtTBC (Food Waste to Transport Biofuel) pathway deployment. [D] stands for detailed calculations of cost and revenues, and [ND] stands for non-detailed estimations of cost and revenues, as shown in aforementioned operational process diagrams. Colour coding: FW components in yellow, AD components in green, RS components in Blue, financial metrics in orange.

Table 47. Summary of (basic) financial revenue, costs and (advanced) return on investment metrics

Component	Equation name	Equation	Abbreviations
FW	FW-ROI	FW revenue (£) / (FW capital cost + FW operational cost) (£) = FW-ROI (no units)	FW-R / (FW-CC + FW-OC) = FW-ROI
AD	AD-ROI	AD revenue (£) / (AD capital cost + AD operational cost) (£) = AD-ROI (no units)	AD-R / (AD-CC + AD-OC) = AD-ROI
RS	RS-ROI	RS revenue (£) / (RS capital cost + RS operational cost) (£) = RS-ROI (no units)	RS-R / (RS-CC + RS-OC) = RS-ROI

*ROI stands for return on investment

The above process diagram schematics and calculations at different levels of technical complexities demonstrates the overall architecture of analysing FWtTBC pathway components from an integrated operational perspective, as summarized in Table 48 below.

Table 48. Table of summary for all operational process diagrams for FWtTBC pathway deployment

	Process diagram name	Abbreviations	Description
1	Basic operational process diagram	bOPD	Process diagram outlining basic material-energy flow calculations
2	Advanced Operational Process Diagram	aOPD-1 aOPD-2	Operational process diagram outlining flow and technical calculations of material-energy, revenues and emissions using conversion factor (CF) coefficients
3	Food waste collection operational process diagram	FWC-OPD	Operational process diagram demonstrating detailed operational costs and revenues associated with food waste collection at local scale, integrated with other general financials associated with AD and RS component
4	Financial process diagram	F-PD	Financial process diagram outlining cost and revenue flows of all FWtTBC pathway components

Here it is worth noting the strong degree of cross-applicability of this method for elucidating and assessing cost-benefit trade-off arising from other similar waste to energy conversion pathways.

4.3.8 Methodology summary, limitations and recommendations

The collective Operational Process Diagrams schematics and corresponding calculation methods above have been designed following sufficient preparatory work on outlining key FWtTBC pathway components. All findings are also used to inform design of downstream methodologies of data collection and excel modelling process that are outlined respectively below (see chapter 4.4 and 4.5).

The process diagram and calculations above present a limited overview of operational process steps deemed to be sufficient for calculation all FWtTBC pathway components. They are however limited by excluding more detailed operational processes specific to each pathway component, such as physical operational conditions and technology deployed in AD pathway component that may result in varying biomethane output. This is instead covered by the data collection design process which matches use of specific technological components to the extent where data is available to their influence on key technical outputs, i.e. in biomethane output from specified quantities of food waste in context of specific operational conditions.

The adopted level of process operation complexity outlined above is also deemed to be optimal when applied in synergy with other research methods outlined in the remaining sections of research methodology, for producing outcomes that would sufficiently inform important real-world policy and investment decision making recommendations without overextending in its complexity (and consequently, time and effort required).

Future research could focus on expanding the process operation complexity (see Table 49) for specific components of the FWtTBC pathway where time and data is available as means to adapt the above process diagram methodology to derive improved findings.

Table 49. Operational expansion for operational process diagram of each main FWtTBC pathway components

Pathway component	Expansion type	OPD diagram abbrevi-ation	Description
Food Waste	Logistical operational collection components	FW-OPD	Operational process to include individual food waste collection components focusing on: <ol style="list-style-type: none"> 1. Food waste collection quantity taking account of collection time and frequency, operational and capital cost breakdowns (fleet, bin, labour, fuel) 2. Fleet route optimization based on distance travelled alongside overall emission reduction and cost savings
Anaerobic Digestion	Technical operational process components	AD-OPD	Operational process to demonstrate effect of AD plant type, operational conditions, food waste composition and other technical elements on output yield and quantity of (given specific food waste input quantity): <ol style="list-style-type: none"> 1. Material - Digestate 2. Energy - Biogas, biomethane, bioelectricity
Refuel Station	Technical operational process components	RS-OPD	Operational process broken down into more elementary technical operations, include: <ol style="list-style-type: none"> 1. Refuelling machinery component design for calculating appropriate estimated loss through biofuel insertion, storage and refuelling. 2. Latter which will be different for BioLBM/BioCBM and Bioelectricity fuel.

4.4 Methodology 3 - Data collection methodology

4.4.1 Data collection methodological approach design

This section outlines the design and implementation of a detailed methodological approach for establishing the most appropriate methodology for collecting relevant (scenario based and technical) data metrics outlined in Methodologies 1 and 2. To this end, representative sample findings are also established in context of their corresponding contribution towards Excel modelling input.



Figure 92. Data collection methodology sub-section highlights

The overall data collection methodological approach (and that for other sections of this research) is designed entirely from the ground-up owing to the lack of existing similar methodology in existing scientific literature available for use.

4.4.2 Data collection methodological design exploration (DCMDE)

The DCMDE design process adopts a systematic approach that outlines key design steps (see Figure 93) used to establish suitable data collection methodologies for collecting scientifically robust, accurate and representative FWtTBC pathway data metrics (see methodologies 1 and 2) destined for Excel modelling input (see methodology 4) (see Figure 93).

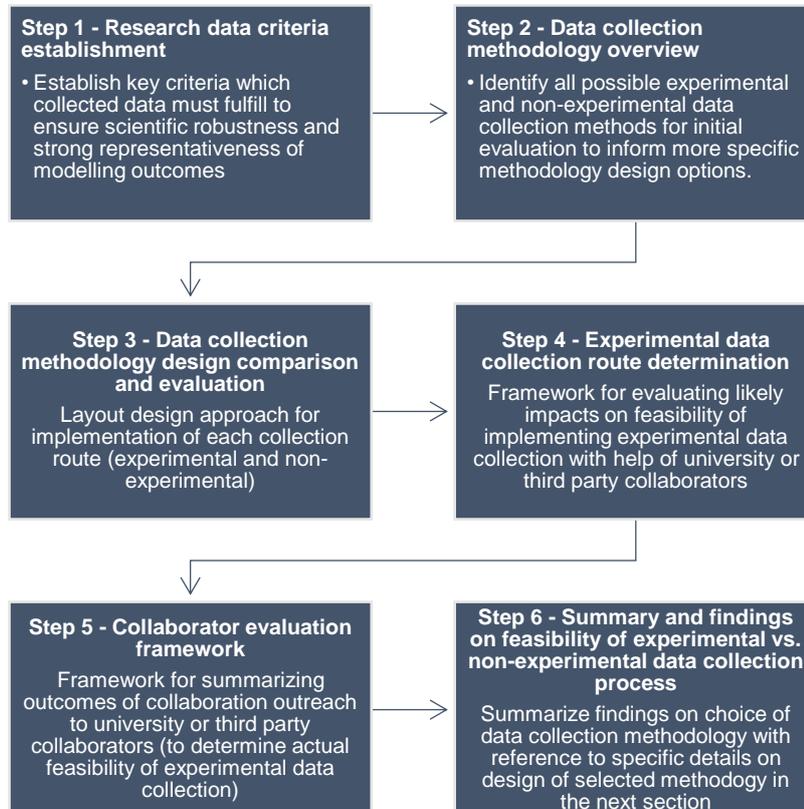


Figure 93. Data collection design process used for establishing suitable collection methodology

This approach in summary sets out key data evaluation criteria, impact and feasibility analysis for all (experimental and non-experimental) data collection approaches to establish a final verdict on the most suitable and feasible data collection methods.

4.4.2.1 DCMDE step 1: Establishing data evaluation criteria (DEC)

The data evaluation criteria is established to assess the relative suitability of each data collection methodology based on general (i) quality & integrity, (ii) representativeness & reliability, and (iii) access and availability, of data which they are able to establish (see Figure 94).

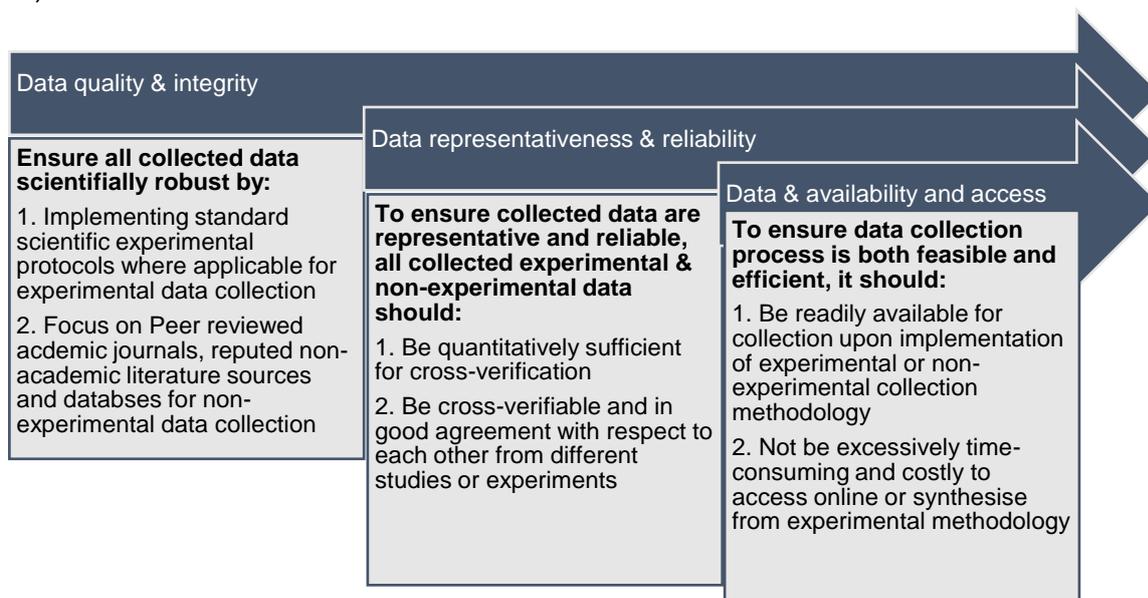


Figure 94. Criteria which the collected research data must fulfil to ensure scientific robustness of excel modelling findings (the method which is outlined in the next section). Details on data metrics can be found in Methodology 1 and 2 section.

These criteria are selectively applied to the remaining sections of methodological design where applicable to inform suitable data collection methodologies, collaborators and strategies.

4.4.2.2 DCMDE step 2: Route exploration and evaluation of experimental vs. non-experimental methodologies

The Data Evaluation Criteria (DEC) is subsequently applied to establish suitable data collection methodologies for all FWtTBC pathway components (outlined in Methodology 2) with specific considerations given to limited availability of experimental facilities and expertise at SCAPE (School of Chemical and Process Engineering) of the University of Leeds under which this research was conducted (see Figure 95).

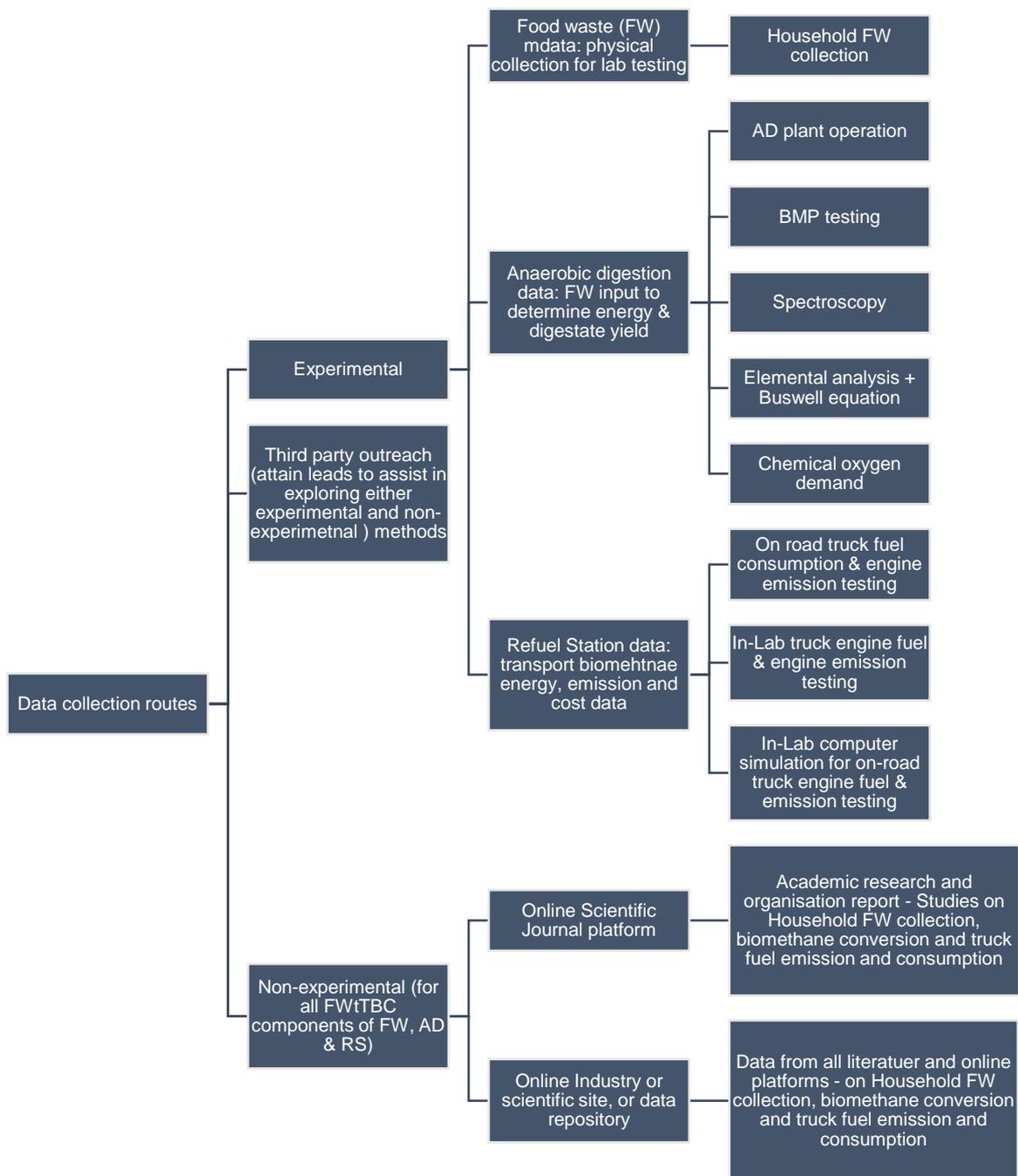


Figure 95. Summary of all research data collection methodologies with proven ability to generate scientifically robust, reliable and representative data (as specified by data evaluation criteria) across all FWtBC pathway metric components (as outlined in pathway operational process diagrams in the previous chapter. Illustrates both experimental and non-experimental methodologies for cross evaluation and comparison.

Here implementation routes and strategies surrounding experimental AD data collection methodologies will be further evaluated in greater depth in the next section. This is due to the finding that they constitute the most technologically complex and significant component with the greatest potential material impact on modelling outcomes based on the collection approach deployed.

4.4.2.3 DCMDE step 3: Anaerobic digestion methodology evaluation

Evaluations on Anaerobic Digestion will be made against 3 specific criteria on (1) data quality, time requirement and feasibility of implementation using university owned facilities, (2) relative advantages and caveats of implementation, and (3) experimental protocol, validity, limitations and overview for comparative analysis of their overall suitability for selection as the primary data collection method (see Table 50, Table 51 and Table 52 respectively).

Table 50. AD experimental data evaluating criteria 1 - on data quality, time requirement and feasibility of methodology implementation in context of available university SCAPE lab facility

Experimental method	Data quality	Required Time investment	Facility available at SCAPE?	Barrier for conducting experiment and data acquisition
Non-experimental	Varied (High-Very high)	Low	N/A	Limitations to online data availability and access (Possibly but unlikely)
Full AD Operational	Very high	Low-Medium	No, require external AD contact	Very high (third-party contact required, facility access, extremely time consuming)
BMP testing	High	High	Yes, but very limited access	High (Very limited facility and equipment access, time consuming)
Spectroscopy	Low-Medium	High	Yes	Medium (Facility and equipment somewhat available)
Elemental analysis + Buswell equation	Medium	High	Yes, with limited access	Low (Facility and equipment available, non-time consuming)
Chemical Oxygen Demand	Low-Medium	High	Yes	Medium (Facility and equipment somewhat available)

Table 51. AD experimental data evaluation criteria 2 on comparison of relative advantages and caveats

Experimental method	Experimental advantage	Experimental caveats
Non-experimental		
Full AD Operational	Operational data collection, with high accuracy with strong real-world relevance	Difficult without establishing strong connection with AD plant operators for conducting experiment at AD plant
BMP testing	Universally used method for sampling biomethane quantity from food waste	Facility access within SCAPE for sufficient sampling of FW to biomethane conversion
Spectroscopy	Easier experimental setup and implementation than most chemical experiments	Returned results likely less accurate than other methodologies when applied to food waste for biomethane yield estimation
Elemental analysis + Buswell equation	Easier experimental setup than other chemical methods for determining maximum biomethane output	Returned results likely not representative of real world conditions as buswell equation calculates theoretical maximal biomethane production from food and other organic wastes (Aragon-Briceno et al., 2017)
Chemical Oxygen Demand	Alternative approach when other experimental method is not applicable	Returned results likely less accurate than other methodologies, with limited facility access

Table 52. AD experimental data evaluation criteria 3 – on additional experimental details

Data quality	Data type	Experimental details
Varied (Low to Highest)	Non-experimental	<ul style="list-style-type: none"> • Protocol: Boolean online keyword search protocol • Scientific validity: Varied, dependent on literature from which data is collected, in general very strong if done correctly from literature that are peer reviewed or from official bodies • Limitations: Data collected is non-original therefore is highly likely to be less representative than experimental data • Overview: Best overall method to supplement any experimental research data or can be used standalone if experimental data is not available
Highest	AD operational data	<ul style="list-style-type: none"> • Protocol: Lab AD or full AD scale testing, using operational AD parameters • Scientific validity: Very strong due to real-world relevance of outcomes • Limitations: Extremely time consuming (1-3 months minimum testing period, typically up to 6 months), no facility access at SCAPE, extremely high barrier (establish contact and/or very high \$ cost) to third-party AD facility access • Overview: Best for data quality, unlikely implementation route due to barrier
High	BMP testing	<ul style="list-style-type: none"> • Protocol: Lab scale testing using manual or automatic system • Scientific validity: Strong due to reliable estimation of biomethane potential given converging average results from enough sampling rounds are made • Limitations: Time consuming (1 week per test sample), very limited SCAPE facility access, high barrier if outsourced (up to £4000 per sample) • Comparison: Easier to set up than AD testing, but more difficult than the rest
Medium	Elemental composition	<ul style="list-style-type: none"> • Protocol: 2-Stage process, 1) compositional testing (proximate/ultimate) in-lab, 2) Buswell equation analysis (theoretical component) thereafter • Scientific validity: high as it constitutes a proven method • Limitations: Limited accuracy & reliability of results as method estimates maximum biomethane yield & is highly dependent on sample composition • Comparison: Ideal for feasible and fast testing at expense of potentially inaccurate and unreliable results due to i) good SCAPE facility access, & ii) fast operational time (as multiple samples can be run in span of a week)
Low	Chemical Oxygen Demand (COD)	<ul style="list-style-type: none"> • Protocol: Use of in-Lab using Fourier Transform Infrared (FTIR) and (Infrared) IR methods for indirect measuring biomethane yield • Scientific validity: Reasonable but limited, as the method is indirect and is based on assumption of 1 mole of methane requires 2 moles of oxygen to oxidise carbon to carbon dioxide and water • Limitations: Limited accuracy of results (See scientific validity) vs. most other alternative methods • Comparison: Only preferable should elemental composition analysis is not available given limited scientific validity and accuracy of results
Lowest	Infrared (IR) analysis	<ul style="list-style-type: none"> • Protocol: Use of in-lab Fourier Transform IR (FTIR) or Near-IR (NIR) analysis to examines key food waste biomethane yield • Scientific validity: Very limited given method less effective on heterogeneous wastes, but give some indication of biomethane yield output • Limitations: See above (on validity) • Comparison: Faster and cheaper than above methods at significant expense of presumed accuracy of results, may be a last experimental alternative, though overall might not be worth the effort

4.4.2.4 Findings from evaluation of Anaerobic digestion experimental methodology

Here initial findings point to 2 significant barriers of SCAPE lab facility access and excessive effort requirements surrounding implementation of desired experimental data collection methods (AD or BMP testing). The adoption of non-experimental data by contrast appears to be comparatively more suitable as they do not face such barriers and will likely enable efficient collection of suitable data, though with potential caveats in relative representativeness and originality of the collected data.

Consequently, 3 follow-up procedures were implemented to additionally explore all other routes, whether such experimental procedures can be established in collaboration or partnership with commercial entities outside of University of Leeds SCAPE department in efforts to surmount these initially discovered research challenges on experimental data collection (see Table 53).

Table 53. Summary of follow up procedures used for accessing experimental data collection methods

	Name	Abbreviation	Description
1	Experimental Route Determination Framework	ERDF	Assess feasibility of experimental data collection from identified key stakeholders and collaborators, in context of difficulty of experimental procedure implementation and return on time investment
2	Stakeholder and Collaborator Evaluation Framework	SCEF	Evaluate additional Stakeholders and Collaborators that could help surmount (i) barriers of access and (ii) excessive time required for experimental data collection
3	Quality Control Protocol	QCP	Set criteria to access overall quality of experimental data collected in context of collaborator and scale of experimental implementation

4.4.2.5 DCMDE step 4: Experimental Data Collection Route Determination

The experimental route determination procedure assesses the overall impact of University or third party collaboration on (i) the implementation barriers of various experimental data collection methodologies, and (ii) the quality of collected data for various scales of FWtTBC pathway deployment. Each scale of pathway deployment is also evaluated for their relative difficulty of experimental methodology implementation and return on time investment.

These assessments are established under assumptions of either the university department or third party collaborators possessing sufficient resources to facilitate experimental data collection implementation at scale that otherwise not achievable through the researcher's own efforts. The choice of collaborators is established by preparatory work that involved numerous consultations with members of University of Leeds SCAPE department and local city council and is outlined in Table 54 and Table 55 below.

Table 54. Collaborator impact analysis on implementation barrier and return on time investment for each experimental data collection method

Implementation strategy analysis (see entire table)	Collaborators (right)		Local authority	Commercial organisation collaboration	University & other educational institution collaboration	Little or No collaboration
			Implementation barrier: Low	Implementation barrier: Medium-High	Implementation barrier: Extremely High	
Implementation scale (below)	Expected outcomes (below)		Difficulty of implementation (DoI) Return on time investment (ROTI)			
Industry standard (existing very large scale operations)	Expected Data quantity: Very Large	Expected Data representatitiveness: Very strong	Expected Data integrity: Very Strong	DoI: Low-Medium ROTI: Extremely high	DoI: Extremely High ROTI: Extremely Low	DoI: Impossibly High ROTI: Impossibly Low
Large scale case study	Expected Data quantity: Large-Very Large	Expected Data representativeness: Strong	Expected Data integrity: Very Strong	DoI: Low ROTI: Extremely high-Very high	DoI: High-Very high ROTI: Very Low	DoI: Extremely High ROTI: Extremely Low
Small scale case study	Expected Data quantity: Medium-Large	Expected Data representativeness: Medium-Strong	Expected Data integrity: Medium-Strong	DoI: Low ROTI: High-Very High	DoI: Medium-High ROTI: Low	DoI: High-Very high ROTI: Low-Very Low
Micro scale case study	Expected Data quantity: Small	Expected Data representativeness: Medium	Expected Data integrity: Medium-Strong	DoI: Very Low ROTI: Medium-High	DoI: Low-Medium ROTI: Low-Medium	DoI: Medium-High ROTI: Low-Medium

The assessment outcome indicates external third party collaboration to be most suitable for enabling effective experimental data collection process for all scales of FWtTBC pathway deployment on basis of significantly removing barriers to, and consequently improving return on time investment for data collection. Collaborations with Leeds University and other educational institutes or no collaboration by contrast are found to face significant barriers toward implementation of experimental data collection and does not present adequate solutions.

This evaluation is based on accompanying findings on the ability of each collaborator to deploy real world operations pertaining to critical corresponding components of the FWtTBC pathway, from which experimental data collection can be designed and implemented to accompany these operations (Table 55).

Table 55. Type of collaborators and their available functional capacity

Macro organisation category	Type of organisation	Example of local collaborator in Leeds	Description on details of collaboration in context of barrier and opportunity access (assessed based on facility access for typical type of organisational – specified in 2 nd column)		
			FW	AD	RS
Local authority	Local Authority (LA)	Leeds City Council	(M) Existing FW collection services (in-house or contracted)	(P) In-house AD plant	(P) In-house refuel station
	AD plant company	Maltings Organics AD plant	(P) In-house FW collection service	(M) Commercial AD plant	(P) In-house commercial refuel station
Relevant local organisation collaboration	Refuel station operator	Leeds city council CNG station	No facility available	No facility available	Commercial Refuel station
	Waste contractor	Biffa	(M) Existing FW collection services (Specialized Business service)	(P) In-house AD plant	(P) In-house refuel station
	Integrated Waste management company	Veolia	(M) (V) Existing FW collection services (Specialized Business service)	(M) (V) In-house AD plant (Specialized Business service)	(M) (V) In-house refuel station (Specialized Business service)
	University	University of Leeds	Existing FW generation with third party collection services	No facility available	No facility available
University & other educational institution collaboration	Non-university College	Leeds Art College	Existing FW generation with third party collection services	No facility available	No facility available
	Secondary school	Seacroft Grange	Existing FW generation with third party collection services	No facility available	No facility available
	Little or No collaboration	N/A	None available	None available	None available
Abbreviations	Abbreviation description for each relevant FWtBC pathway component above				
(M)	Main operational facility which the organisation or company typically operates				
(P)	Additional potential operational facility which the organisation or specific company may operate (depending on the type of organisation and company involved) in addition to the main				
(V)	Veolia has waste incineration plant instead of AD plant for treating a diverse categories of wastes but do present an integrated waste management business model where they are in the business of waste conversion for energy generation, and are hence included in the example				

4.4.2.6 DCMDE step 5: Collaborator Evaluation framework

Throughout the course of the research, each potential collaborator was further independently contacted by the researcher with regard to potential collaboration in context of each FWtBC pathway component, with outcomes outlined in two separate formats in Table 56 below.

Table 56. Exploration of all experimental methods of collecting technical food waste (FW), FW to biomethane conversion, and biomethane truck emission and fuel consumption data (as outlined by the basic and operational FWtTBC pathway process diagram).

Component	Method	Explorative steps	Outcome following inquiry and contact
1	Food waste collection	Household food waste collection	<p>Researched possibility of household (or alternative) waste collection at Leeds – with main supervisor and local city council</p> <p>Collaboration not possible with Leeds City Council or food waste collection companies for experimental data collection.</p> <p>Only food waste collection at local primary school is feasible (contact via university), following implementation, it was discovered to be too difficult and time consuming for intended purpose of this research.</p>
2	FW to biomethane conversion	AD plant operation	<p>Contacted Maltings Organics and other local AD plants regarding studies and data on food waste to biomethane conversion</p> <p>Response indicated no chance of collaboration with Maltings organic for collecting representative technical operational data. Other AD plants did not yield any significant response to the quest.</p> <p>Contacted Leeds city council for potential data or outreach assistance</p> <p>Leeds city council provided information surrounding previous unsuccessful plans for establishing a Leeds based AD plant but could not provide further assistance</p>
3		BMP testing	<p>Inquired about using BMP facility at SCAPE, University of Leeds or commercial BMP facilities at cost outside university</p> <p>Unable to conduct BMP testing at University of Leeds or from commercial BMP testing companies due to it being fully booked and too expensive (with request to university for implementing either method rejected), respectively.</p>
4		Spectroscopy	<p>Researched spectroscopy facility at Leeds for use</p> <p>Very limited spectroscopy facility access at SCAPE, University of Leeds for use, and issues surrounding collecting representative food wastes further prevents these experimental approaches to be explored.</p>
5		Elemental analysis + Buswell equation	<p>Researched on use of facility for elemental analysis to calculate FW biomethane yield</p>
6		Chemical oxygen demand	<p>Researched on use of facility for conducting COD to calculate FW biomethane yield</p>
7		Biomethane consumption and emission in Truck	On road truck fuel consumption & engine emission testing
8	In-Lab truck engine fuel & engine emission testing		
9	In-Lab computer simulation for on-road truck engine fuel & emission testing		
10	Leeds city council operated biomethane refuel station		<p>Contacted Leeds city council about collection biomethane refuel station operational data</p> <p>No collaborations are possible for experimental data collection but outlined ambition to build a secondary biofuel refuel station in the foreseeable future</p>

These prevailing verdicts arising from the design and implementation of explorative data collection methodological approach outlined above points to the impossibility of experimental data collection arising from lack of facility access and suitable collaboration, despite extensive efforts from the researcher in reaching out to potential collaborators.

They however did elucidate valuable technical and operational information surrounding current trends in FWtTBC pathway deployment from overview and selective assessment of all experimental data collection methodologies (Table 57), and selective outputs of collaborator engagement. This design of non-experimental data collection methodology will consequently consider and integrate these elements to add further value and insight where applicable, as outlined in table below.

Table 57. Exploration of non-experimental methods

	Component	Method	Explorative steps	Verdict
1	All – FW, AD, RS	Online Scientific Journal platform	Search all major journal platforms including ScienceDirect, Google Scholar and Scopus	Indication of sufficient journal articles on food waste to biogas and biomethane conversion, biomethane truck consumption and emission, in addition to relevant policy and financial data
		Online Industry or scientific site, or data repository	Search relevant data platforms such as the waste data flow	

4.4.2.7 DCMDE step 6: Summary and findings on feasibility of experimental vs. non-experimental data collection process

This is further supported by indication of sufficient availability of representative, accurate and reliable data that connects to each critical component of the FWtTBC pathway from initial literature search across major research literature and data platforms. A regimented data collection process for non-experimental data is subsequently developed to ensure collected data is of at minimum, sufficient quality, integrity, representativeness and reliably for input into the subsequent Excel modelling process (see next section on Excel Modelling).

4.4.3 Non-experimental data collection methodology implementation

For non-experimental data collection, a Boolean search protocol is established. The protocol applies a number of keyword search terms under Boolean search conditions on relevant online literature and data platforms for obtaining academic and industry literature, reports and data (see Table 58 below).

Table 58. Search method and term for non-experimental routes with search platform and data metrics for compilation

Boolean search terms	FWtCTB Pathway component	Key words	Initial Search platforms	Data metrics for compilation*
Boolean search terms: <u>AND</u> , <u>OR</u> and <u>NOT</u> used with keywords and on specific platforms	Food Waste (FW)	[UK] <u>AND</u> [Household <u>OR</u> Domestic] <u>AND</u> [Food <u>OR</u> Lunch <u>OR</u> Meal] <u>AND</u> [Waste] <u>AND</u> [Output <u>AND/OR</u> Collection] <u>AND</u> [Studies <u>OR</u> Data <u>OR</u> Database]	Search Engine: Google	Domestic FW generation & collection (+ relevant cost & revenues)
	Anaerobic Digestion (AD)	[UK] <u>AND</u> [Food Waste] <u>AND</u> [Conversion] <u>AND</u> [Biomethane <u>OR</u> Biogas <u>OR</u> Bioenergy <u>OR</u> Energy <u>OR</u> Electricity <u>OR</u> Transport fuel] <u>AND</u> [Anaerobic] <u>AND</u> [Digestion <u>OR</u> Plant <u>OR</u> Digester] [Output <u>AND/OR</u> Studies <u>OR</u> Data <u>OR</u> Database]	Scientific platforms: ScienceDirect, Google scholar, Website of science (Scopus)	FW to Biofuel (i.e. Biomethane, Biogas, Electricity) & Digestate (tonnes) conversion yield (+ relevant cost & revenues)
	Refuel Station (RS)	[Transport <u>OR</u> Fleet <u>OR</u> HGV <u>OR</u> Truck] <u>AND</u> [Fuel <u>OR</u> Biofuel <u>OR</u> Biomethane] <u>AND</u> [Emission <u>OR</u> Cost <u>OR</u> Energy] <u>AND</u> [Trial <u>OR</u> Studies <u>OR</u> Savings <u>OR</u> Experiment <u>OR</u> Studies <u>OR</u> Data <u>OR</u> Database]	Industry specific platforms: WRAP, ADBA, NFCCC	Emission, Cost or Fuel saving or displacement for fleet or individual HGVs (+ relevant cost & revenues)

*Note expected metric results are for material-energy, emissions and corresponding financials (costs & revenues)

All primary research literature from each platform relevant to each FWtTBC pathway component are subsequently compiled, collated and systematically reviewed for their content, with relevant data being captured for Excel modelling input (see the next section Excel model). In compliance with established data evaluation criteria, the finding will aim to include robust, cross-verifiable data from a minimum number of scientific research and non-research literature pertaining to each FWtTBC pathway component, alongside those outlined by the set research scenario conditions.

Here the scientific literature search would include research and review papers on specific experiments conducted for estimating specific mass energy conversions outlined in the operational process diagrams in the previous section, with technical conversion of food waste to biogas or biomethane being a critical component. To this end, data derived from research literature on the use of real world anaerobic digestion plant technology for under either real world or simulated conditions for such estimations is strongly preferred given their overall high representativeness, followed by data derived from use of BMP testing and other less representative technologies (see Table 59).

Table 59. Summary of technical scientific research literature expected to be collated for data collection

FWtTBC pathway component	Data	Preferred tech component
Food waste collection	Collected household food waste characterisation and composition analysis data (from collected food waste)	N/A
Anaerobic digestion	Food waste to Biogas conversion data Food waste to Biomethane conversion data	AD, BMP technology AD, BMP technology
Refuelling station	Biomethane or Electric Vehicle data on fuel efficiency (MPG) and emissions	Biomethane or EV propulsion system

By contrast, non-scientific literature search will include reports on deployment of existing logistical trials pertaining to food waste collection, anaerobic digestion or HDV transport biomethane refuelling trials, to attain relevant operational logistics data. To this end, the search will also include reports or databases containing relevant macro data required for conducting case study scenario analysis, i.e. population and individual or total food waste output data over time or fall within specific geographical regions (Table 60).

Table 60. Summary of non-scientific research literature expected to be collated for data collection

FWtTBC pathway component	Non-research literature focus
Food waste collection	Reports on food waste collection trials
Anaerobic digestion	Reports on anaerobic digestion trials using household food waste
Refuelling station	Reports on biomethane powered truck refuelling and operation trials

In theory, inclusion of the above reports and derived data sets should enable collection of all required data in a manner that is both real-world representative and scientifically robust, for input into the Excel modelling process, the design which will be outlined in the next section.

4.4.4 Methodology Summary, limitation and recommendations

For Excel modelling input, non-experimental data collection method using Boolean keyword search was deemed to be the most suitable method. This is largely due to significant limitations in access to experimental facility or operational trials either with Leeds University SCAPE or third party collaborators as had been thoroughly evaluated and attempted throughout the data collection process, which constitutes an unsurmountable barrier preventing collection of experimental data.

The experimental data collection explorative process however did establish critical insights to help inform the overall data collection process, such as to prioritize on finding literature containing technically robust and representative data based on the methodology used (i.e. AD or BMP for FW to biomethane conversion). Here additional insights attained from Leeds city council on their historical AD plant implementation efforts, forthcoming strategies and plans adopted to establish a new city wide food waste collection scheme and biofuel refuel station further helps to inform scenario based modelling for deploying FWtTBC pathway at Leeds city region.

4.5 Methodology 4 - Excel modelling

4.5.1 Excel modelling Introduction

The Excel modelling methodology design adopts a bottom-up approach that collectively integrates key findings arising from other methodology sections to ensure all relevant factors are considered for designing a modelling approach that could sufficiently addresses all research key aims and objectives. These are respectively outlined in Table 59, and further summarized in the section below (see Figure 96).

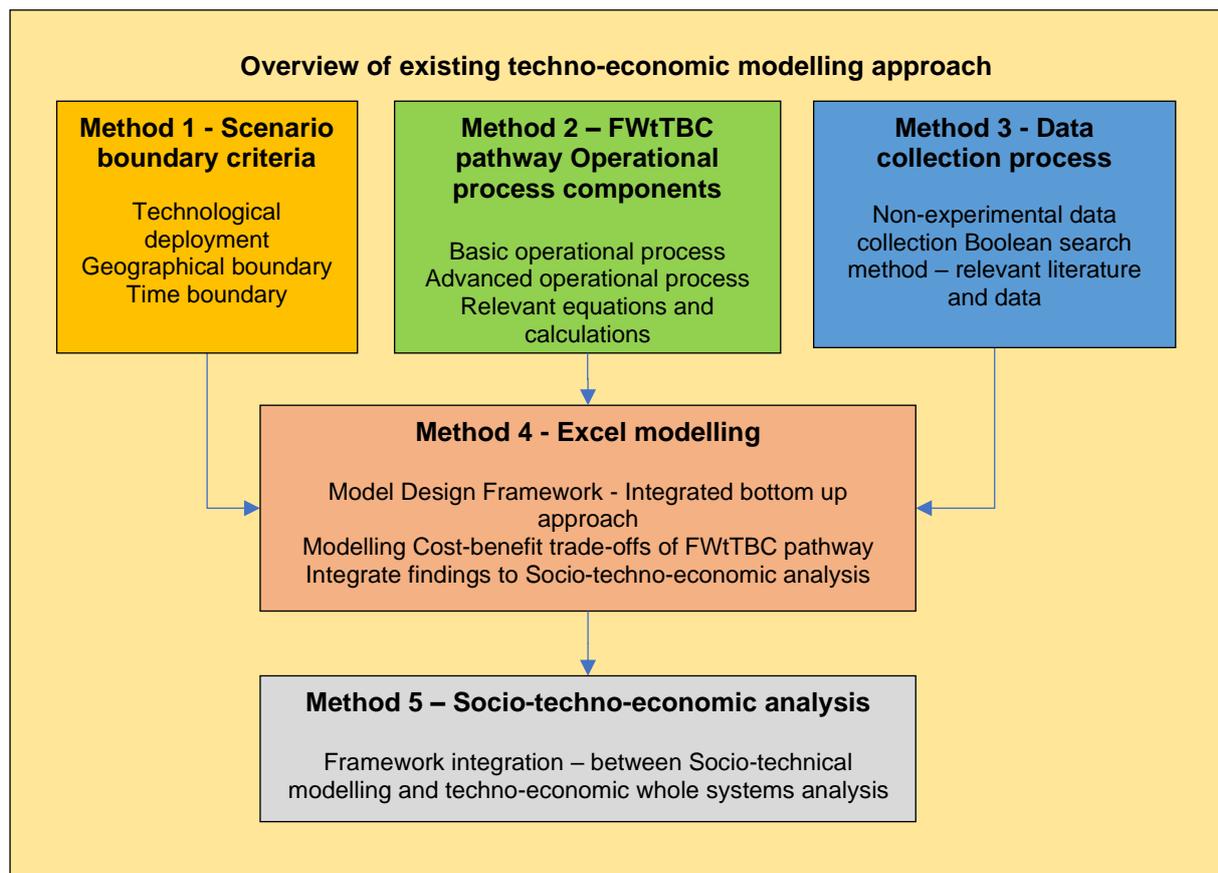


Figure 96. Schematic diagram of Excel modelling design with respective to contributions from other methodologies

The integration process will also be implemented under the consideration of existing relevant techno-economic Excel models available for reference, and to ensure that the modelling approach is both novel and functionally more suitable for addressing key aims and objectives outlined for this research.

4.5.2 Review of existing relevant Excel modelling approach

These technical models are reviewed and assessed for the inclusion specific modelling processes, to inform suitable processes for inclusion for the modelling design of the present study (see Table 61, Table 62 and Table 63).

Table 61. FW collection models processes in the techno-economical model design

		Eunomia (Eunomia, 2020)	WRAP (WRAP, 2012)	DEFRA Food Disposal Model (WRC, 2009)	World Biogas association (World Biogas Association, 2018)	PhD Research Model
Access	Paid commercial access	X				
	Free		X	X	X	X
Modelling Area	Logistics mapping of FW collection	X	X			
	Economic & Financial	X	X			X
Process required	Bin tipping	X				
	Transport logistic	X				
	FW storage depot	X				
Financials	Transport storage depot	X				
	Cash flow	?	X			X
	CAPEX	X	X	X	X	
	OPEX	X	X	X	X ¹	
	Revenues	X ¹	X			X
	IRR	X ¹				
	NPV	X ¹		X		
Does model connect to AD plant costs?	Yes			X		
	No		X			
	Unsure	X				
Model format (As found)	Excel spreadsheet	X ¹	X	X ¹		
	PDF			X	X	
	Unsure				X	

X¹ As assumed to be true based on existing data found.

Font colour coding - Green and yellow highlight indicates model elements to be included and in consideration to be included the operational diagram process, respectively.

Table 62. Summary of commercial financial techno-economic modelling tools associated with Anaerobic Digestion and rest of the Food Waste to Transport Biomethane Conversion (FWtTBC) pathway

		AMEC	Biomethane regions	Biowaters	E&J Solutions	Golder Associates	KTBL	Laurence Gould Partnership	ORA	Ramboll UK	NNFCC	PhD Research Model
Access	Paid commercial access	X		X	X	X		X	X	X	X	
	Free		X ¹				X ²					X
Purpose	Engineering	X	X	X		X		X	X	X		
	Economic	X	X	X	X		X	X	X	X	X	X
Process covered	Waste collection									X		X
	Pre-treatment								X	X	X	
	Anaerobic digestion	X		X	X	X	X	X	X	X	X	X

	Biogas upgrading to biomethane	X	X						X	X	X	X
	Biogas use in CHP	X			X	X	X	X	X	X	X	X
	Biogas other uses	X							X	X	X	
	Post digester treatment	X										
	Emission control	X						X				
	Digestate use						X	X		X	X	X
Financial outputs	CAPEX	X	X				X		X	X	X	X
	OPEX	X	X		X		X	X	X	X	X	X
	Life cycle replacement	X	X				X	X	X	X		
	Revenues	X		X	X		X	X	X	X	X	X
	IRR	X			X			X	X	X	X	
	NPV	X			X				X	X		
	EBITDA				X		X	X	X			
	Other	X	X		X		X	X	X			

X¹ Stated by document to be free, but none can be found via external link (in a different language).

X² Did not state by document to be free or not, assume free, although model cannot seem to be accessed easily via External link (in a different language), adapted from (WRAP, 2013)

Font colour coding - Green and yellow highlight indicates model elements to be included and in consideration to be included the operational diagram process, respectively.

Table 63. Summary of existing research on FWtBC pathway deployment, outlining source, format, extent of info access, pathway components covered and succinct description

Model creator (Model name – if known)	Source Reference	Excel format accessed?	What model info is accessed ¹	Pathway component ²	Pathway description	Access type for full excel model
Eunomia (HERMES model)	(Eunomia, 2020)	No	Model related documents	FW, AD	Food waste collection	Paid commercial
WRAP	(WRAP, 2012)	Yes	Full Excel model	FW	Cash flow model for food waste collection services	Free
DEFRA	(WRc, 2009)	No	Model related documents	FW, AD	Food disposal services modelling	Free ³
NREL (CREST)	(NREL, 2010)	Yes	Full Excel model	AD	AD operational and costing model	Free
CSANR (AD SEBC)	(CSANR, 2018)	Yes	Full Excel model	AD	AD enterprise costing calculator	Free
World Biogas association	(World Biogas Association, 2018)	No	Model related documents	AD	Models for food waste to biomethane conversion via anaerobic digestion route using various techno-economic parameters of AD economics associated with plant operations	Free ³
AMEC	(WRAP, 2013) ⁴	No	Model related documents	AD		Paid commercial
Biowaters		No		AD		
E&J Solutions		No		AD		
Golder Associates		No		AD		
Laurence Gould Partnership		No		AD		
ORA		No		AD		
Ramboll UK		No		AD		
NNFCC		No		AD		
Biomethane regions		No		AD		
KTBL		No		AD	Free ³	
LowCVP by TTR	(LowCVP, 2011)	No	Model related documents	RSVF	Low carbon truck vehicle costings	Free ³

¹Key documents and studies pertaining to the model output is accessed for those with no access to full version of excel model due to circumstances surrounding the research, constituting an insurmountable barrier that can be optimized for future research

²Pertain to FW (food waste), AD (anaerobic digestion) or RSVF (refuelling station and vehicle fleet components)

³Models suggested to be free although the excel version cannot be found directly via homepage

⁴Main central report which shows individual website links to corresponding model creators

The findings collectively outlines several key existing modelling trends, namely restricted focus on singular pathway components (i.e. food waste or anaerobic digestion) of the FWtTBC pathway, varying levels of techno-economic complexity as determined by inclusion of specific operational processes and financial metrics, and lack of sufficient techno-economic complexity for all non-commercial free models, that help to informs the design of a novel modelling approach for the present research (see Table 64).

Table 64. Summary of key components of existing excel models

Component	Existing model strength and limitations	Novelty model attributes
1 FWtTBC pathway component	- Each excel model focuses either on modelling outputs of food waste collection or anaerobic digestion component of the pathway, but not both	Integrate both FW and AD component – for establishing novel model
2 Process operations	- Each model differs in their techno-economic complexity based on the specific combinations of process operations and financial metrics they include	Integrate suitable balance of techno-economic complexity and make the resulting model to be freely available – to add robust economic dimension to findings
3 Techno-economics complexity	- Techno-economic complexity of both FW collection and AD operations models varies greatly depend on inclusion of selective process operations components and financial metrics	
4 Model access	- Commercial models possess greater level of techno-economic complexity, and greater data input requirement	The resulting developed model will be made publicly available for access

The novel Excel model design consequently adopts a suitable integration of FW and AD operational process components as outlined under the PhD research model (Table 65) to ensure commands the right balance of techno-economic complexity to suitably accommodate input of expected data input and findings (see Methodology 2 and Methodology 3).

To elaborate, the adoption of an Excel modelling framework with a low to moderate techno-economical complexity is deemed to be the most balanced approach given that best available data for collection and use is limited to real-world representative non-experimental data (see Methodology 3 for details) for the present study.

Table 65. Techno-economic complexity of modelling framework design

Techno-economic complexity level of Model			Low	Moderate	High
Typical model accessibility			Free public access		Paid (commercial) access (Purchase or subscription)
Data specificity of focus			Low	Moderate	Very high
Data specificity in context of relevant operational processes			Use of general operational and financial data from all generic studies	Use of more specific and representative operational and financial data from representative non-experimental research studies	Use of highly tailored experimental data only from relevant experimental operations
What operational data is used?			General (non-operational) non-experimental data from existing literature	Non-experimental operational data from existing literature	Experimental operational data from relevant trials
FWtCTB Pathway component	Operational Process	Facility	Using data from (with results applicable to)		
FW	Food waste collection	Collection Fleet depot	General (total) UK FW collection non-experimental data	Region or local authority specific UK FW collection non-experimental operational data	Experimental operational data from dedicated UK FW collection trials
AD	Anaerobic digestion plant operation	AD plant	General non-experimental data from anaerobic digestion or BMP experiments	Non-experimental operational data from relevant anaerobic digestion or BMP experiments	Experimental operational data from anaerobic digestion plant operations for specific waste collection trial
RSFV	Biofuel Refuelling	Refuel station	General non-experimental fleet and refuel station data	Non-experimental operational fleet and refuel station data	Experimental operational fleet and refuel station data for specific refuelling trial
Accuracy of findings			Low-Medium	Medium-High	High-Very high

Here it is also worth noting that the choice of operational processes specified from design of existing techno-economic model is also in good agreement with those outlined by separately developed basic and advanced operational process diagram schematics (see methodology 2), which indicate strong robustness of model design from a technical standpoint.

The researcher also intends to ensure the developed modelling approach is both modular and adaptable for the input of more techno-economically complex data as part of future studies should they become available, and to render the resulting model to amongst the first that is of sufficient techno-economic complexity and be publicly available upon request or for access online in future (i.e. via online research websites and platforms such as research gate) by relevant end users and stakeholders which could benefit significantly from derived knowledge and insights.

The next section outlines all modelling framework elements in its entirety to summarize outputs and relevance of other methodologies.

4.5.3 Excel modelling component integration

This section outlines the specific integration of key modelling methodological components that collectively complete the Excel model design. The established Excel modelling framework consequently integrates relevant details and findings from other research methodology sections to ensure all relevant factors are considered for designing a modelling process that could sufficiently address all research key aims and objectives. These are respectively outlined in Table 66, and further summarized in relevant sections below.

Table 66. Summary of excel modelling components relevant section link and description

Relevant section	Relevant methodology section	Framework elements	Description
Methodology 1	Establishing Real-world scenario deployment boundary conditions	Real world scenario assumptions	Outlined 4 real world case-study scenario conditions with specific technology choice, geographical scope and time scale of FWtTBC pathway deployment – to set out conditions for metric calculations
Methodology 2	Define FWtTBC pathway Process & Metrics	Operational Process Diagram metric and calculations	Define basic and advanced process operations associated with FWtTBC pathway deployment and relevant calculations using operational process diagrams and calculation tables – to establish specific calculation
Methodology 3	Data collection	Quantitative Data collection summary	Input of standardized technical quantitative data from existing research literature, reports, database and other best-available data sources for modelling input .
Methodology 4*	Whole systems analysis	Socio-techno-economic modelling	Prepare quantitative excel modelling results for integration of social-techno-economic modelling approach by adding effects of alternative policy and investment support scenarios, for more in-depth whole systems analysis. Outcomes can be used to make additional recommendations on investment and policy decisions. .

*Social-techno-economical analysis framework will be outlined in the next methodology section – see Methodology 4 (Whole systems analysis).

4.5.3.1 Excel modelling component integration from Methodology 1 – Establish real world scenario deployment boundary conditions (See Chapter 4.2 - Methodology 1)

Methodology 1 mainly outlines 3 key deployment factors that satisfy real-world case scenario deployment of the FWtTBC pathway. Namely, these include suitable technology of choice, in addition to geographical scope and timescale of coverage for pathway deployment, as outlined in Table 67 below.

Table 67. Real-world scenario assumption element 1 of 2 – on specified geographical and time boundaries (original details outlined in Chapter 3 - Methodology precursor)

Case study scenario	Region of coverage	Technology deployment	Time duration (applicable to all scenarios)
1	Local (Rothwell)	Anaerobic digestion (AD) technology and AD plant infrastructure	Short term - 2020-2030
2	Leeds city		Medium term - 2020-2040
3	Metropolitan regions of each NPH city	Transport Biomethane refuel station and propulsion system (vs conventional fuel alternatives)	Long term - 2020-2050

*NPH region pertains to Northern Powerhouse City regions of Greater Manchester (Manchester), West Yorkshire (Leeds), Merseyside (Liverpool), South Yorkshire (Sheffield) and Tyne and Wear (Newcastle).

Data surrounding these relevant metrics are then combined with that outlined in methodology 2 (both implemented using data collection methodology specified in Methodology 3), to ensure that the results can measure relative cost-benefit trade-offs of FWtTBC pathway deployment with respect to changes in geographical scope and timescale of pathway deployment (pertain to each 4 scenarios) via the use of AD technology and infrastructure.

Integration of these components can help inform establishment of relevant policy and investment recommendations that materially affect overall cost-benefit trade-off of FWtTBC pathway deployment by indirectly affecting changes to populations, infrastructure capacity, or technology use pertaining to each scenario, which constitute a valuable contribution of this research.

4.5.3.2 Excel modelling component integration from Methodology 2 – Define FWtTBC pathway operational process and metric components (See Chapter 4.3 - Methodology 2)

Methodology 2 outlines integration of calculations specified by both basic and advanced operational process diagrams which act as main input and output metrics of the main Excel modelling (see Table 68).

Table 68. Operational process diagram (OPD) for FWtTBC pathway deployment (see Chapter 4.1 for details)

	Diagram type	Description	Relevance sources (figures and tables)
1	Basic OPD	Material-energy conversions without accounting for real-world physical material losses or technical conversion inefficiencies	OPD Schematic - Figure 87 Calculation equations - Table 34, Table 35
2	Advanced OPD	Material-energy conversions whilst accounting for real-world physical material losses or technical conversion inefficiencies occurring 'at gateway points'	OPD Schematic - Figure 89 Calculation equations - Table 39, , Table 42

These respectively outlines conversions of key FWtTBC pathway input-output metrics with or without accounting for real world operational inefficiencies, i.e. in form of either physical material-energy losses or technical inefficiencies of material-energy conversions, for comparative analysis, as respectively summarized in Table 69 and Table 70.

Table 69. Summary of FWtTBC input-output metrics that are of significant value to justify pathway deployment

	Input or output Metric	Description
1	Food waste	Household food waste, primary input
2	Biogas	Primary energy source from FW conversion, suitable grid injection, combustion for CHP generation or upgrade to biomethane
3	Biomethane	Secondary energy source from FW conversion, attained from biomethane upgrade, can be compressed to form transport biomethane
4	Digestate	Material output of anaerobic digestion of FW
5	Combined Heat and Power (CHP)	Can be separated into heat or power or both simultaneously, resulting from combustion of biogas produced

6	Revenue (and costs)	Calculated from commoditizing all above outputs through either sales or government's financial incentives (and costs associated with additional technologies investments required for relevant scenario)
7	Emissions savings	Calculated from displacement of conventional HDV transport fuel use by use of biomethanes

To this end, the Excel model will adopt 3 levels of operational inefficiencies (low, medium and high) against the baseline perfect scenario of zero operational inefficiency using theoretical or real-world data to the extent in which they are available.

Table 70. Potential causes of real world losses from operational inefficiencies (see Advanced Operational Process Diagram section in Chapter 4.1. for details)

	Metric affected	Material energy loss	Type of Operational inefficiency	Optimization strategies
1	Food waste (FW) loss	1.1 FW loss through kerbside storage 1.2 FW loss through collection and transport to AD plant	Loss – Logistical (Storage) Loss – Logistical (Collection & transport)	Upgrade FW bin storage system Upgrade collection system or binman training
2	Biogas	2.1 Biogas loss through food waste to biogas conversion process in AD plant 2.2 Biogas loss through storage at AD plant site 2.3 Biogas loss through grid injection at AD plant (for gas transport) 2.4 Biogas energy loss through CHP operations	Technical inefficiency Loss – Logistical (Storage) Loss – Logistical (Transport)	Upgrade AD biogas conversion technology Upgrade biogas storage solution Upgrade biogas grid injection tech Upgrade AD biogas boiler tech
3	Biomethane	3.1 Biomethane loss through biogas upgrading process 3.2 Biomethane loss through storage at refuel station 3.3 Biomethane loss through refuelling at refuel station	Technical conversion inefficiency Loss – Logistical (Storage) Loss – Logistical (Refuelling)	Improve biogas upgrade system Upgrade biomethane storage system Upgrade biomethane refuelling system

*Cumulative loss arises from accumulation of multiple operational efficiencies arising from either logistical loss or technical inefficiency

Resulting findings are subsequently used to assess effective deployment, investment and policy strategies for optimizing key operational processes to ensure minimal material-energy losses can be achieved in a cost-effective manner (see Table 70, optimization strategies column), serving as an area of novel modelling and research contribution.

4.5.3.3 Excel modelling component integration from Methodology 3 – Data collection (See Chapter 4.4 - Methodology 3)

Methodology 3 further consolidates findings of process operation diagram (OPD) metrics and calculations as outlined in methodology 2 (see section above and chapter 4.3 for details) by establishing additional data inputs based on findings arising from implementation of the non-experimental data collection method (see Chapter 4.4 for details). Here the inherent assumption would be that all data and inputs outlined in methodology 2 is elucidated via implementation of specified non-experimental data collection method, and theoretical data is

used based on reasonable assumptions given balance of information provided where literature data is not immediately available.

Namely, they include critical technical factors such as food waste composition, AD operational conditions and type, biogas upgrade technology in addition to HDV engine type and conventional fuel type displaced by biomethane use, that affect key FWtTBC pathway deployment outputs, i.e. outputs in biogas, biomethane and emission savings (see Table 71 and Table 72).

Table 71. Technical data integrated for modelling outputs of FWtTBC pathway deployment

FWtTBC pathway component	Non-technical elements relevant to scenario deployment related metrics and calculations	Implication	Example Source
Technology	See AD and HDV biomethane propulsion system and emissions in Table 72.	Affect biogas & biomethane production	Office for National Statistics (ONS)
Geographical and time coverage	<p>Population data – number of individuals involved (and potential change in their total population overtime) in food waste recycling trials for FWtTBC pathway deployment across specified geographical scope under each scenario</p> <p>Waste output data per individual – average waste output per person with specified region and under specified timeframe (typically by city and computed annually, as per output by waste data flow)</p>	Affect total food waste output (and consequently all other downstream data metrics)	Office for National Statistics (ONS) Waste Data Flow (WDF), WRAP

*Note information from multiple official sources are cross-referenced where applicable, with either the most official source or a selective average is used for all data metrics involved

Table 72. Technical engineering data integrated for modelling outputs of FWtTBC pathway deployment

FWtTBC pathway component	Technical elements relevant to operational process diagram metrics and calculations	Parameters	Example Source
Food waste (FW)	Food waste type by source Food waste composition	Affect biogas yield	Various academic paper and on anaerobic digestion of food waste
Anaerobic Digestion plant	AD operational condition – temperature, on-loading rate AD type – thermophilic vs mesophilic digester AD operational scale - bench vs. pilot vs true scale digester	Affect biogas and biomethane yield	
HDV biomethane Propulsion system and Emissions	HDV biomethane engine type Type of conventional fuel displaced and their typical emission parameters	Affect revenue and emission savings	CENEX report

*Note information from multiple official sources are cross-referenced where applicable, with either the most official source or a selective average is used for all data metrics involved

These are respectively used to further optimize calculations of cost-benefit trade-off in material, energy and financials arising from FWtTBC pathway deployment under each of the 4 case study scenarios specified in methodology 1 (see Chapter 4.2 for details). Applicable findings could collectively contribute to establishing suitable recommendations in support of those already outlined in chapter 4.5.3.1 and 4.5.3.2 above (see relevant section for details).

4.5.3.4 Excel modelling component integration from Methodology 5 – Whole system socio-techno-economic analysis (See Chapter 4.6 - Methodology 5)

Methodology 5 outlines a whole systems social-techno-economic framework used in conjunction with quantitative Excel modelling findings to help inform suitable FWtTBC deployment strategies alongside policy and investment recommendations centred on removal of critical barriers to deployment. To this end, the framework utilizes 5 assessment components as outlined below to assess relative barriers and challenges for each specified FWtTBC pathway deployment scenario as outlined in Figure 97 and Table 73 below.

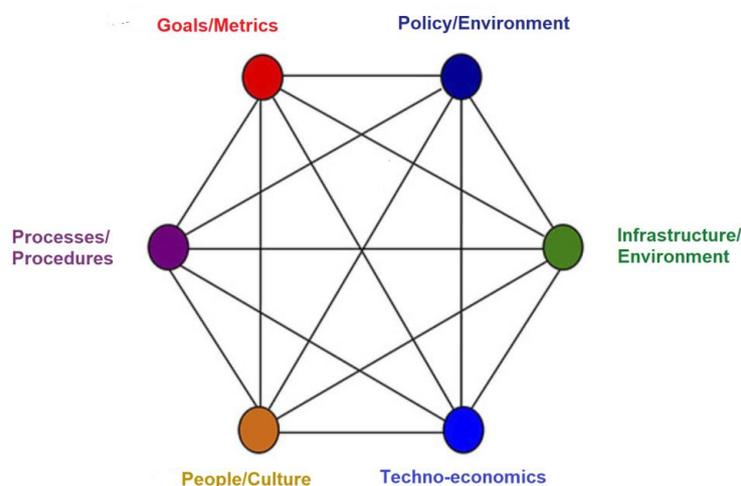


Figure 97. Integrated whole systems (social-techno-economic) analytical framework, containing adapted elements of the social technical framework outlined in Figure 98 (for full details please see Chapter 4.4.4)

Table 73. Brief description of each of the 6 elements of the integrated framework

Component name	Abbreviations	Description and examples
1 Policy/Environment	P/E	National policy that reflects financial support for FW recycling or biomethane use, in context of environmental benefits attainable from FWtTBC pathway deployment
2 People/Culture	P/C	People and local culture's acceptance and contributory action in support of FWtTBC pathway deployment, i.e. partaking in food waste collection trials
3 Process and Procedures	P/P	Operational and technological process and procedures involved in FWtTBC pathway deployment
4 Infrastructure/Investment	I/I	Technological infrastructure from rollout and any beneficial implications arising from implementing process/procedures associated with each pathway
5 Techno-economics	TE	Economics of utilizing technologies associated with deployment of each individual components (or stages) of the FWtTBC pathway
6 Goals/Metrics	G/M	Goals and metrics associated with the above 5 elements, in-line with the SMART framework

Example barriers pertaining to deployment of individual FWtTBC pathway components is outlined in Table 74 below.

Table 74. Whole systems framework assessment used for succinctly outlining example barriers of FWtTBC pathway deployment (full framework assessment is outlined in **Error! Reference source not found.**, see Chapter 4.4 for full methodology details).

Framework component	Food waste (FW)	Anaerobic digestion (AD)	Biomethane refuelling and use in HDV vehicles (in biomethane propulsion systems)
Goal/metrics	Insufficient food waste recycling	Insufficient biogas and biomethane generation	Insufficient biomethane demand
People/Culture	Insufficient public support for food waste recycling participation	Insufficient public support for AD plant establishment or operations	Insufficient public support for biomethane refuel station and HGV deployment and operations
Techno-economics	Expensive FW collection related costs relative to revenues	Expensive AD related costs relative to revenues	Expensive refuel station related costs relative to revenues
Infrastructure/Investment	Insufficient fleet & storage capacity for FW collection	Insufficient AD capacity for processing FW	Insufficient biomethane refuel station capacity & HGV demand
Policy/Environment	Insufficient policy support in form of financial incentives, and/or insufficient environmental impact arising from effect of such policies		
Process/Procedures	Ineffective process/ procedure resulting in significant added costs in relevant FWtTBC pathway components		

These are further elaborated in full in context of specific FWtTBC pathway deployment scenarios in Chapter 4.6.4 for outlining relevant policy, investment and deployment strategies that are applicable to removal of specific deployment barriers, which constitute an important novel finding contribution of the present research.

4.5.4 Excel modelling limitations and further development

The established Excel modelling approach presents several key limitations with regard to its design and implementation for the purpose of conducting real-world real world scenario based modelling of cost-benefit trade-off pertaining to FWtTBC pathway deployment.

To elaborate, the quality of the modelling could be improved by including relevant input fields (i.e. material and energy metrics) that relate to more specific and complex process operations, i.e. those associated with higher tech-economic complexity pertaining to all relevant FWtTBC pathway components of food waste collection, anaerobic digestion and refuel station operations. The extent to which this can be achieved however is strongly positively correlated to the extent of time and technical data availability, both which are limited given unique circumstances of time and experimental facility access limitations surrounding the present study.

To this end, it is recommended for studies with sufficient capability in attaining experimental operational data of high economic complexity to integrate additional process operations to the extent they are able, for attaining more technical robust modelling results that consequently impact all modelling outputs (of material, energy, financials and emissions). An alternative and more practical method of implementation could entail specific collaboration between different methods and models.

4.5.5 Excel modelling Summary

This section outlined the design of a unique Excel modelling approach for conducting real world case study scenario modelling of cost-benefit trade-off pertaining to FWtTBC pathway deployment. The approach also outlined selective integration of key modelling components derived from other research methodology sections, i.e. of real-world deployment boundary conditions, FWtTBC pathway process and metric components, data collection, and whole systems analysis, to ensure all outcomes are both sufficiently relevant for real world application and technically robust.

Implementation of the model will be achieved through applicable of collected data in conjunction with the above modelling component integration framework set out, and with results to be outlined in selective findings section for post-modelling analysis discussions.

4.5.6 Excel modelling tool as a novel research contribution

The researcher also intends to make the established modelling approach and tool (in Excel format) to be available for access by other researchers under the agreement of fair use for advancing research in this field following publication of this thesis on key research platforms, driven by the current observation of there being a lack of existing free models that command sufficient information, context and insight for modelling FWtTBC pathway deployment. This is further supported by literature review findings of there being a general lack of existing academic research focusing on conducting integrated modelling and analysis on waste to renewable energy conversion pathways.

In doing so, the researcher endeavours to bridge the aforementioned knowledge and information gap that exist for elucidating cost-benefit trade-off attainable from FWtTBC (and with suitable adaptation, other waste to energy conversion) pathway deployment under real world case study scenarios to consequently help inspire further studies in this largely overlooked but highly applicable and important area of research.

4.6 Methodology 5 - Define whole-system analytical framework

4.6.1 Scope and coverage of whole systems analysis

Whole Systems (WS) analysis adopts the integration of several analytical techniques under the rationale of real-world decision making which often takes account of multiple system level factors beyond quantifiable material-energy and financial metrics.

This research particularly focuses on the integration of social technical framework with techno-economic analysis methodology, for analysing and evaluating important qualitative benefits, i.e. in form of technological transition or redistribution of social wealth, attainable from relevant FWtTBC pathway deployment scenarios.

4.6.2 Social technical framework

Traditionally social technical framework is used to evaluate the effectiveness of operations within organisations based on assessment of 6 key criteria and their relevant interactions outlined in Figure 98 and elaborated in Table 75 below. For purpose of this research however, their application is extended to evaluating effectiveness of deployment with respect to each individual components of the FWtTBC pathway as part of whole systems integrated framework (see Chapter 4.6.4), from which the overall pathway deployment effectiveness can be assessed to reasonable degree of judgement.

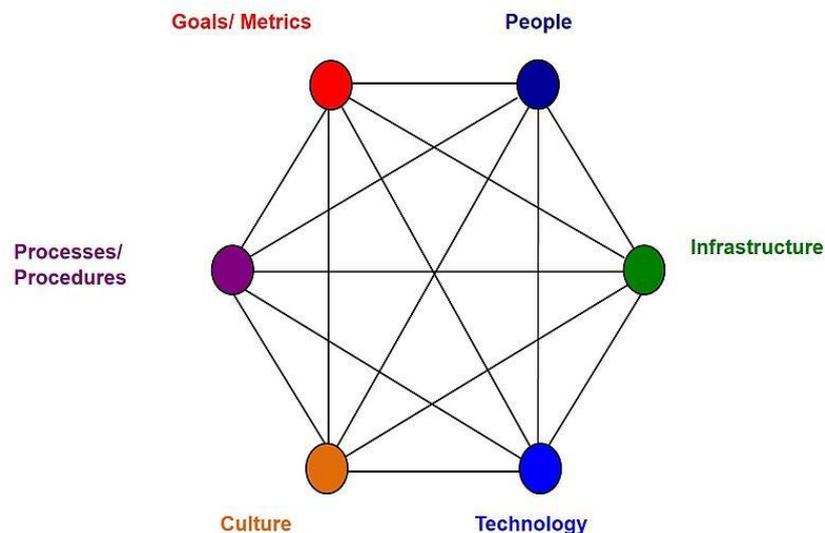


Figure 98. Social-technical framework outlining the 6 key elements and their interactions. Connection between different areas are represented by the specific connecting lines.

Table 75. Elaborations of social-technical hexagon framework elements

Element	Description
People	Beneficiaries of the process and applications related to biomethane for heating and transport
Culture	Local cultural acceptance and popularity of each biomethane application in Leeds
Process and Procedures	Technological process involved in biomethane application pathways (i.e. for transport and heat)
Infrastructure	Technological infrastructure from rollout and any beneficial implications arising from implementing process/procedures associated with each pathway
Technology	Basic and additional technologies required for implementing each application pathway
Goals/Metrics	Goals and metrics associated with the above 5 elements, in-line with the SMART framework

4.6.3 Techno-economic analysis

Details surrounding techno-economic analysis metrics and calculations is outlined in methodology 2, with chosen depth of analysis outlined in methodology 4 (see chapter 4.5.2).

These includes total cost estimates (both capital and operational) surrounding use of specific technology involved for the deployment of each FWtTBC pathway component (food waste, anaerobic digestion or HDV refuel station and refuelling).

A simplified summary of techno-economic analysis implementation in context of cost factors against attainable financial benefits and relevant technical factors connecting both is outlined in Table 76 below. Here it is worth noting that establishment and quality of relevant findings is highly dependent on data availability and accuracy. Given aforementioned limitations to the data collection process (see Methodology 3), availability of more readily available commercial data, i.e. on cost of each FWtTBC pathway component, is likely to be limited, and if so, suitable evidence based estimates (i.e. from other well informed sources) will be used instead to complete the analytical approach.

Table 76. Techno-economic analysis of FWtTBC pathway deployment

	Food waste	Anaerobic digestion plant	Refuel station
1. Cost factors	Established Fleet – Operational cost of fleet use	Established AD plant – Operational cost of technology use	Established Refuel station – Operational cost of technology use
	New fleet – capital and operational cost of fleet deployment and use	New AD plant – capital and operational cost of technology deployment and use	New Refuel station – Capital and Operational costs of technology deployment and use
2. Financial Benefits	Reduced landfill fees for food waste, also potential funding support for scheme rollout	Energy (biogas or biomethane) sales revenue	HDV Biomethane fuel sales revenue
		RHI tariff incentive income for each unit of Biogas produced	RTFC tariff incentive income for each unit of Biomethane produced
3. Technical factor affecting cost and benefit	Fleet capital cost relative to operational cost – especially fuel efficiency	Technology used affecting magnitude of biogas or biomethane attainable from specified food waste quantity	Biomethane HDV and refuel station capital cost relative to operational cost – especially fuel efficiency for HDV

4.6.4 Integrated whole systems social-techno-economic framework

The integrated whole system framework further adapts the original social-technical framework for conducting system level assessment and analysis by consolidating relevant framework components whilst adding and applying additional components to such effect. To this end, the framework adopts additional criteria of techno-economics, policy/environment and Infrastructure/Investment in place of technology, culture and infrastructure alongside merging people and cultural into a single component for assessment, and with goal/metrics processes/procedures unchanged.

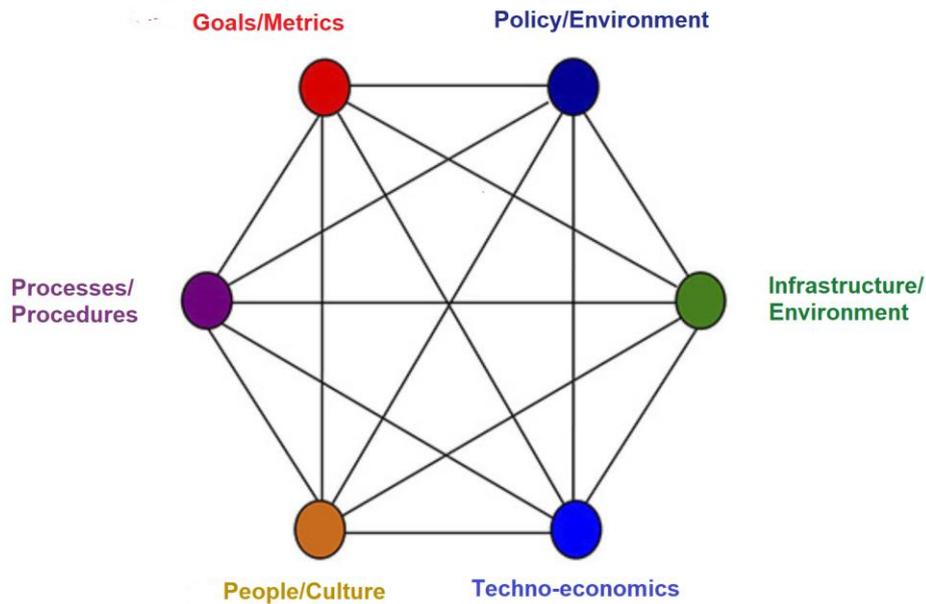


Figure 99. Integrated whole systems (social-techno-economic) analytical framework, containing adapted elements of the social technical framework outlined in Figure 98 above as outlined further in Table 78 below

Table 77. Brief description of each of the 6 elements of the integrated framework

N	Component name	Abbreviations	Description and examples
1	Policy/Environment	P/E	National policy that reflects financial support for FW recycling or biomethane use, in context of environmental benefits attainable from FWtTBC pathway deployment
2	People/Culture	P/C	People and local culture's acceptance and contributory action in support of FWtTBC pathway deployment, i.e. partaking in food waste collection trials
3	Process and Procedures	P/P	Operational and technological process and procedures involved in FWtTBC pathway deployment
4	Infrastructure/Investment	I/I	Technological infrastructure from rollout and any beneficial implications arising from implementing process/procedures associated with each pathway
5	Techno-economics	TE	Economics of utilizing technologies associated with deployment of each individual components (or stages) of the FWtTBC pathway
6	Goals/Metrics	G/M	Goals and metrics associated with the above 5 elements, in-line with the SMART framework

Here the key goal would be to assess the effect of policy and investments to other framework components given their strong impact on the overall cost-benefit trade-off attainable from FWtTBC pathway deployment under each case study scenario.

To this end, specific barriers pertaining to each stage of FWtTBC pathway deployment in relation to each framework component are assessed to determine how they can be mitigated or removed via proposed policy and investment strategies, which typically constitute the key driver of most system level changes (see Table 78).

It is generally assumed the removal of these 'gateway' barriers will disproportionately increase the attractiveness and feasibility of deployment for relevant FWtTBC pathway components, or for the entire pathway should all such barriers be removed.

Table 78. Whole systems assessment framework components for FWtTBC pathway deployment outlining all relevant barriers to deployment

Framework component	Food waste	Anaerobic digestion	Biomethane refuelling and use in HDV vehicles (in biomethane propulsion systems)
Goal/metrics	Insufficient % and total output captured to justify existing FW collection trial	Insufficient biogas and biomethane generation output to justify existing AD plant operation or new AD plant construction	Insufficient biomethane demand by or supply to existing HDVs to justify existing refuel station operation or conversion
People/Culture	Insufficient acceptance, habit of good practice or action taken towards FW recycling leading to reduced individual and total FW output, may lead to insufficient FW recycling to justify collection as outlined in goal/metrics	Insufficient public and cultural support towards deployment of local anaerobic digestion plant infrastructure for biogas or biomethane production, leading to reduced funding for such projects	Insufficient public and cultural support towards deployment of local biomethane refuel station and biomethane powered HGV fleet for biogas or biomethane production, leading to reduced funding for such projects
Techno-economics	Expensive overall technology-related capital and operational cost of FW collection relative to attainable economic benefits	Expensive overall technology-related capital and operational cost of anaerobic digestion relative to attainable economic benefits	Expensive overall technology-related capital and operational cost of refuel station deployment and biomethane-powered HGV production relative to attainable economic benefits
Infrastructure/investment	FW collection fleet either with insufficient capacity to justify full scale deployment or would run over-capacity where cost of collection is not justified	Local AD plant capacity inefficient to justify FW collection trial implementation at desired scale	Local refuel station and biomethane fleet usage (based on supply-demand) capacity inefficient to justify FW collection trial implementation at desired scale
Policy/Environment	Policy on production of biogas or biomethane i.e. via RHI or RTFC incentives, and relevant environmental benefits in form of emission reductions does not justify the extra total AD related techno-economic costs involved when compared to non FWtTBC pathway deployment scenario		
Process/Procedures	Process and procedure not sufficiently streamlined lined accounting for all of the above factors, to result in excessive cost against FW collected	Process and procedure not sufficiently streamlined lined to accommodate all of the above factors and dependent on food waste collected, to result in excessive cost against biogas and biomethane produced	Process and procedure not sufficiently streamlined lined accounting for all of the above factors and dependent on biomethane produced, to result in excessive cost against biogas and biomethane use in HDV transport

The above assessment framework will also be used for relative assessment of barriers for each FWtTBC pathway deployment scenario using limited real world data. Application of assessment framework to Rothwell region for example suggests there being low barriers of deployment across most whole systems framework components for all FWtTBC pathway components, which consequently outlines high chance of deployment feasibility at least at the local level. This however is likely due to existing precedence of food waste collection trials at Rothwell for over a reasonably long period of time (since 2010), in which its implementation had seen gradual improvements across all whole system framework components through adequate strategizing and repeated consultations (see Table 79).

Table 79. Relative barriers for FWtTBC pathway deployment at Rothwell trial region level usable as benchmark for assessment for further expansion to Leeds city wide region

Framework component	Food waste	Anaerobic digestion	Biomethane refuelling and use in HDV vehicles (in biomethane propulsion systems)
Goal/metrics	Low Good level of FW collection participation (>60%) based on target metrics outlined (see below)	Low Affected by FW collected arising from good level of individual participation based on target metrics set (see below)	Low Sufficient demand for HDV use with refuel station capacity based on target metrics set (see below)
People/Culture	Low Good level of FW collection participation (>60%) by individuals and cultural acceptance	Low Presumed adequate level of public and cultural acceptance towards deployment of biomethane HDV fleet and station	Low Presumed adequate level of public and cultural acceptance towards deployment of biomethane HDV fleet and station
Techno-economics	Medium Assumed acceptable levels of techno-economic involved (cost relative to benefit) based on relative modern fleet used by 2 biomethane HDVs	Medium Assumed acceptable levels of techno-economic involved (cost relative to benefit), arising from use of relatively modern AD technology at maltings organics	Medium Assumed acceptable levels of techno-economic involved (cost relative to benefit) based on relative modern refuel stations and biomethane HDVs fleet (of 2 HDVs)
Infrastructure/Investment	Low Existing precedence of FW collection using biomethane	Low AD station situated close by (maltings organics) and with sufficient capacity	Low Existing refuelling station situated close by for biomethane truck refuelling (2 vehicles total)
Policy/Environment	High No specific supporting incentives, indirect ones include those in AD and biomethane refuelling section	Low RHI claim for generation of surplus (or dedicated) renewable heat from FW anaerobic digestion process	Low RTFC reclaim for use of biomethane for HDV use
Process/Procedures	Very Low Process and procedures already in place at Rothwell region, and can be improved based on previous experiences	Very Low Process and procedures already in place at Rothwell region, and can be improved based on previous experiences	Very Low Process and procedures already in place at Rothwell region, and can be improved based on previous experiences

The upscaling of FWtTBC pathway deployment trial will likely face greater challenges surrounding acquiring sufficient infrastructure capacity and establish processes/procedures for efficient deployment. Conversely, effective deployment will likely enable much improved techno-economics through economy of scale, where useful biogas and biomethane outputs could contribute to greater current energy demand (see Table 80).

Table 80. Relative barriers for FWtTBC pathway deployment at Leeds city region level using existing pathway deployment at Rothwell region as benchmark for assessing suitability of and relative strategies to be considered surrounding pathway deployment (all criteria are based on estimations rather than real figures)

Framework component		Food waste	Anaerobic digestion	Biomethane refuelling and use in HDV vehicles (in biomethane propulsion systems)
Goal/ metrics	Barrier	Moderate	Moderate	Very Low
	Observed Rationale	Moderate level of FW collection participation (40-60%) based on target metrics outlined (see below)	Affected by FW collected arising from moderate level of individual participation based on target metrics set (see below)	Sufficient demand for HDV use with refuel station capacity based on target metrics set (see below) – higher priority for cities given standards surrounding clean air requirements
People/ Culture	Barrier	Low	Low	Very Low
	Observed Rationale	Moderate level of FW collection participation (40-60%) by individuals and cultural acceptance	Presumed adequate level of public and cultural acceptance towards deployment of biomethane HDV fleet and station	Presumed high level of educated public and cultural acceptance towards deployment of biomethane HDV fleet and station to reduce city region pollution
Techno-economics	Barrier	Low	Low	Low
	Observed Rationale	Assumed very good levels of techno-economic involved (cost relative to benefit) based on choice of using modern cost-efficient fleets and , beneficial effects of upscaling	Assumed very good levels of techno-economic involved (cost relative to benefit), arising from use of relatively modern AD technology, alongside beneficial effects of upscaling	Assumed very good levels of techno-economic involved (cost relative to benefit) based on choice of using modern cost-efficient refuelling stations and fleets, and beneficial effects of upscaling
Infrastructure/ Investment	Barrier	High	High	High
	Observed Rationale	Existing precedence of FW collection using biomethane	AD station situated close by (maltings organics) and with sufficient capacity	Existing refuelling station situated close by for biomethane truck refuelling (2 vehicles total)
Policy/ Environment	Barrier	High	Low	Low
	Observed Rationale	No specific supporting incentives, indirect ones include those in AD and biomethane refuelling section	RHI claim for generation of surplus (or dedicated) renewable heat from FW anaerobic digestion process	RTFC reclaim for use of biomethane for HDV use
Process/ Procedures	Barrier	Low	Moderate	Moderate
	Observed Rationale	Process and procedures can be learnt from Rothwell food waste collection trial and existing waste collection trials	Process and procedures can be Rothwell trial in terms of transport logistics and plant operations, but require establishing new or finding existing local AD plant to accommodate increase in food waste capacity input	Process and procedures can be Rothwell trial in terms of transport logistics and plant operations, but require establishing new or finding existing local refuel stations to accommodate increase in biomethane HDV refuelling

A comparison of initial assessment findings outlines some basic insights regarding specific actions, strategies and investments or combination thereof required to adequately strategize and maximize pathway deployment success based on achievement of pre-established cost-benefit trade-off targets (with relevant metrics outlined in methodologies 2 and 3).

This translates to a need for greater investment and policy support focus for AD and refuel station infrastructure establishment or acquisition to potentially achieve more effective FWtTBC deployment at Leeds city region level, as will be informed in detail using relevant Excel modelling outputs.

4.6.5 Further whole system analysis applications

Similar comparative assessments will be adopted using real-world data or reasonable data driven inferences where applicable, to evaluate relative barriers and challenges surrounding FWtTBC pathway deployment. This will occur in context of each whole-systems framework component for other research modelling scenarios, i.e. for Leeds (and potentially other NPH) city and metropolitan county regions.

Results of all findings will be used to subsequently establish effective deployment strategies for overcoming relevant barriers of FWtTBC pathway deployment often attributed to the aforementioned chicken and egg conundrum (CAEC) and lock-in effect (LIE) as alluded to earlier in Chapter 1.2.8 (see Figure 100).

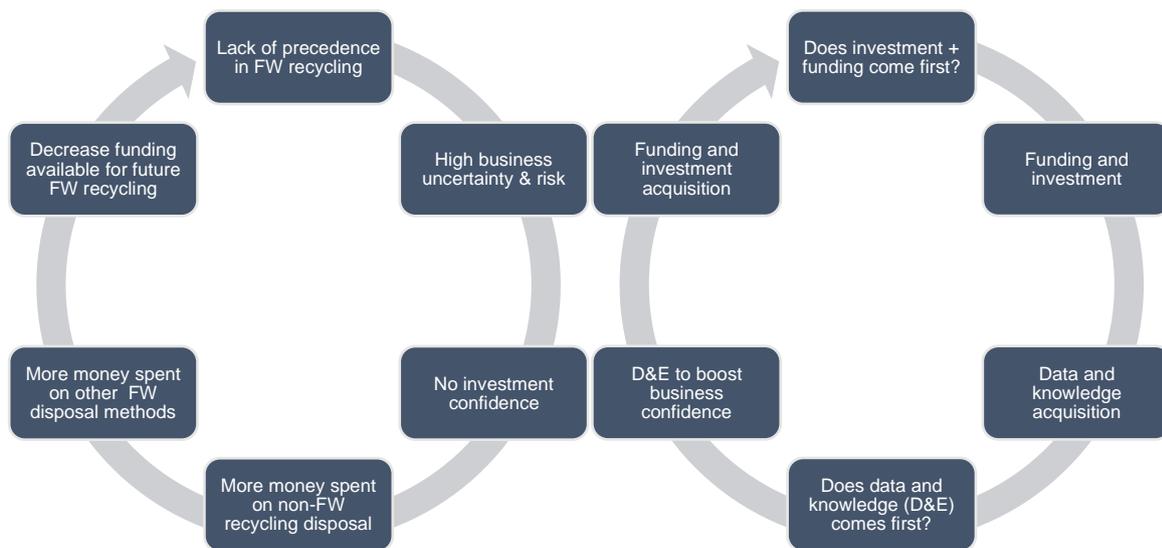


Figure 100. (Left) Lock-In Effect that reinforces the status quo of non-implementation of FWtTBC pathway trials and schemes, (Right) Chicken And Egg Conundrum (CAEC) responsible for non-implementation of FWtTBC pathway trials and schemes, with both effects hampering deployment. Original details outlined in Chapter 1.2.8.

Here it is worth noting such strategies will prioritize on addressing the most vulnerable FWtTBC pathway deployment components that present the greatest risk of 'failure' or 'hindrance' which could ultimately deter key stakeholder participation, to ensure preservation of overall pathway integrity, i.e. AD and refuel station infrastructure availability for Leeds city deployment scenario (see Figure 101).

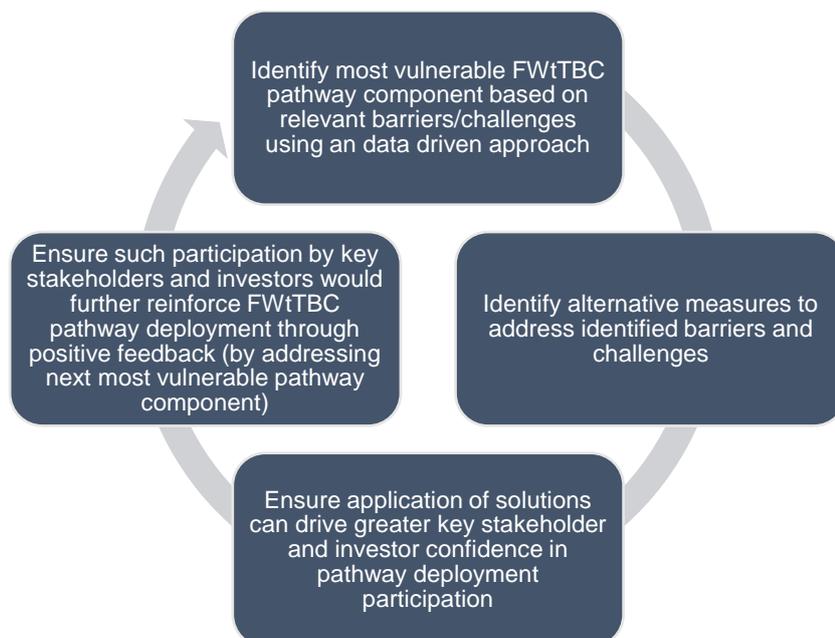


Figure 101 Application of the whole systems socio-techno-economic framework for reinforcing FWtTBC pathway deployment by overcoming CAEC and LIE.

Examples of relevant key stakeholders are outlined in Table 81 below.

Table 81. Key FWtTBC pathway deployment stakeholders in context of main drivers and relative involvement in each pathway component

FW component	Main drivers of FWtTBC pathway deployment	FW	AD	RS
1 Leeds city council	Cost-effective food waste recycling, and biogas or biomethane generation via use of in-house infrastructure or third party contracts. Focusing on balance of generating financial and social public benefits and positive reputation	Y	O	O
2 AD plant operator	Maximizing profits from anaerobic digestion of received food wastes, i.e. through biogas and/or biomethane sales and claiming RHI tariff incentive comes	N	Y	O
3 Refuel station operator	Maximizing profits from provision of fuel to HDVs via refuelling process, i.e. through biomethane sales and claiming RTFC tariff incentive comes	N	N	Y
4 Relevant Investor	Maximizing profits from anaerobic digestion of received food wastes, i.e. through biogas and/or biomethane sales and claiming tariff incentive comes	O	O	O
5 Public	Feeling of participation and contribution for actively participating in food waste collection trials and schemes on grounds of helping the environment with or without supporting incentives, i.e. financial or other	Y	N	N

Abbreviations - Y, P and N represents compulsory, optional and no involvement, respectively.

4.6.6 Conclusions and summary

This methodology chapter outlined both the design and application of the whole systems assessment framework, which will be applied to Excel modelling results for comparatively assessing key pathway deployment barriers and challenges, and how they can be used address through specific measures in policy, investment or other support.

Outcomes are subsequently used to establish specific policy, investment and pathway deployment recommendations to outline effective deployment strategies and conditions that

are relevant to each FWtTBC pathway deployment case study scenario. To this end, each key stakeholder (see **Error! Reference source not found.**), would play a different but important role in their contribution towards collectively overcoming the CAEC (Chicken and Egg Conundrum) and LIE (Lock-in Effect) to help drive increasingly effective implementation of real world deployment of the FWtTBC pathway, at the local, city and metropolitan county level across short, medium and the foreseeable long term.

4.6.7 Limitations and further development

Key limitations in the design of this whole systems methodology mainly arises from its limited coverage of 6 assessment components, which, although covers all key social-techno-economic areas pertaining to pathway deployment for evaluation, could be made even more comprehensive and specific. This can be achieved thorough precise separation of existing combined fields into individual fields or with addition of relevant new fields as outlined in Table 82 below, though was not used for applied to this research given restrictions in time and data availability.

Table 82. Adjustments to whole systems assessment fields that can be made to improve the overall methodology to remove specified limitations for future studies

Original combined assessment components		Separation into individual assessment components (removal of limitation)	
1	People/Culture	1	People
		2	Culture
2	Techno-economics	3	Technology
		4	Economics
3	Policy/Environment	5	Policy
		6	Environment
4	Infrastructure/Investment	7	Infrastructure
		8	Investment
5	Procedures/Processes	9	Procedures/Processes
6	Goals/Metrics	10	Goals/Metrics

Here specific improved applications would be the greater degree of freedom arising from assessing each assessment component relative to other components from which additional barriers and recommendations could be established. A prominent example would be to assess, pertaining to FWtTBC pathway deployment, investment with respect to infrastructure, technology, culture and procedure/processes, as opposed to the more limited assessment of infrastructure/investment with respect to techno-economics.

It is hoped for future studies with sufficient time and resources to adopt this proposed methodological approach where enhanced quality and specificity of the results can be justified, i.e. towards evaluating critical investments on key FWtTBC pathway components in greater depth and with greater clarity.

The next chapters will outline all critical findings and discussions arising from the outputs of the data collection and Excel modelling methodology outlined above (see chapters 3 and 4 respectively).

Chapter 5. Findings and discussions

5.1 Results and findings introduction

This chapter outlines research findings and data pertaining to each component of the FWtTBC pathway. These include (i) FW collection, (ii) Anaerobic Digestion (AD) technical operations, (iii) emission reduction arising from biomethane refuel station (RS) refuelling and displacement of conventional fuel use in HDVs, and (iv) relevant financial and whole-system analysis data across all 3 pathway components (see Figure 102).

1. Food waste collection data	<ul style="list-style-type: none">• Present all findings on 3 real-world food waste collection trials (1 from WRAP and 2 from Waste data flow) and ONS 2018 population data estimations to estimate aggregate food waste collection for each deployment scenario (each NPH city and metropolitan county region across 2010-2050)• Relevant for calculating aggregate technical findings (i.e. biogas, biomethane, revenue and emission reduction) in the ensuing sections.
2. AD Technical operation al data	<ul style="list-style-type: none">• Presents all findings on technical food waste biogas and biomethane yield from academic research papers based on FW composition, AD technical parameters.• Combine these technical findings with aggregate food waste collection data (finding 1) to establish bioga and biomethane potential for each deployment scenario (i.e. for each NPH city and metropolitan county region across 2010-2050).
3. RS Emissions (& refuelling) data	<ul style="list-style-type: none">• Presents all findings on biomethane transport refuelling and emission reduction when compared vs. conventional fossil fuel use in the same vehicles (aggregate across NPH region and 2010-2050) using finding 1 and 2 results• Assessing specific deployment barriers to establish recommendations on corresponding supporting mechanisms (i.e. strategies, policy and investments) for enabling effective FWtTBC pathway deployment.
4. Financial data	<ul style="list-style-type: none">• Present all findings on aggregate potential revenues and costs associated with each component of FWtTBC pathway deployment (food waste, collection, AD operations, refuel staton operations) for each NPH region and 2010-2050• Present these findings for case specific deployments in Leeds assuming for use of existing AD plant or new AD plant deployment

Figure 102. Description of findings pertaining to each methodology

Details of each section on data finding is further elaborated in Table 83 below in context of relevant collected data sources, methodology, description, pathway component, data source type and references. These data findings originate from a diverse group of different governmental, research and non-profit organisations that focuses specifically on each segment of the FWtTBC pathway, which also highlights the relative importance of multistakeholder collaboration for integrated research projects of this nature.

Here two key organisations, Waste Data Flow, WRAP and Office for National Statistics, ONS are shown to play a pivotal role in their contributions to data on FW output. Likewise, relevant academic and industry driven research papers presented key contributions to FW biogas and biomethane yields, emission savings arising from biomethane use to displace conventional fossil fuels in Heavy Duty road transports and relevant financials. The amalgamation of all data findings are consequently used to complete the whole systems analysis segment of the

research to derive further insight on the current state of FWtBC pathway implementation on a system level and its future potential optimization strategies that is self-reinforcing and propagating, i.e. from an investment and infrastructure development perspective.

Table 83. Data collection findings - on data sources and publications (with relevant data as outlined in basic and advanced process operation metrics schematics, see Methodology 2).

Section	Type of Data collected	Original Source	Relevant methodology	Description	Pathway component	Source type	Reference
5.2	Food waste collection data – from Real-world scenario deployment	Waste data flow data	Methodology 1 & 2 (See Chapter 4.1 and 4.2)	Food waste collection data from 2010 across UK geographical cities and regions	Food waste	National database	(Waste Data Flow, 2016)
		WRAP reports		Food waste collection trial data	Food waste	Official study reports	(WRAP, 2018)
		Office for National Statistics data		Population data exhibiting population change over time across scenario relevant Northern Powerhouse (NPH) city regions	All (FW, AD, RS)	National database	(ONS, 2018)
5.3	Process operations technical (mass, energy) data findings	Academic journal platforms, i.e. Science-direct, google-Scholar, etc	Methodology 2, 3 & 4) (See Chapter 4.2, 4.3 and 4.4)	Technical data on conversion of food waste to biogas and biomethane via anaerobic digestion (with inclusion of technical process operation data)	Anaerobic digestion	Research publications	See relevant section
5.4	Process operations emission data findings (fuel use)	CENEX reports		Biomethane transport refuelling and refuel station data	Refuel station & HDV refuelling	Official study reports	(Scholfield & Carroll, 2014)
5.5	Process operations financial data findings (fuel generation and use)	Relevant Online data platforms, i.e. government, business news, financial data		Financials data for costs of AD establishment and capacity, Biomethane sales values and tariffs incentives	All (FW, AD, RS)	Online data	See relevant section
5.6	Whole systems (socio-techno-economic) analysis	N/A	Methodology 5) (See Chapter 4.5)	Whole systems analysis of all output Excel modelling data	All (FW, AD, RS)	N/A	N/A

These findings collectively fulfils the following research aims and objectives: Aims 2 & 3 (Obj. 2.1, 3.2, 3.3) and Aim 4 (Obj. 4.1-4.3) (see Chapter 1.8 for details), as outlined in Table 84 below.

Table 84. Summary of section findings in context of specified aims and objectives set out by the research (please see Chapter 4 for details on fulfilment of the remaining research aims and objectives).

Aim	Objectives	Description outline	Covered by Chapter 4 (Methodology) (Y/N) / Relevant chapter	Covered by Chapter 5 (Results and Findings) (Y/N) / Relevant chapter
1		Source verified data collection		
	1.1	Establish key pathway data metrics	Y / 4.2	
	1.2	Establish novel methodology for data collection	Y / 4.3	
	1.3	Conduct data collection for all identified parameters		Y / 5.2, 5.3 & 5.4
2		Establish high level pathway deployment metrics		
	2.1	Evaluate household food waste collection data		Y / 5.2
	2.2	Establish operational process diagrams	Y / 4.2	
	2.3	Establish whole systems analysis metrics	Y / 4.4	
3		Establish detailed case study scenario elements		
	3.1	Establish boundary conditions and parameters	Y / 4.2	
	3.2	Establish cost-benefit trade-offs analysis of all metrics from FWtTBC pathway deployment		Y / 5.2, 5.3 & 5.4
	3.3	Conduct sensitivity analysis in relation to Obj 3.2		Y / 5.2, 5.3 & 5.4
4		Conduct whole-systems analysis with target oriented focus on policy, investment, barriers		
	4.1	Maximize reduction in FW output		Y / 5.5
	4.2	Maximize key financial return on investment		Y / 5.5
	4.3	Maximise emissions savings potential		Y / 5.5

The next section respectively outlines findings corresponding to each section of the FWtTBC pathway in detail. These include findings on FW data collection, FW to biogas and biomethane potential, financial data and whole systems analysis, as respectively elaborated in Chapters 5.2, 5.3, and Chapters 6 and 7 respectively.

5.2 Food waste data collection findings

5.2.1 Overview

This section outlines findings of real-world scenario deployment data for food waste collection, and presents findings in relation to:

- (i) Real-world household food waste collection data arising from any relevant food waste collection trials within these or other representative regions (see Chapters 5.2.2.1-5.2.2.3),
- (ii) Time-adjusted population data for each of the 5 NPH regions of Leeds, Manchester, Liverpool, Sheffield and Newcastle at the city and metropolitan county level (see Chapter 5.2.2.4),
- (iii) Total potential food waste availability for collection under each NPH region by combining findings in (i) and (ii).

These findings are derived from relevant food waste collection real-world representative trial data from the Waste Data Flow (WDF) database and WRAP's dedicated reports on the UK household FW collection, which are outlined in chapter 5.2.2 and 5.2.3, respectively. These are then summarized collectively in chapter 5.2.4 for an integrated analysis and review.

5.2.2 Per capita FW collection data - Waste Data Flow (WDF)

5.2.2.1 Waste Data Flow (WDF) data for all local authority dedicated FW collections (2020-21)

This section outlines food waste collection data findings across all local authority regions with dedicated FW collection schemes captured by the UK government's WDF database. For comparative analysis, these includes dedicated food waste collection data from (i) all eligible local authority regions in 2020-21, and from (ii) Leeds city council operated region of Rothwell for all eligible years (2010-2020) (Gov.uk, 2022b).

5.2.2.2 Dedicated food waste collection data for all local authorities (2020-21)

Table 85 below outlines per capita household food waste collection data across all local authority regions with dedicated food waste collection schemes for the 2020-2021 collection period. These data findings have been compiled from the original raw database and shows large variations in the total and per capita annual household food waste output between different regions.

Table 85. Waste data flow (WDF) dedicated household food waste collection data from all eligible local authority councils in 2020-21 (Gov, 2022)

	City council	Total Food waste collected (kg/year)	Population of Authority	Number of Households	Index of Deprivation	Food waste per person (kg/capita/year)
1	Maldon District Council	2599.1	64926	25000	14.169	98.28697
2	North Devon District Council	6640.36	97145	38000	20.559	68.35514
3	South Oxfordshire District Council	7105.82	142057	53000	8.459	50.02091
4	East Devon District Council	7262.83	146284	57000	12.764	49.64883
5	Vale of White Horse District Council	6422.34	136007	46000	8.358	47.22066
6	Watford Borough Council	1023.9	96577	32000	15.41	46.97806
7	Teignbridge District Council	6292.55	134163	54000	15.893	46.90228
8	Surrey Heath Borough Council	3917.751	89305	32000	8.066	43.86934
9	West Oxfordshire District Council	4784.72	110643	39000	8.684	43.24467
10	Dorset Council	16336.45	378508	153000	15.735	43.16012
11	Woking Borough Council	4283.274	100793	38000	10.804	42.49575
12	Torridge District Council	2896.9	68267	27000	23.269	42.43485
13	Bath and North East Somerset Council	8145.96	193282	73000	11.745	42.14547
14	Isle of Wight Council	5918.791	141771	60000	23.294	41.74895
15	Cotswold District Council	3749.26	89862	36000	11.061	41.72242
16	Oxford City Council	6313.28	152457	55000	16.707	41.41023
17	St Albans City and District Council	6121.38	148452	54000	8.339	41.23474
18	Somerset Waste Partnership	22540.83	562225	220000		40.09219
19	Elmbridge Borough Council	5428.219	136795	53000	7.944	39.68141
20	Tandridge District Council	3471.39	88129	32000	11.896	39.38987
21	Mid Devon District Council	3422.56	82311	30000	16.928	39.31061
22	West Devon Borough Council	2146.88	55796	21000	18.052	38.47731
23	North Somerset Council	7908.44	215052	83000	15.825	36.77455
24	Bromley LB	12183.94	332336	129000	14.163	36.66151
25	Chelmsford Borough Council	6496.96	178388	67000	12.221	36.42039
26	Tewkesbury Borough Council	3445.12	95019	33000	12.142	36.25717
27	Uttlesford District Council	3297.61	91284	28000	9.258	36.12473

28	Dacorum Borough Council	5555.92	154763	57000	13.004	35.89954
29	Wokingham Council	6119.79	171119	59000	5.846	35.76336
30	South Northamptonshire District Council	3373.32	94490	34000	7.652	35.70029
31	Bristol City Council	16429.16	463377	169000	26.363	35.45528
32	Reigate and Banstead Borough Council	5266	148748	53000	11.276	35.40216
33	Harlow District Council	3067.82	87067	33000	21.413	35.23516
34	South Gloucestershire Council	9924.02	285093	101000	11.66	34.80976
35	Colchester Borough Council	6701.02	194706	67000	16.778	34.41609
36	Guildford Borough Council	5107.817	148998	53000	9.395	34.28111
37	Cheltenham Borough Council	3916.9	116306	49000	14.26	33.67754
38	Three Rivers District Council	3088.36	93323	34000	9.871	33.09324
39	Forest of Dean District Council	2865.66	86791	33000	18.013	33.01794
40	Cheshire West and Chester	11210.22	343071	136000	18.083	32.67609
41	Stroud District Council	6231.04	119964	46000	10.797	32.65772
42	Royal Borough of Kingston upon Thames	5784.36	177507	3723	11.381	32.58666
43	East Northamptonshire Council	3050.28	94527	33000	13.897	32.26888
44	Gloucester City Council	4162.96	129128	47000	21.807	32.23902
45	Epsom and Ewell Borough Council	2577	80627	28000	8.833	31.962
46	Broxbourne Borough Council	3077.81	97279	35000	17.989	31.639
47	Daventry District Council	2699.13	85950	30000	13.184	31.40349
48	Braintree District Council	4758.84	152604	57000	14.723	31.18424
49	Tendring District Council	4534.52	146561	64000	30.484	30.93947
50	Buckinghamshire Council	16314.27	543973	190000		29.99096
51	Runnymede Borough Council	2678.7	89424	32000	12.012	29.95505
52	Telford and Wrekin Council	5338.22	179854	66000	24.988	29.68085
53	Croydon LB	11415.41	386710	144000	22.477	29.5193
54	Harrow LB	7293.76	251160	80000	15.031	29.04029
55	Spelthorne Borough Council	2803	99844	38000	14.943	28.0738
56	Enfield LB	9038.1	333794	112000	25.781	27.07688
57	Calderdale MBC	5559.6	211455	83000	26.351	26.29212
58	Castle Point Borough Council	2374.48	90376	36000	16.842	26.27335
59	Central Bedfordshire	7515.48	288648	99000	12.152	26.03683
60	Norwich City Council	3549.458	140573	57000	27.599	25.24993
61	Southend-on-Sea Borough Council	4577.34	183125	72000	22.375	24.99571
62	Torbay Council	3300.62	136264	59000	28.104	24.22225
63	Chichester District Council	2924.64	121129	47000	14.085	24.14484
64	Hounslow LB	6112.94	271523	84000	21.487	22.51353
65	Ealing LB	7468.44	341806	118000	22.71	21.84994
66	Bexley LB	5410	248287	91000	16.273	21.7893
67	Brent LB	7078.83	329771	101000	25.558	21.4659
68	Peterborough City Council	4250.38	202259	67000	27.821	21.01454
69	Northampton Borough Council	4347.686	224610	83000	23.358	19.3566
70	St Helens MBC	3159.2	180585	74000	31.518	17.49425
71	Hackney LB	4892.98	281120	87000	32.526	17.40531
72	Brentwood Borough Council	1329.24	77021	30000	10.007	17.25815
73	Windsor and Maidenhead Borough Council	2548.46	151422	56000	8.376	16.83018
74	Merton LB	6381.38	206548	81000	14.649	16.57029
75	Derbyshire Dales District Council	1070.22	72325	30000	11.895	14.79737
76	Richmond upon Thames LB	2929.154	198019	80000	9.425	14.79229
77	Bournemouth, Christchurch and Poole Council	5363.49	395331	153000	18.173	13.56709
78	Mole Valley District Council	3235.696	87245	34000	9.511	11.90131
79	Camden LB	3100.82	270029	98000	20.131	11.48329
80	Haringey LB	3032.3	268647	94000	27.956	11.2873
81	Reading Borough Council	1414.21	161780	59000	19.619	8.741563
82	Welwyn Hatfield Council	1005.2	123043	41000	14.215	8.169502
83	Waverley Borough Council	4537	126328	48000	7.494	7.957064
84	Corby and Kettering Shared Service	1177.38	173994	58000		6.766785
85	Eastleigh Borough Council	839.75	133584	48000	10.192	6.286307
86	Bracknell Forest Borough Council	535.86	122549	44000	10.241	4.372618
87	Westminster City Council	1107.78	261317	111000	20.339	4.239219
88	Swindon Borough Council	823.46	222193	77000	18.622	3.706057
89	Newcastle-under-Lyme Borough Council	1038.33	302820	116000	29.79	3.428869
90	South Kesteven District Council	300.9	142424	54000	13.499	2.112706
91	Waltham Forest LB	518.74	276983	91000	25.209	1.872823

92	Halton Borough Council	233.54	129410	49000	32.325	1.804652
93	Royal Borough of Kensington and Chelsea	219.74	156129	88000	21.526	1.407426
94	Hammersmith and Fulham LB	201.14	185143	79000	22.27	1.086403
95	South Hams District Council	83.04	87004	35000	13.724	0.954439
96	Solihull MBC	145.057	216374	82000	17.37	0.670399
97	North Lincolnshire Council	84.028	172292	66000	22.096	0.487707
98	Plymouth City Council	93.18	262100	106000	26.619	0.355513
99	Kings Lynn and West Norfolk Borough Council	34.5	151383	61000	23.72	0.227899
100	Southwark LB	47.34	318830	110000	25.811	0.14848
101	Wolverhampton MBC	33.7	263357	99000	32.102	0.127963

These findings are also illustrated in Figure 103 and

Figure 104 below, which respectively shows a log₁₀ and normal scale bar chart representation of household FW collected on a per capita basis across all LA regions from the highest (left) to the lowest (right) figures. Interestingly, Maldon and Wolverhampton MBC district council has registered the highest and lowest per capita household FW collection of 98kg to 0.128kg respectively, although the latter figure appear to be unrealistically low and should be cross-evaluated with other household FW data collection sources.

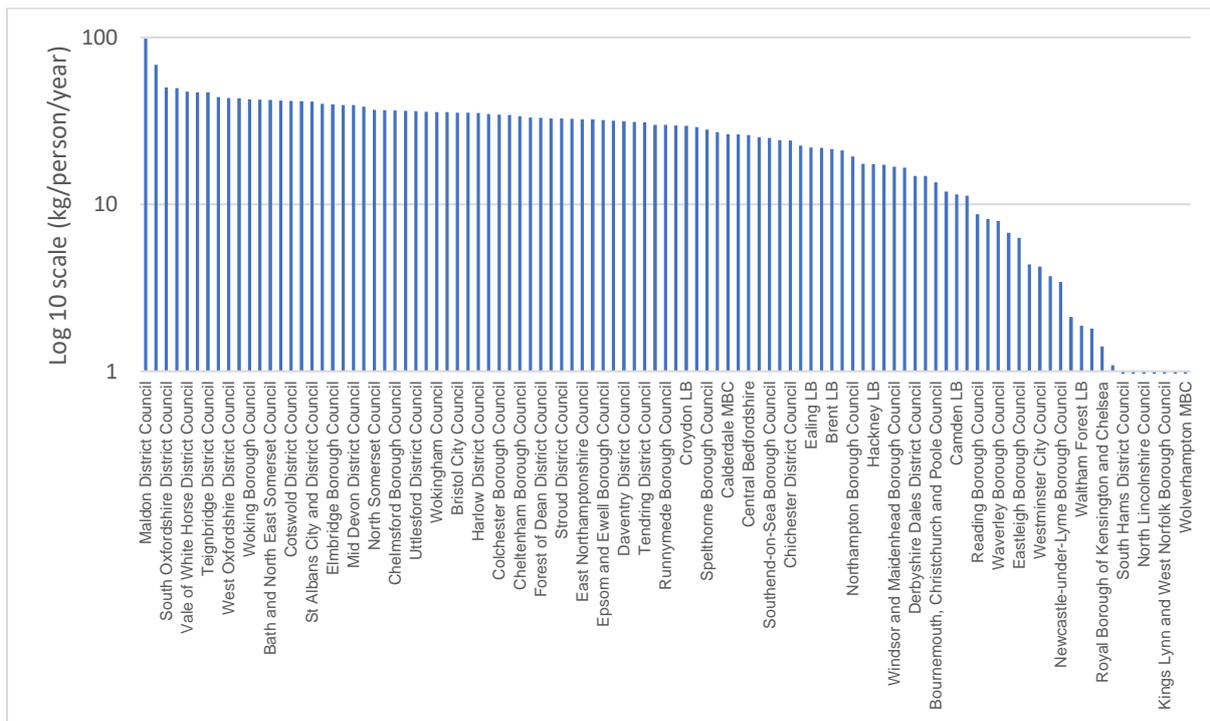


Figure 103. Waste data flow dedicated household food waste output per capita for all eligible local authority regions in 2020-21 (using log₁₀ scale)

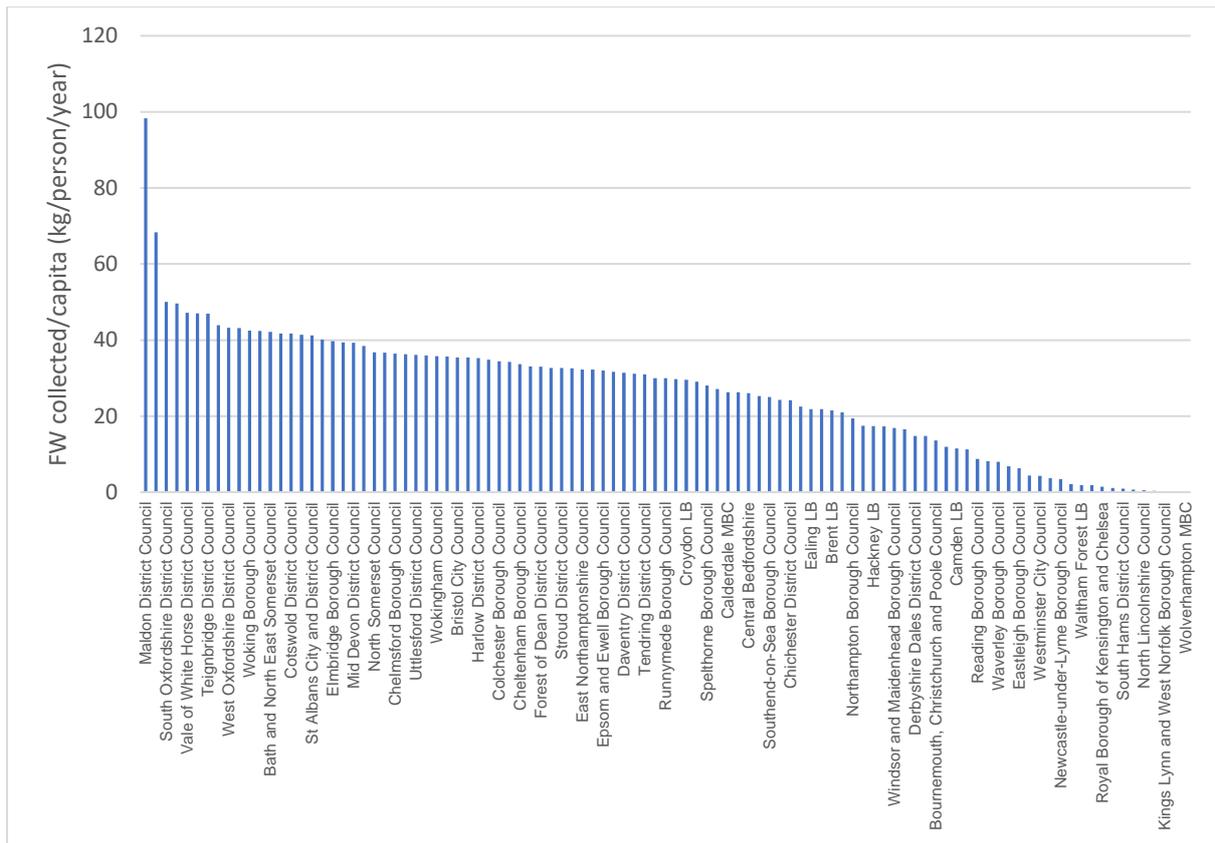


Figure 104. Waste data flow dedicated household food waste output per capita for all eligible local authority regions in 2020-21

For estimating an acceptable average value output for per capita FW collection, a median and mean approach is consequently adopted alongside a value based inclusion criteria to remove potential outliers. Here the inclusion criteria will apply the reasonable assumption of these to be a minimum quantity of household FW output per capita within the participating LA where the FW collection trials were conducted to justify the pre-trial planning, on-trial implementation and post-trial assessment.

By setting this minimum quantity figure to be between 10 and 50 kg/capita, a range of secondary findings was consequently established, which is outlined in Table 86 and Figure 105 below.

Table 86. Waste data flow (WDF) dedicated household food waste output per individual based on inclusion criteria (via removal of assumed outliers datasets for each criteria) (Gov, 2022).

	Inclusion criteria* (FW output/person)	Median (kg/person/year)	Mean (kg/person/year)
1	All	26.56664	29.95505
2	>10 kg/capita	32.72882	32.66691
3	>20 kg/capita	35.8171	34.61293
4	>30 kg/capita	39.72198	36.42039
5	>40 kg/capita	48.38731	43.20239
6	>45 kg/capita	58.20184	49.64883
7	>50 kg/capita	72.22101	68.35514

*Note each inclusion criteria only accepts values specified and assumes any values outside of that criteria are outliers. Per capita and person are used interchangeably.

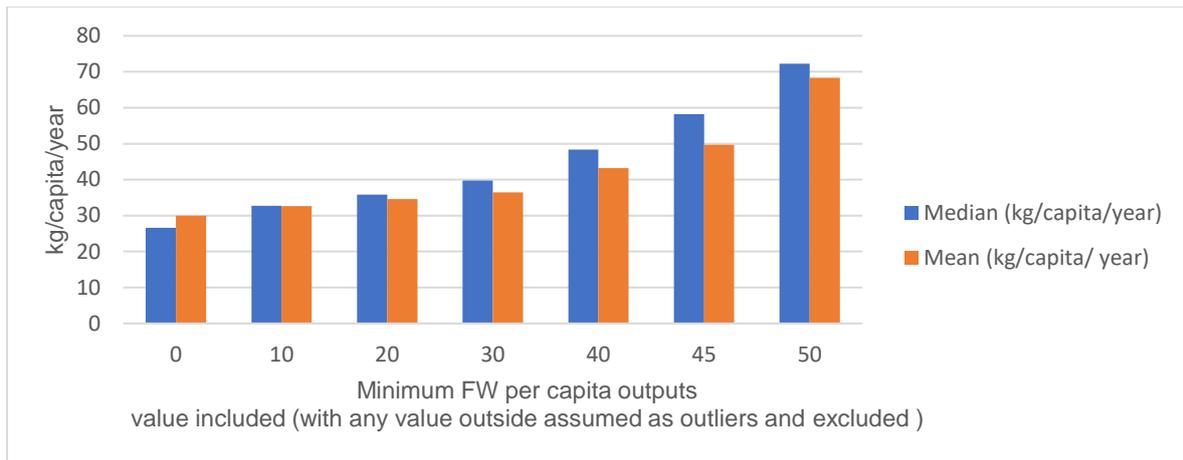


Figure 105. Mean and Median household food waste output per capita values based on inclusion criteria (via removal of assumed outliers datasets for each criteria) (Gov.uk, 2022b).

These results outlines a median value range of 26.67 to 72.22 kg/person/year and mean value range of 29.96 to 68.36 kg/person/year. This includes the interim ranges of 33, 36, 40, 48 and 58 (median values) and 33, 35, 36, 43 and 50 (mean values) respectively.

This somewhat large range in mean and median values of per capita FW collection is likely to be reflective of the overall real-world barriers, which each LA faces towards implementing their own FW collection trials, such as household participating and waste output, collection efficiency, etc.

Whilst it is beyond the scope of this study to explain for such discrepancies in FW collection quantity between LA, a general comparison of the WDF data findings outlines here with that of WRAP findings outlined in the section 5.2.3 would provide some insight on the discrepancies between a real-world and dedicated collection trial (see section 5.2.4).

5.2.2.3 Dedicated household food waste collection data for Rothwell region only (for 2010-2020)

Using the same WDF datasets across NPH region focusing on collection of household FW only, Leeds was found to be the only region with a consistent longstanding dedicated household food waste collection trial scheme at the local level at Rothwell since 2010.

Although not publicly noted, the Rothwell FW collection trial is likely created by Leeds LA with the intention to establish data and insight to determine the feasibility and likely cost-benefit trade-off of implementing city wide FW collection trial at Leeds.

The data spans for a period of a decade from 2010 to 2020, and captures FW per person output and total FW output against number of participating households and individuals at Rothwell region (see Table 87 below).

Table 87. Leeds city food waste collection data at the Rothwell food waste collection trial region between 2010 and 2020 recorded by waste data flow

All data combined	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-2018	2018-19	2019-20
Food waste per person output (kg/year)	48.59	45.2	39.76	43.79	39.91	43.11	47.84	37.88	38.23	23.26
Total FW output (tonnes)	1007	939	819	1328	1217	1327	1487	1189	1205	736
No. of participating Households	20725	20768	20605	30321	30499	30768	31078	31386	31511	31609
No. of participating individuals	8455	8454	8454	12326	12336	12365	12366	12366	12366	12336

*Food waste per capita data calculated by dividing total annual food waste production by number of participating individuals

Here the results exhibit an annual per capita food waste collection of between 23.26 and 48.59 kg/person/year between 2010 and 2020 (Figure 106). A visual trend analysis demonstrating there to be a gradual decline in per capita food waste collected since 2010, with the decline being most notable in 2019-20.

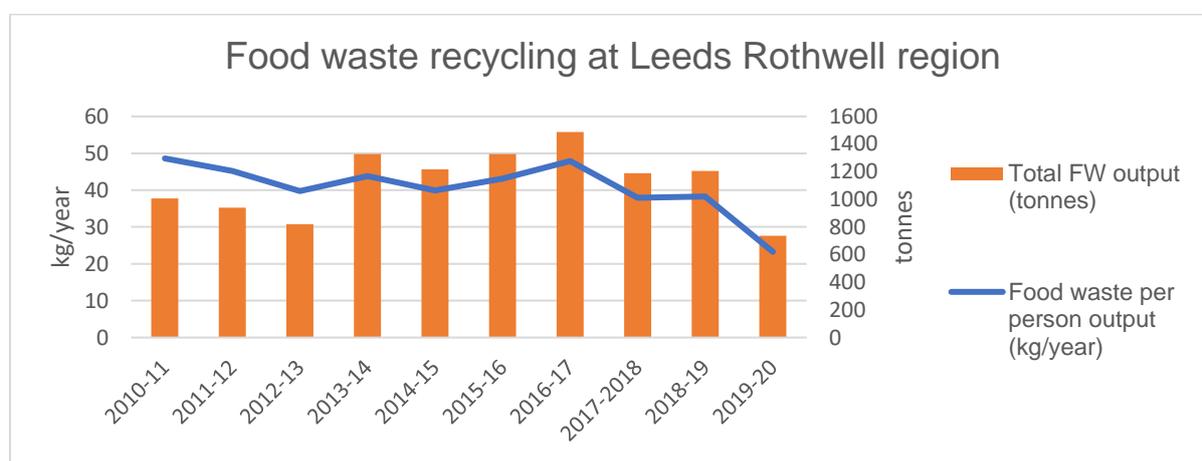


Figure 106. Graph illustrating trends in per capital food waste collected at Rothwell region (of Leeds city) between 2010 and 2020 as recorded by waste data flow

A mean, median and interquartile analysis is further conducted and returned a general per capita annual food waste collection value of 40, 41.51 and 38.61/41.51/44.85 (for first/second/third quartile) kg/person/year, respectively (see Table 88).

Table 88. Alternative analysis of Leeds city council Rothwell food waste collection trial data using 2 data criteria

Analysis criteria	All data inclusion (kg/person/year)	Exclude 2019-20 results (assumed to be outlier) (kg/person/year)
1 Mean	40.76	42.70
2 Median	41.51	42.70
3 Max	48.59	48.59
4 Min	23.26	37.88
5 Range	25.33	10.71
6 First Quartile	38.61	39.76
7 Second Quartile	41.51	43.11
8 Third quartile	44.85	45.20

These single FW collection values is further supplemented by the use of 3 separate regression trendlines (RT) calculated using Excel's inbuilt chart regression trendline function to establish the potential medium and long term trend in declining FW collection in Rothwell overtime. These includes trendlines, relative to WDF Rothwell data as shown above, that accounts for (i) all data (RT1), (ii) all but 2019-20 data (RT2) and (iii) all but 2016-17 and 2019-20 data (RT3). The latter two trendline scenarios is established on the assumption that the relevant data excluded (2016-17 for RT2, both 2016 and 2019-20 for RT3) are irrelevant outliers.

For RT2, reasonable assumptions applied include FW collection being much reduced in comparison to normal by unforeseen impact of COVID-19 lockdowns (i.e., societal, policy, economic and combination thereof) (Figure 108). For RT3, this reasonable assumption extends further to eliminating outliers that significantly deviates from the observed general decline in FW collection between 2010 and 2020 (see Figure 109).

The results returned indicates that the latter regression trendline (for iii) is considered to be the most suitable for use due to it possessing the highest R values (of >0.60) of the 3 respective scenarios (see Figure 107, Figure 108 and Figure 109, respectively).

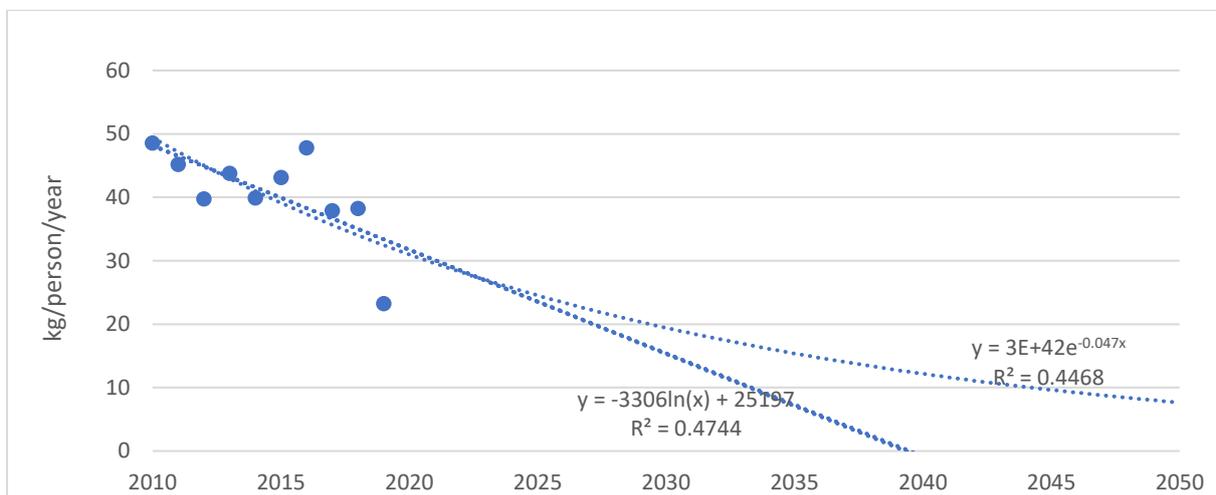


Figure 107. Food waste collected per person output in Rothwell with regression trendline (RT1, Include all waste data flow data)

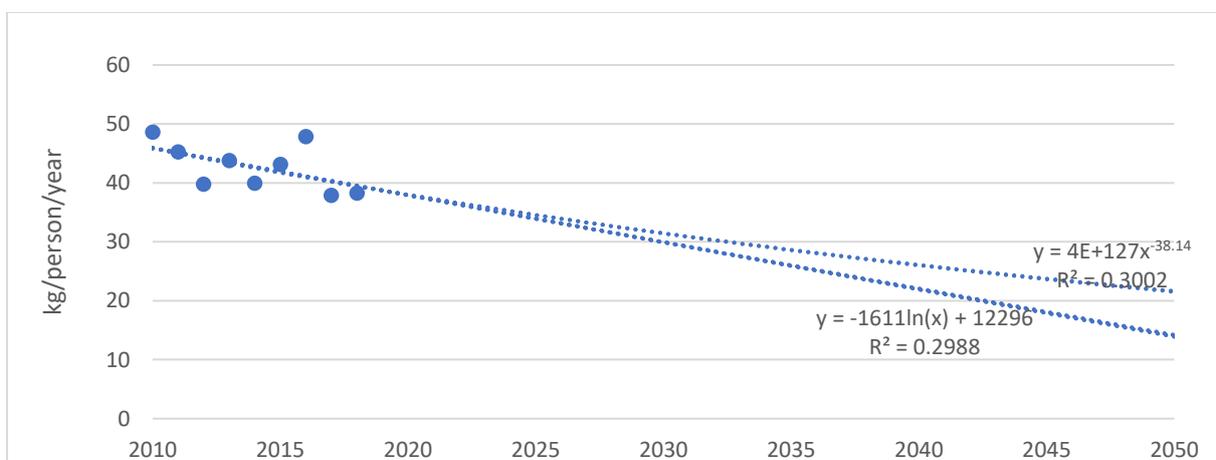


Figure 108. Food waste collected per person output in Rothwell with regression trendline (RT2, exclude 2019 waste data flow data)

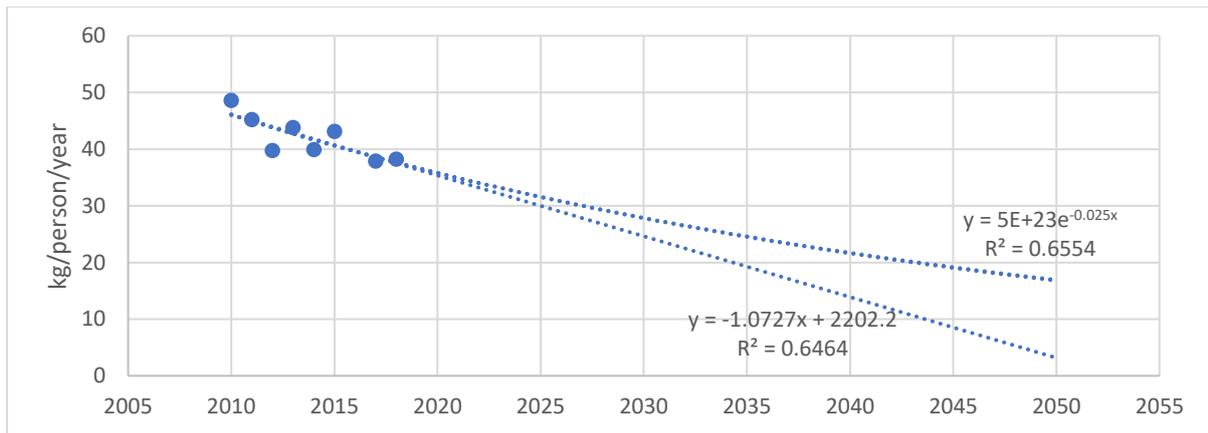


Figure 109. Food waste collected per person output in Rothwell with regression trendline (RT3, exclude 2016 and 2019 waste data flow data), represent most suitable regression trendline given R values being over 0.50

A comparison of three trendlines shows R^2 values of 0.4744, 0.2988 and 0.6464 for linear regression and R^2 values of 0.4468, 0.3002 and 0.6554 for exponential regression for RT1, RT2 and RT3, respectively.

The R^2 are further accompanied by respective chart equations that shows to be $y = 3306\ln(x)+25197$, $y = -1611\ln(x)+12296$ and $y = -1.0727x+2202.2$ for linear regression and $y = 3E+42e^{-0.047x}$, $y = 4E+127x^{-38.14}$ and $y = 5E+23e^{-0.025x}$ for exponential regression for RT1, RT2 and RT3, respectively.

Here one key inference would be that whilst all trendlines exhibit a R^2 value of less than 0.90 ($R < 0.90$) which is typically used to demonstrate strong correlation, R^2 value of RT3 (both linear and exponential) do constitute a moderately strong correlation deemed to be acceptable for use for inferring future trends in declining FW collection (until further data becomes available) given the lack of existing datapoints present.

Although there is room for some debate, the initial confluence of data suggests exponential regression trendline is likely to be more representative of the reduction in real-world FW collection trends. This is attributed to (i) the observed greater R^2 values for exponential trendlines in RT2 and RT3 in which the major anomaly data point of 2019-20 (attributed to COVID-19) was removed, and (ii) the inferred nature of real-world decays in most instances being almost always exponential in their decline. Consequently, RT3 exponential regression trendline is chosen to be the most accurate regression line on the above basis, and possesses a half-life of approximately 30 years. A summary relevant data and assumption outlined above leading to the choice of this most likely future household FW collection trend scenario at Rothwell is outlined in Table 89 below.

Table 89. Rothwell FW collection regression line summary of R² values, equation and assumptions

Trendline number	Linear regression		Exponential regression		Assumption	
	Data exclusion	R ² values	Equation	R ² values		Equation
RT1	None	0.4744	$y = 3306\ln(x) + 25197$	0.4468	$y = 3E+42e^{-0.047x}$	All data are representative
RT2	2019-20	0.2988	$y = -1611\ln(x) + 12296$	0.3002	$y = 4E+127x^{-38.14}$	2019-20 data excluded due to Impact of COVID-19
RT3	2016-17 & 2019-20	0.6464	$y = -1.0727x + 202.2$	0.6554	$y = 5E+23e^{-0.025x}$	2019-20 data excluded due to Impact of COVID-19 and 2016-17 data appear to be surprisingly high in context of downtrend in FW collection

With the most likely scenario established for projecting Rothwell household FW collection until 2050, a key inference here would be to assume the forthcoming 40-year projections are by no means certain, but a moving trajectory determined largely by combined effects arising from key drivers of household FW collection.

By understanding the relative contribution and impact of these key drivers, the UK government could consequently establish a set of policy and regulatory guidelines to meet or alter the predicted household FW collection (exponential regression) trend for RT3. Elaboration on both these drivers and corresponding supporting policy are outlined below alongside their potential impact on affecting household FW collection trajectory using WDF Rothwell trajectory data as a default or target baseline.

Here the observed downward trend of household FW collection is likely affected by the confluence of real-world variables affecting FW supply and overall FW collection efficiency. These include likely changes to a non-exhaust list of factors including but certainly not limited to (i) household trial participation rate, (ii) individual buying and eating behaviour affecting total FW output, (iii) wider economic conditions affecting such behaviour (either through financial, supply chain or psychological effects), (iv) operational logistics that affects FW collection efficiency and (v) data input protocols (see Figure 110).

During engagements with Leeds city council it was conveyed that the Rothwell FW collection trial operations and data input protocol had been improved since initial implementation in 2010, though there were no concrete explanation given for other drivers (either operational, social or other) behind the general decline in FW collection at Rothwell region. It was also known for most UK local city councils including Leeds LA to operate on significantly reduced budget (due to consistent central government funding cuts since 2010) which may also contribute significantly to the operational logistics and capture efficiency of FW collection. A main indicator of this would be changes to less frequent collection of general wastes across Leeds city, although it was not established whether this is the same for household FW across Rothwell.

Other aforementioned potential social drivers of the Rothwell household FW collection data trend including household participation and individual eating or buying behaviour were not investigated further directly with Leeds LA as it was deemed to be beyond the scope of this research and would likely detract the researcher from focusing on the main aims and objectives. There however does appear to be indirect indications of the impact of UK's

worsening economy attributed to the Brexit decision in 2016, which may have led to social and behavioural changes (i.e., less FW production and participation at the household level) that contributed to the incremental reduction in FW available for collection in the years ensuing 2016.

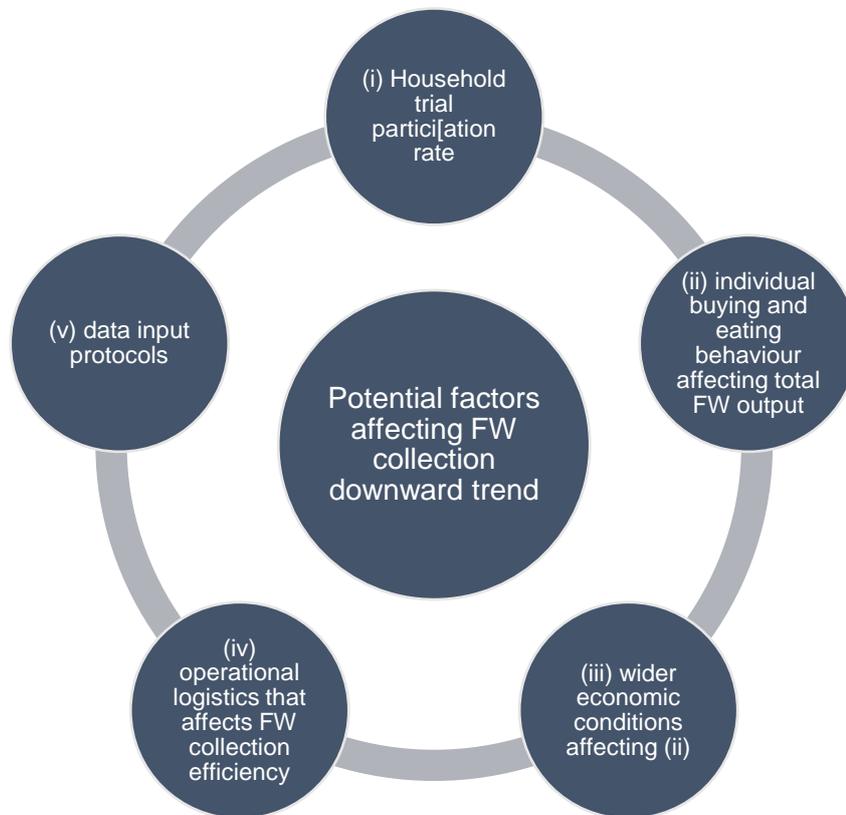


Figure 110. Overview of potential factors affecting observed downward trend of household FW collection at Rothwell region

Table 90. Potential factors affecting Rothwell household FW collection, and their potential impact on collection results between 2010-20

Factor type	Description	Inferred evidence (strong, moderate or weak evidence)
Administrative and Strategic	FW collection trial implementation and data collection	Strong: Initial implementation and administrative data input of results gradually optimized over time, according to Leeds LA
Logistical	FW capture efficiency	Moderate: Likely reduced to due indirect evidence of Leeds LA funding cuts leading to more infrequent collection of FW and other wastes
Social and behavioural	Household participation rate	Weak: Same or reduced participation rate to be likely given extensive length of trial and lack of incentives for household FW recycling other than it being a common duty
	Individual behaviour – buying and eating	Weak: Likely noticeable reduction in FW production and sorting at household level due to worsening economy (see below)
Economic	Wider economic conditions affecting behavioural factors above	Weak: Effects of Brexit and gradual economic decline may have led to reduced FW available for collection through reduced FW production or sorting at household level

This could however form a relevant and solid basis for a comprehensive, standalone future research project for establishing critical findings that could help further optimize and expand household FW collection trial to city level and beyond across Leeds and other regions.

These findings evidently point to the likely effect of specific social and economic policies tailored towards finding a balanced approach towards maximising collection of available household FW whilst simultaneously promoting FW reduction to enable the UK to move towards a zero food waste to landfill economy by 2030 (Gov.uk, 2018). Such policies would however need to simultaneously tackle FW reduction and collection trial participation at the individual and household level and support FW collection at the local authority level, by means of specific target driven incentives. A good framework applicable to this scenario would be the specific, measurable, achievable, relevant and time-bound (SMART) framework, that would enable any supporting policy and their intended goals or outcomes to be SMART.

A few examples of appropriate and relevant policy that will likely achieve this include those that offer attractive incentives for both households and LA to recycle FW, though this may prove to be a difficult challenge given the inevitable reality of increasing tight budget constraints which Leeds (and most other UK) LA faces due to the lack of available central government funding supports. This consequently leads to the logical conclusion that any effective policy must ultimately enable the FW recycling process itself to be financially self-sufficient, to enable long-term continuation of relevant recycling schemes (i.e., the Rothwell household FW collection trial) by attracting additional non-government or private investments. Central to this financial self-sufficiency would involve costs against returns associated with FW recycling, where sales of FW derived biomethane, digestate and landfill tax avoided must exceed the total cost of FW collection trial implementation.

This feeds back to the aforementioned effect of Chicken and Egg Conundrum (CAEC) or Lock-In Effect (LIE) alluded in the literature review which typically underpins the success or failure of projects under conditions by which additional funding is limited or not available as with the case for household FW condition under current macro-economic conditions (see section 1.2.8 or Figure 7).

In light of the general direction of these policies is clear, a few specific example policy recommendations is outlined in Table 91 below to illustrate the approach which the UK government can adopt to ensure implementation of a financially self-sustainable FW collection scheme in a manner that minimizes FW output whilst maximising FW capture rate.

Here it is critical to emphasise that this list of policy recommendations are by no means exhaustive and can be further expanded to address the changing aims and objectives of the UK central and local governments on tackling FW collection and recycling. The confluence of the 4 policy recommendations however would serve as an adequate starting point to (i) improve FW collection operations, (ii) promote greater stakeholder engagement and participation, (iii) identify key strategies for reducing general household FW production, and (iv) offer suitable incentives in promoting assessment, planning and deployment of FW recycling strategies that are financially more self-sufficient through multi-stakeholder collaboration.

Table 91. Supporting policies for FW collection trial at Rothwell region under Leeds LA jurisdiction

	Perceived barrier	General Policy focus
1	Operational inefficiency of FW collection due to lack of funding and investment	Offer funding support either in form of conditional investment or loan to Leeds LA to promote more efficient implementation of FW collection trial to ensure
2	Lack of networking to pave way for potential future collaboration, establish a sense of general solidarity in FW collection	Promote greater networking opportunities between the private sector, Leeds LA and participating households at Rothwell to bridge relations and possible future collaboration between all parties, i.e. via private sector investment and involvement in the FW recycling process
3	Increase household FW participation & capture rate, and establish more data at the household level on effective FW reduction strategies	Offer incentives for household to participate in FW collection, and bonus rewards for those partaking in a more in depth trial whereby they are actively involved in efforts or strategies leading to reduced household FW production and with all activities documented for assessment
4	Incentivise FW recycling in a financially viable manner (through combined effects of above 1-3 supporting policies)	Offer reports on the financial returns to both Leeds LA, Rothwell households and any participating private entities current costs vs. expenditure of FW recycling schemes, and where a financial return of such schemes is attained, equitably distribute a portion of the revenues to all parties involved

The selected exponential regression trendline of RT3 (see Figure 109 and Table 89) should consequently also act as a default or reference trendline which reflects these 2 key objectives underpinned by the SMART framework, as the same trendline can also be achieved through alternative less desirable scenarios involving general trend in increasing household FW production coupled with (to a greater relative degree) worsening FW capture rate, i.e. arising from operational inefficiencies or lack of household participation. In light of this, it is however not suitable to rule out the other established regression trendline scenario (RT1, RT2 and RT3, linear or exponential) on FW collection, as their R^2 values may likely change with input of future available data.

To this end, it would be useful for Leeds LA and other LAs to implement additional metrics that proactively measure FW capture rate and estimated FW to landfill quantities to supplement the WDF FW collection data illustrated above to establish a more accurate picture of actual quantity FW not captured for anaerobic digestion and landfilled or disposed of in other less sustainable manners. Across the broader spectrum of waste recycling and other recycling, the aim would involve conditional application of abovementioned policies and strategy for the reduction of other waste types involving multi-stakeholder collaboration (i.e. Leeds LA, Rothwell household and any potential private collaborators under the current household FW collection trial at Rothwell) to help the UK government in meeting its landfill obsolescence target by 2050 as part of its clean growth strategy (Resource.co, 2017).

Below outlines 5 yearly interval data arising from the extrapolation of the selected regression trendline data with the highest R^2 value (RT3, exponential regression curve), though here it is critical to emphasise again that given the limited dataset provided (2010-2020, 8 data points), such extrapolations are likely to be much more accurate for the short to medium term (2025, possibly 2030) over longer term periods beyond 2035 (Table 92). This projection will consequently need to be subjected to continuing updates with input of new data in the foreseeable (i.e. extending into 2021-2030 and so on), and serves as the best estimation at the current point in time, as opposed to being assumed to be universally accurate. Again, key

success to this as elaborated above should be attributed more to an actual increase in FW capture and reduction in landfill of FW rather than reduction or increase in FW collection.

Table 92. Future anticipated food waste collection based on Leeds Rothwell FW collection data from Waste Data Flow (WDF) database using selected 'best fit' regression graph equations.

Type	2010	2015	2020	2025	2030	2035	2040	2045	2050
Exponential	46	40	35	32	28	25	22	19.5	17
Linear	46	40	35	31	25	19	15	9	4

5.2.3 Per capita FW collection data - WRAP food waste collection trial data

The above data findings on per capita food waste collected from real-world collection trials is further supplemented by WRAP's own FW collection trial data, which shows a significantly higher original value range of 66.50-90.90 kg/person/year between 2007 and 2018 as outlined in Table 93 below. Here it is assumed that the region where such WRAP FW collection trials occurred would be a mix of different LAs which willingly participated in their own dedicated household FW collection trial, this discrepancy could be potentially attributed to more ideal conditions surrounding the trial implementation with some levels of supporting measures and policies in place i.e. where household participation, FW output and capture rate is high. This by no means discredits the WDF data at Rothwell region, but rather adds another important dimensions to the current and future research on discerning the underlying reasons that led to much greater WRAP (compared to WDF) FW collection data.

Table 93. Table of data showing estimated annual household Food waste collected per capita in UK (kg/person/year) between 2006 and 2018 WRAP compiled research data (WRAP, 2018)

Year	Food waste in kerbside residual	Food waste in kerbside collections targeting food waste	Total food waste (kerbside residual plus collections targeting food waste)	95% confidence interval
2007	89.50	1.40	90.90	±3.7
2008	N/A	N/A	N/A	N/A
2009	N/A	N/A	N/A	N/A
2010	68.90	4.70	73.50	±2.3
2011	N/A	N/A	N/A	N/A
2012	63.40	8.40	71.90	±2.7
2013	N/A	N/A	N/A	N/A
2014	65.00	9.30	74.30	±2.3
2015	63.20	9.80	73.10	±1.9
2016	N/A	N/A	N/A	N/A
2017	60.20	11.30	71.50	±1.5
2018	54.80	11.70	66.50	±3.9

ND represents no data, N/A represents not applicable. Colour coding: Green represent original data values obtained from WRAP, yellow represents estimated values in the missing years using 2nd order averages based on original values

Interestingly, WRAP's household FW collection data also illustrates similar trends in gradual decline of per capita annual kerbside household food waste collection year-on-year, coupled with general increase in collected of dedicated kerbside food waste bins (see Figure 111). The latter observation is likely attributed to increasing deployment of dedicated food waste collection trials and schemes by local authorities to ensure good waste separation for post-collection processing.

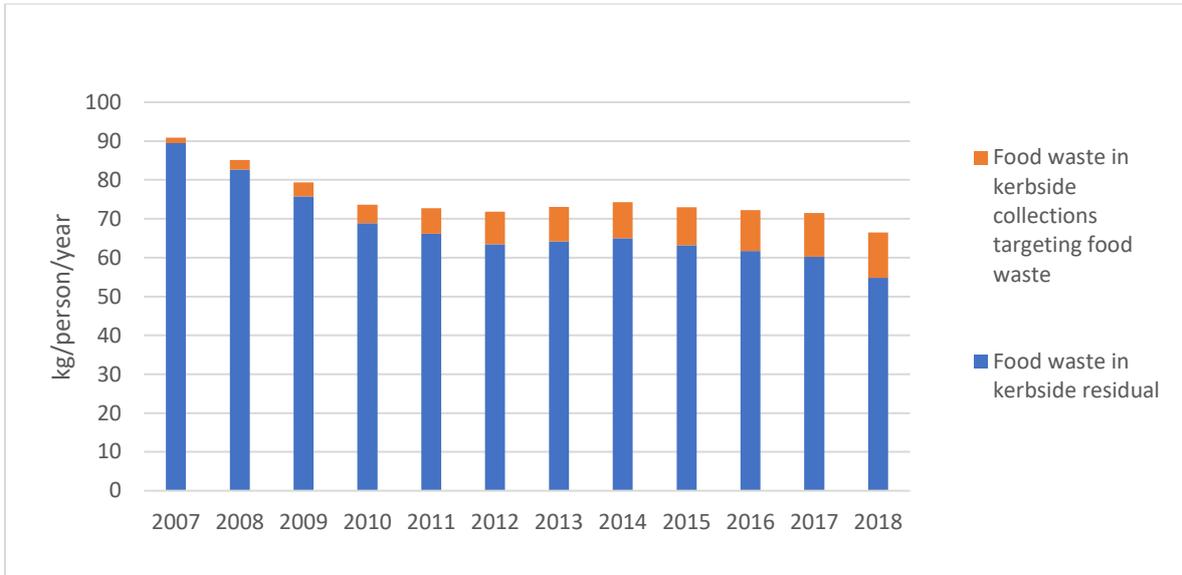


Figure 111. Hybrid graph showing estimated annual household Food waste collected per capita in UK (kg/person/year) for each year and general trend in findings values across 2007 and 2018 WRAP compiled research data (WRAP, 2018)

Regression trendline analysis of WRAP data to determine future likely projected short to long term future food waste collection values established 2 best fit curves with suitable R-values of >0.8.

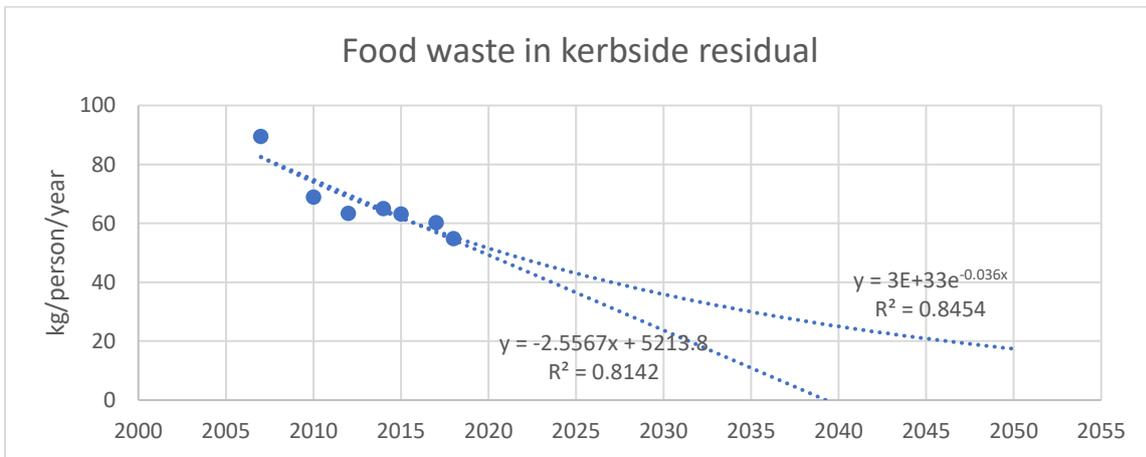


Figure 112. WRAP food waste collection trial regression curve analysis with equation and R values

This regression trendline interestingly exhibit the same coincidental exponential decay pattern compared with the WDF RT2 and RT3 exponential regression curve (see Table 89 for relevant exclusion of data point outliers), albeit with a higher starting FW collection value in 2007, before reaching similar FW collection values of approximately 20 kg/person/year. Interestingly, the higher R value for the WRAP data suggests there to be a stronger correlation between all data points, and thus with derived projections deemed to be more reliable than that from WDF data.

Here comparison of the two results suggests that WRAP may a deliver more consistent performance in terms of FW collection trial deployment, with precise reason for these discrepancies to be not 100% clear. This may in part be attributed to the implementation of FW collection trials and schemes across greater numbers of UK LA regions where changes to various elements affecting FW collection are more consistent as a whole than when compared

to that of a single region at Rothwell (i.e., economic, policy or social factors or combination thereof).

Here again it is critical to note that the WRAP results in exhibiting consistent decline in annual FW collection should be subjected further investigation (alongside WDF results) to establish with greater accuracy the changing annual trade-off in financial cost-benefits of deploying FWtTBC pathway across both regions, in addition to accompanying underlying FW diverted from landfill during this period (as an additional critical metric, as mentioned above).

5.2.4 Per capita FW collection data - WDF and WRAP FW collection data summary

The findings between WDF and WRAP data draws a number of parallels and differences in the trend of household FW collection over the past decade (2010-2020). A key similarity observed to reiterate includes a general and steady decline in the FW collection during this period, with extrapolations coincidentally leads to a convergence in the estimated FW collection of 20 kg/person/year in 2050 quantity for the most likely trendline scenarios (with greatest R² values).

Where notable discrepancy lie however, would be in the quantity of FW collected by WDF at LA Rothwell region and by WRAP selected regions, with WRAP showing a greater quantity in initial FW collection coupled with a greater year on year decline in FW collected in these same regions compared to WDF data (thus resulting in the convergence of FW collected in 2050).

These discrepancies may also be attributed to the difference in the level of support offered to the implementation of FW collection, as it would be assumed the WRAP trials would have brought forward greater levels of dedicated expertise and support compared to the standalone FW collection trials of local authorities (LA) such as those occurring in Rothwell by Leeds LA. Although beyond the scope of this research, this can be further verified through a deeper understanding of the resources (i.e., networks, financing) and strategies utilized towards the respective implementation of WRAP and WDF Rothwell FW collection trials.

In context of the above, it is generally agreed that the proposed government policy support outlined in the WDF findings section would be applicable universally to enable more efficient FW collection in a manner that simultaneously reduce available FW production (thus available for collection) overtime and general FW landfilled (see Table 91).

A summary of all FW collection data from both the WDF and WRAP collection schemes is shown below to establish most suitable values for use in combination with the Office for National Statistics (ONS) population data to estimate total food waste output for each of NPH region over the scenario specified time period of 2020-2050.

These include determining most suitable single-time point and time-adjusted FW collection data estimations to represent total quantity of FW available at the upper to lower extreme end and also over a specified period of decay (as the above trendline shows) respectively for Excel modelling (see Table 94).

Table 94. Comparison of household food waste collection data from real world dedicated collection trials from different sources and methods of analysis

Source	Data description	Abbreviation	Value range for food waste collected (kg/person/year)	
1	Waste Data Flow (WDF)	All local authority regions original (2020-21)	All LA (2020-21)	0.13-98.29
		All local authority regions Mean with inclusion criteria (2020-21)	All LA Mean with IC (2020-21)	26.57-72.22
		All local authority regions Median with inclusion criteria (2020-21)	All LA Median with IC (2020-21)	29.96-68.36
		Leeds city council operated Rothwell region only (2010-2020)	LCC Rothwell only (2010-2020)	23.26-48.59
2	WRAP	Dedicated combined collection trials (2010-2020)	WRAP all FWC trials	66.50-90.90

Figure 113 below further outlines the upper and lower boundary of FW collection arising from each dataset, which presents the great range (between upper and lower boundary) for results returned from the WDF dataset. Notably these includes all LA without accounting for any inclusion criteria whereby the relevant outliers are removed, followed by data from all LA that accounts for median and mean inclusion criteria.

This leaves WDF data for FW collection at LA Rothwell region and WRAP data findings to have the smallest range between the upper and lower data findings, demonstrating greater consistency of these two findings. Here however it is not known whether if the final WRAP data already accounted for the removal of relevant outliers prior to publication of their data, which is already in presentable format as opposed to the raw data arising from the WDF dataset which could have led to a smaller range in the observed results. Although beyond the scope of this research, for standardisation it would be important to take account of this potential discrepancy before further commenting further.

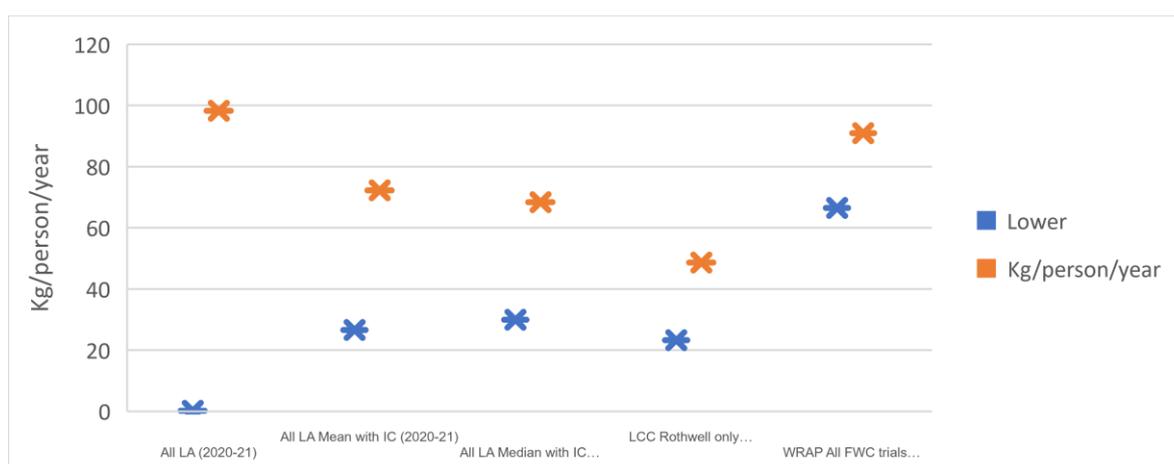


Figure 113. Graph illustrating potential value range for food waste collection from dedicated household FW collection trials. Space in between lower and upper dot under each field represent the range of potential food waste collected under each scenario.

All output FW collection data findings have been subsequently accessed to determine both single time point and time adjusted FW collection data trends.

5.2.4.1 Single time point food waste collection data

For single time point food waste collection data, 20, 40 and 100 kg/person/year are selected for excel modelling, based on summarized findings outlined in Table 95 to demonstrate large variations in in potential per capita household food waste that can be collected from dedicated trials. This is likely to be attributable to a combination of factors such as geographical region which may affect public participation level and acceptance to FW collection trials, in addition to strategy, funding alongside networking or other policy support surrounding collection trial design and deployment.

These values of 20, 40 and 100 kg/person/year respectively represent (i) minimum acceptable average values (WDF, 2019-2020), (ii) Leeds city Rothwell values (WDF, 2010-2020) and (iii) maximum demonstrated values (WDF, Maldon District, 2019-2020) of food waste collection derived from the real-world datasets, as outlined in Table 95 below.

Table 95. Real-world representative capita food waste collection values (kg/person/year) used in FWtTBC pathway deployment

	Food waste collection output level	Dedicated household food waste collection values (kg/person/year)	% Compared to baseline very low scenario
1	Minimum acceptable (based on trial data used)	20	100%
2	Leeds City Rothwell	40	200%
3	Maximum achievable (based on trial data used)	100	500%

These findings also point to the huge discrepancy in the FW collected between the highest to lowest output regions. Although beyond the scope of this research, it is also worth mentioning that in accounting for such differences, different operational strategies, costs and revenues will likely to be involved across different regions in which relevant quantity of FW collection is to occur.

5.2.4.2 Time-adjusted food waste collection data

For time adjust food waste collection data, exponential regression trendlines from both WRAP and Waste Data Flow data for Rothwell region is used for aforementioned reasons of their values to be most representative for estimating future food waste collection outputs, with respective 5 year interval values summarized in Table 96 below.

Table 96. Comparison of Time-adjusted values in food waste collection data from WRAP and WDF collection trials (5 year intervals)

Scenario	2010	2015	2020	2025	2030	2035	2040	2045	2050
WDF (Leeds Rothwell)	46	40	35	32	28	25	22	19.5	17
WRAP (All trial regions)	73	60	52	42	35	30	25	21	18

A graphical illustration of these values shows clearly highlights the convergence of annual household FW collection data between both WRAP and WDF regression trendlines in 2050, with WRAP exhibiting much greater FW collection value in 2020 but also greater rate of year on year declines than WDF FW collection trends (see Figure 114). Here it is important to re-iterate that this convergence is largely coincidental thus demonstrating good agreement between both findings at least in the longer term.

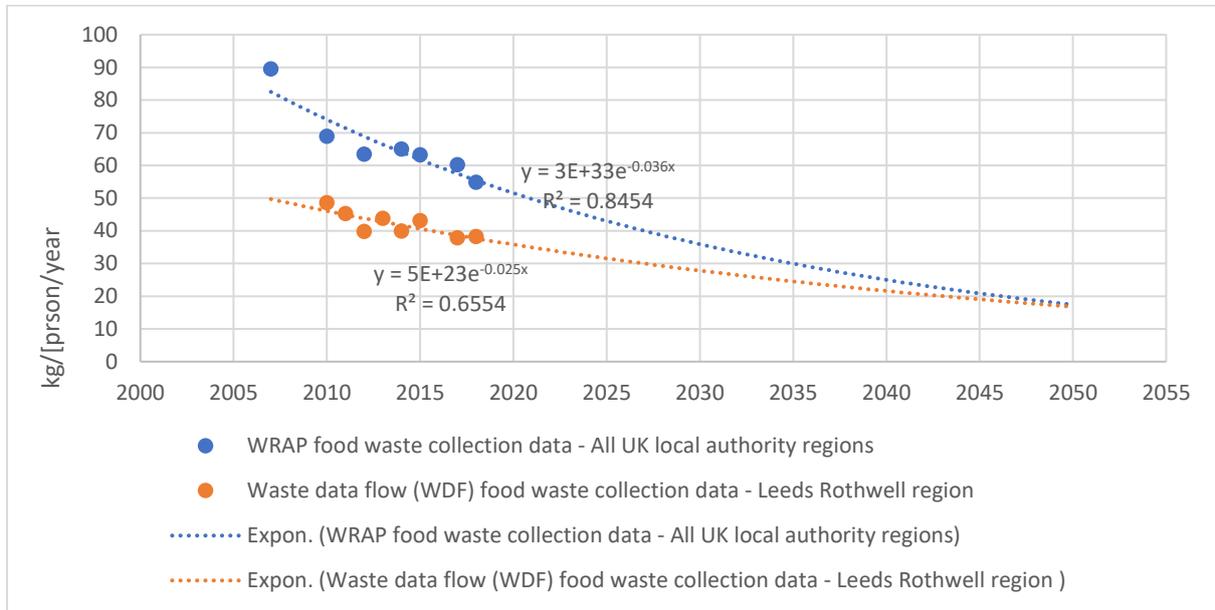


Figure 114. Comparison of Food waste collection data from WRAP collection trials (All UK Local Authority regions) and Waste Data Flow (WDF) data (Leeds Rothwell region).

Both findings nonetheless spell potentially significant negative implications for FWtTBC pathway deployment from a material and energy transfer standpoint give the sharp rate of decline, as such pathways are typically deployed under strong medium to long term confidence of it being both scalable and profitable. This brings to light an additional need of greater bridging support, i.e. financial or other, from the UK government to assist relevant LA regions towards downsizing FW collection operations in line with anticipated reduced FW output, to help promoting more LA to participate in FW collection schemes with greater confidence and certainty of the higher relative benefits against costs they are to incur.

Here it is also critical to re-iterate how the design of such policy must also be tailored to ensure the FW collection trials is financially self-sustainable or profitable in the short to medium term to buffer against the potential losses that are more likely to incur in the longer term as household FW collection decreases. This consideration however omits the collection of other sources of FW, i.e. from commercial outlets such as restaurants and supermarkets which could utilize the established infrastructure for household FW collection, and would remain to be an open possibly when factoring additional real world adjustments that lies beyond the scope of this research.

A few target-oriented examples of specific policy support is outlined in Table 97 below.

Table 97. Specific policy support towards helping UK Local Authorities (LA) to downsize their FW collection trial in line with anticipated reduction in FW collection quantities for the foreseeable future to 2050

	Policy focus	Specific policy description	Intended outcome
1	Data driven incentive	Provide incentive to LA demonstrating accurate and efficient collection of FW output data	Improve data collection and insight
2	Incentive on FW collection optimization	Provide incentive to LA demonstrating high optimized FW collection trial, including high household participation and high FW capture rates	Improve FW collection operation
3	Incentive on FW reduction	Provide incentive to LA demonstrating a clear decline in household FW produced and FW landfilled locally through established initiatives, as reflected in reduced FW collection	Improve FW reduction schemes & initiatives

These three policies focus would largely be to incentivise improvement in (i) the collection of key data and insight, (ii) FW collection and household participation, and (iii) reduced household FW output or landfilled for each LA as a result of continuing improvements to the overall FW collection trial deployment. To this end, it is highly likely that such incentives will include a mix of financial (loan and investment) and non-financial support instruments to participating LA of FW collection trials and schemes.

5.2.4.3 Summary of application of collected FW data (fixed vs. variable)

Moving forward, both fixed and variable scenarios outlined above will be assessed to equal degrees of complexity to establish output differences in the event where current food waste collection reduction trends continue or remain stationary at the chosen values.

These findings on single point or time-adjusted per capita household food waste collection data values will subsequently be combined with ONS population data (see next section) for estimating total food waste collection potential within each NPH region across all scenario specified timeframes of 2010-2041 or 2010-2050 (to the extent where data is available), from which technical estimations of total energy (biogas and biomethane), revenue and emission reduction potential (see Chapter 5.2.3) can subsequently be made for each FWtTBC pathway deployment scenario.

5.2.5 Population data – by ONS for all Northern Powerhouse (NPH) regions

This section presents ONS population data covering all Northern Powerhouse (NPH) city regions (see Figure 116) and metropolitan county regions (see Figure 117) of Leeds, Manchester, Liverpool, Sheffield, Hull and Newcastle (as re-iterated in Figure 115) for the scenario specified time periods of 2010-2050 (see Chapter 4.2.4, Methodology 1 for details).

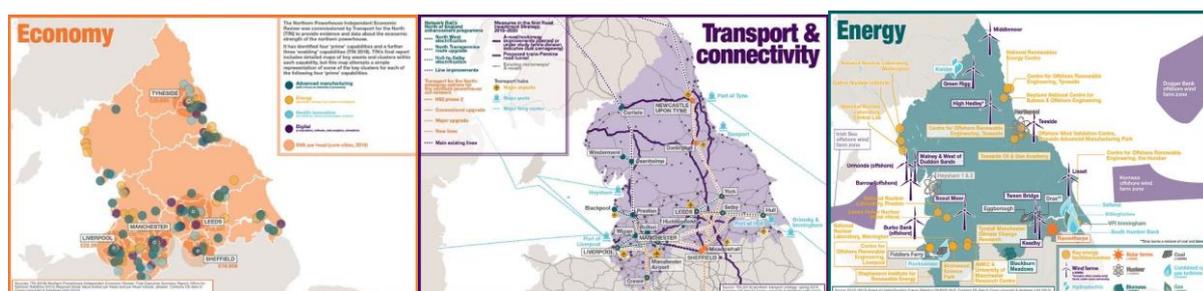


Figure 115. Northern Powerhouse cross-industry focus on key HiTECH developmental industries (left), Transport industry development of Northern Power House (middle) and renewable energy development sector (right) (IPPR, 2016), original diagram depiction in Figure 82

To this end, National Population Projections of 2018 based data was used as the most recently available data collected during time of research, covering population estimations to 2041 (ONS, 2018). Here regression trendline is used to further extrapolate ONS' own extrapolated population data for up to 2050, which is not ideal however is deemed sufficient on basis of the high resulting R values (>0.95).

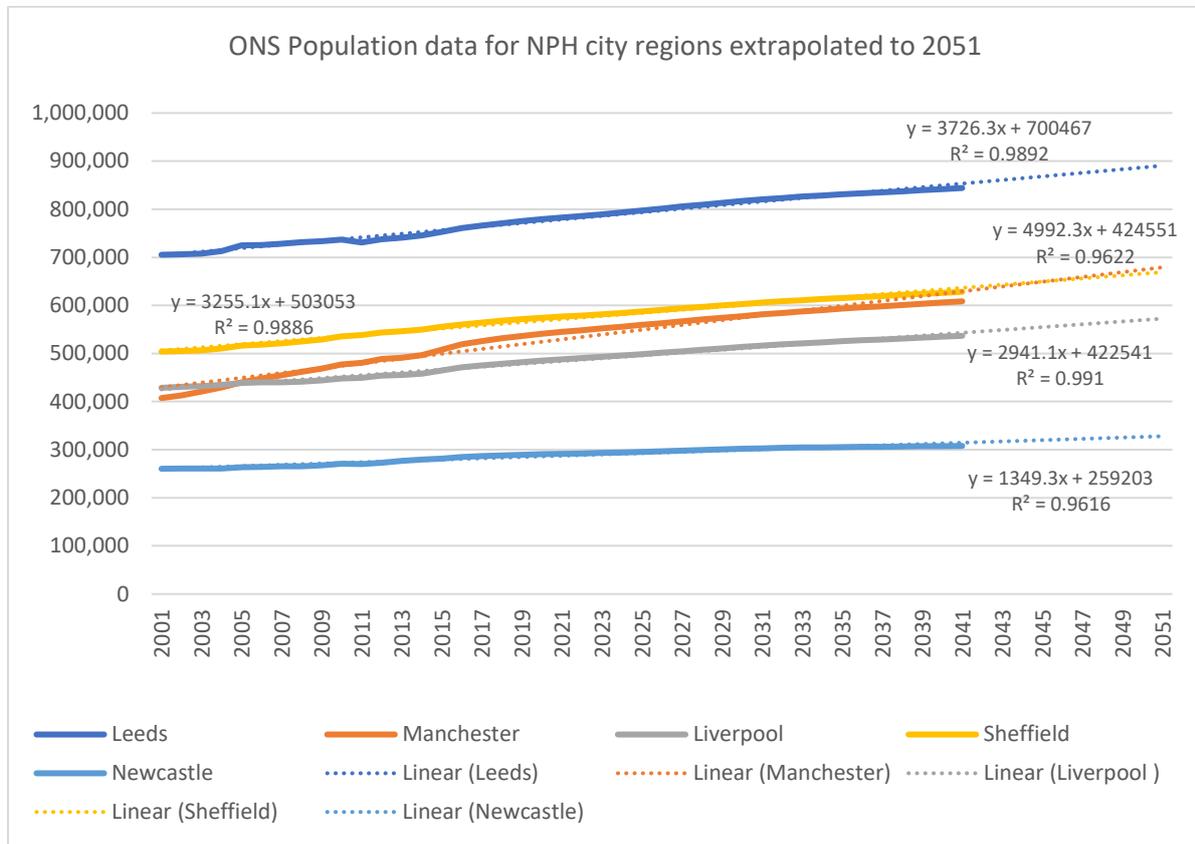


Figure 116. Time adjusted population data at Northern Powerhouse (NPH) city region level based on ONS data records and ONS estimations (2001-2041), extrapolated further to 2050, note all dotted linear lines represents extrapolation results of original ONS data up to 2050 which is necessary for later calculations of estimated FW collection until 2050, and are accompanied by respective equation and R² values (2001-2041) (ONS, 2018)

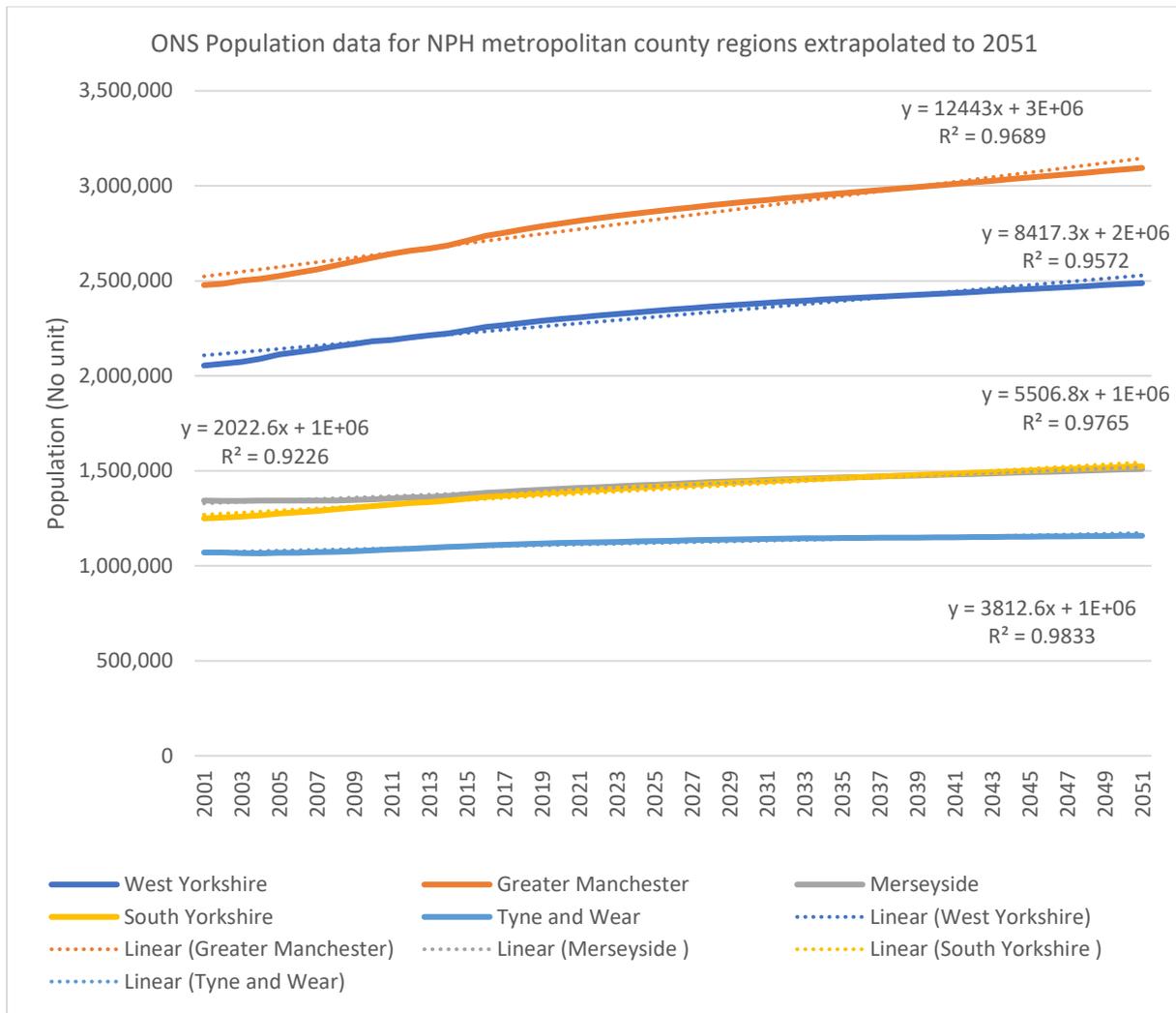


Figure 117. Time adjusted population data at Northern Powerhouse (NPH) metropolitan county region level based on ONS data records and estimations, note all dotted linear lines represents extrapolation results of original ONS data up to 2050 which is necessary for later calculations of estimated FW collection until 2050, and are accompanied by respective equation and R² values (2001-2041) (ONS, 2018)

A comparison of relative population findings for NPH city region and metropolitan county region data also exhibits a much greater population base for the latter (by a multiplier of about 3 to 6 times depending on the region, see Figure 118 for details), with Leeds being the largest NPH city region and Greater Manchester being the largest metropolitan county region. This observation is important when accounting for estimation of total FW output, which according to the ONS data indicates the greatest FW potential in Leeds in comparison to all NPH cities and Greater Manchester in comparison to all NPH metropolitan counties, as the next section will establish in more detail.

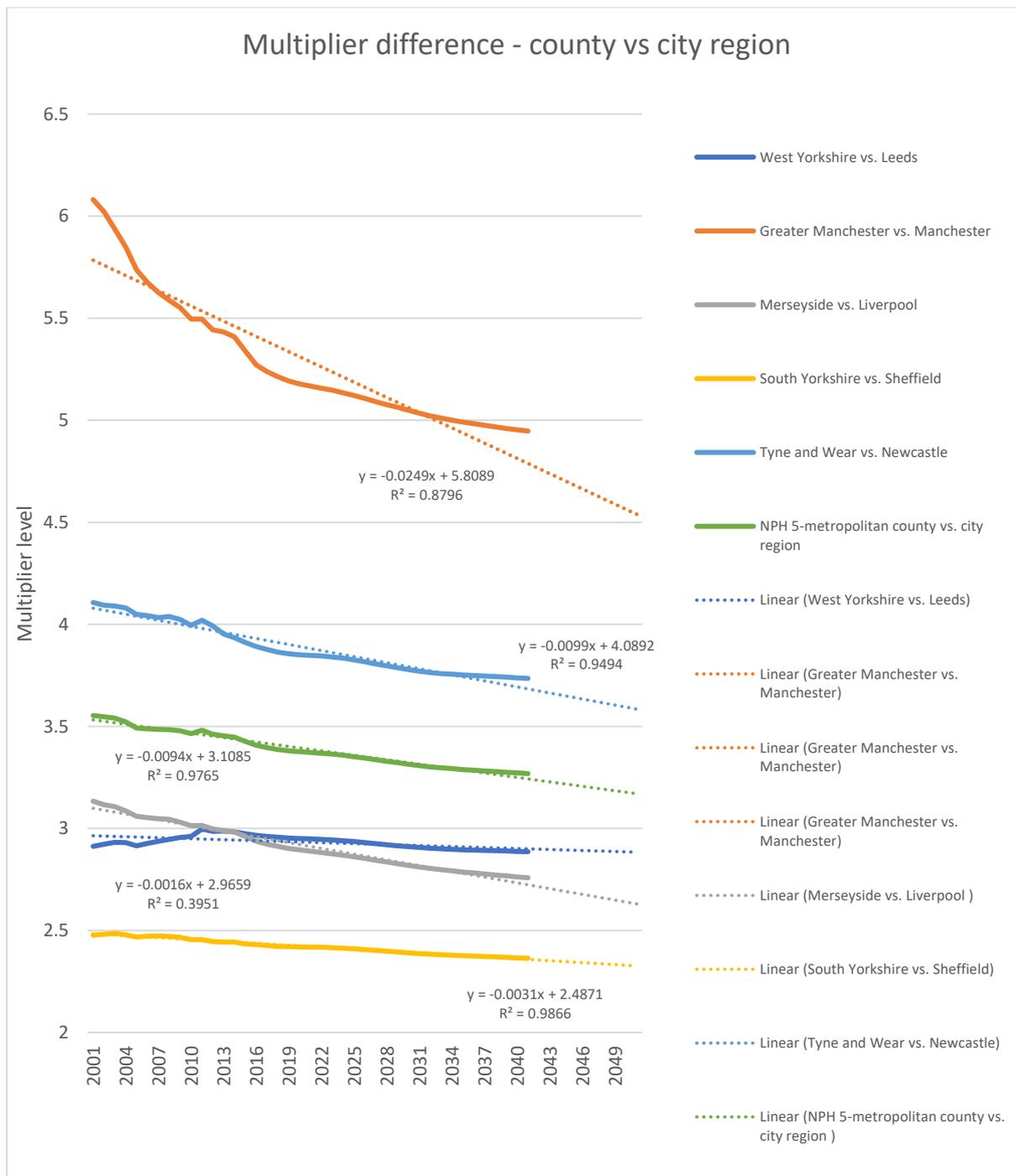


Figure 118. Population multiplier difference between NPH county region and city region data (for individual regions and total 5-NPH region total) across 2001-2041.

5.2.6 Total FW collection data – combined WDF and WRAP data for all NPH regions

This section presents results on estimate total food waste collected across each NPH region using existing data findings on per capita food waste collection data and ONS population data outlined above. To this end, a number of different results are established using single point and time-adjusted food waste collection data as summarized in Table 98 below.

Table 98. Table of summary details for calculations of all total food waste data for scenario specified geographical regions and time-deployment periods

Food waste collection data type		Food waste collection data quantity (kg/person/year) for 2010-2050	Relevant graphs	ONS data	
1	Single time point data	1. 1	20	Figure 119	2018 ONS UK population data (for 2001-2041 time period)
		1. 2	40	Figure 120	
		1. 3	100	Figure 121	
	1. 4	20, 40, 100	<p>By contrast, estimation of total FW output using same ONS population data and time-adjusted FW output data from WRAP suggests an exponential decay in output value with a half-life of approximately 20 years across all NPH city and metropolitan county regions. A similar exponential decay trend in total time-adjusted FW output is observed using data from Waste Data Flow (WDF), albeit with a longer half-life of 30-35 years. These are respectively outlined in the figures below, from which respectively shows dotted line which represents collected data, with dashed line representing a trendline curve of best fit across the collected data (shown in dots) created using excel's exponential best fit function, from which relevant equation is determined.</p>		

				<p>Figure 123. Total food waste outputs (tonnes) across all NPH city regions for time adjusted food waste collection scenarios using Waste Data Flow (WDF) FW collection trial data (for data used, please refer to Appendix table 9) (dotted line represents collected FW data, whilst dashed line represents best fit trendline created using Excel's regression trendline function, from which relevant equation and R2 value is determined).</p> <p>Figure 122</p>
2	Time-adjusted data	2.1	17 to 46 – WDF data	Figure 123, Figure 125
		2.2	18 to 73 – WRAP data	Figure 124, Figure 126 Figure 127
		2.3	17 to 46 and 18 to 73 WDF & WRAP combined data	Figure 127, Figure 128 and Figure 129

Summarized results for total food waste collection data for all NPH regions using abovementioned individual and time-adjusted data is shown below (see Figure 119, Figure 120 and Figure 121).

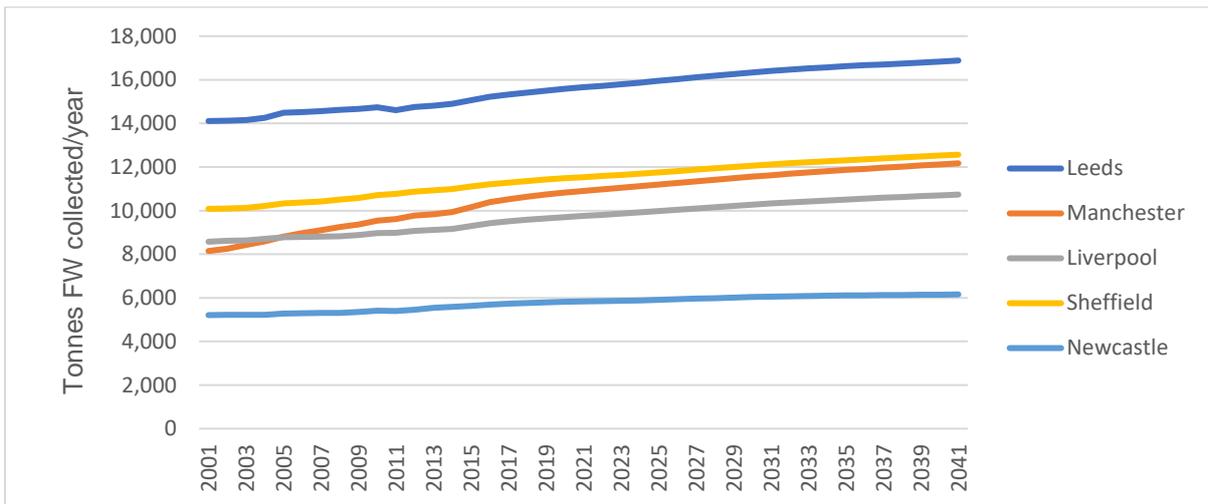


Figure 119. Total food waste data for each NPH region based on minimum acceptable single point food waste collection data of 20 kg/person/year

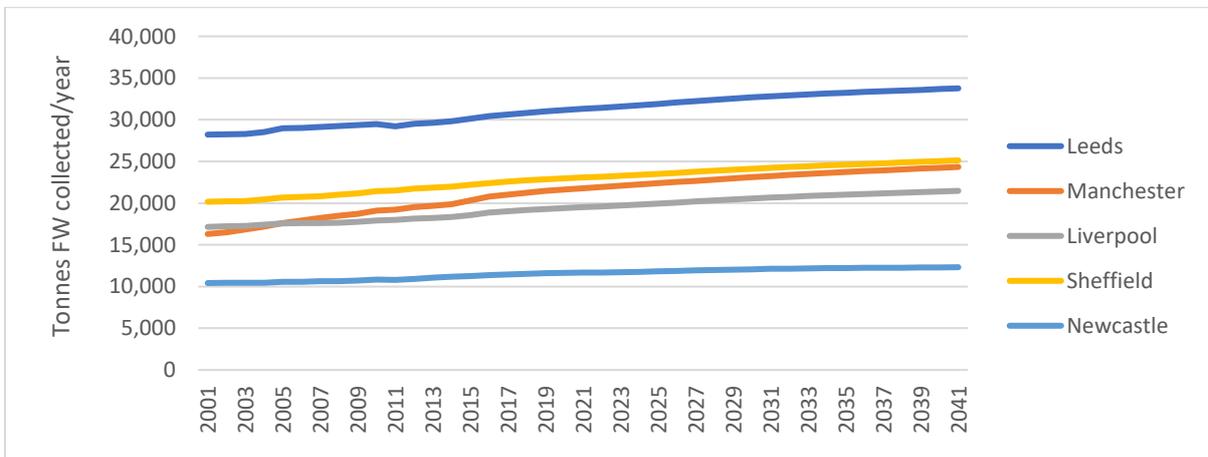


Figure 120. Total food waste data for each NPH region based on Leeds Rothwell representative single point food waste collection data of 40 kg/person/year

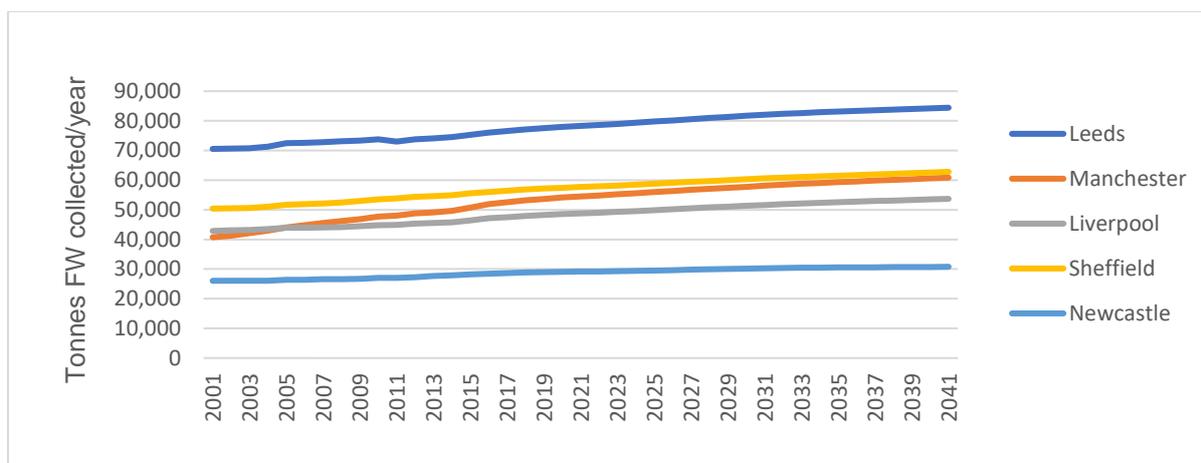


Figure 121. Total food waste data for each NPH region based on Maximum achievable single point food waste collection data of 100 kg/person/year

Total results for food waste outputs across all NPH regions and all single data FW collection scenarios of 20, 40 and 100 kg/person/year are illustrated. The results demonstrate a FW collection range of 5 to 14 tonnes in 2001, increasing to 6 to 17 tonnes in 2041 for the 20 kg/person/year fixed FW scenario. This would be increased by a factor of 2 (to 10 to 28 tonnes, and 12 to 34 tonnes of FW collected) and factor of 5 (to 25 to 70 tonnes, and 30 to 85 tonnes of FW collected) for the 40 and 100 kg/person/year FW collection scenarios respectively.

A graphical summary of all total household FW collected between 2001 and 2041 for all 5 NPH city regions for low, medium and high fixed FW collection scenarios (of 20, 40 and 100 kg/person/year) is illustrated in Figure 122 below. The illustration shows a clear and substantial difference in the total FW collected across different NPH city regions, and a gradual increase in total quantity of FW collected directly attributed to population increases between 2001 and 2041.

Here it is worth noting that this range of values, should be further explored given the high impact potential between the material, energy and revenue output arising from the lowest to the highest FW collection scenario, which will most likely materially impact stakeholder decisions on pathway deployment as well as the scale and nature of deployment itself.

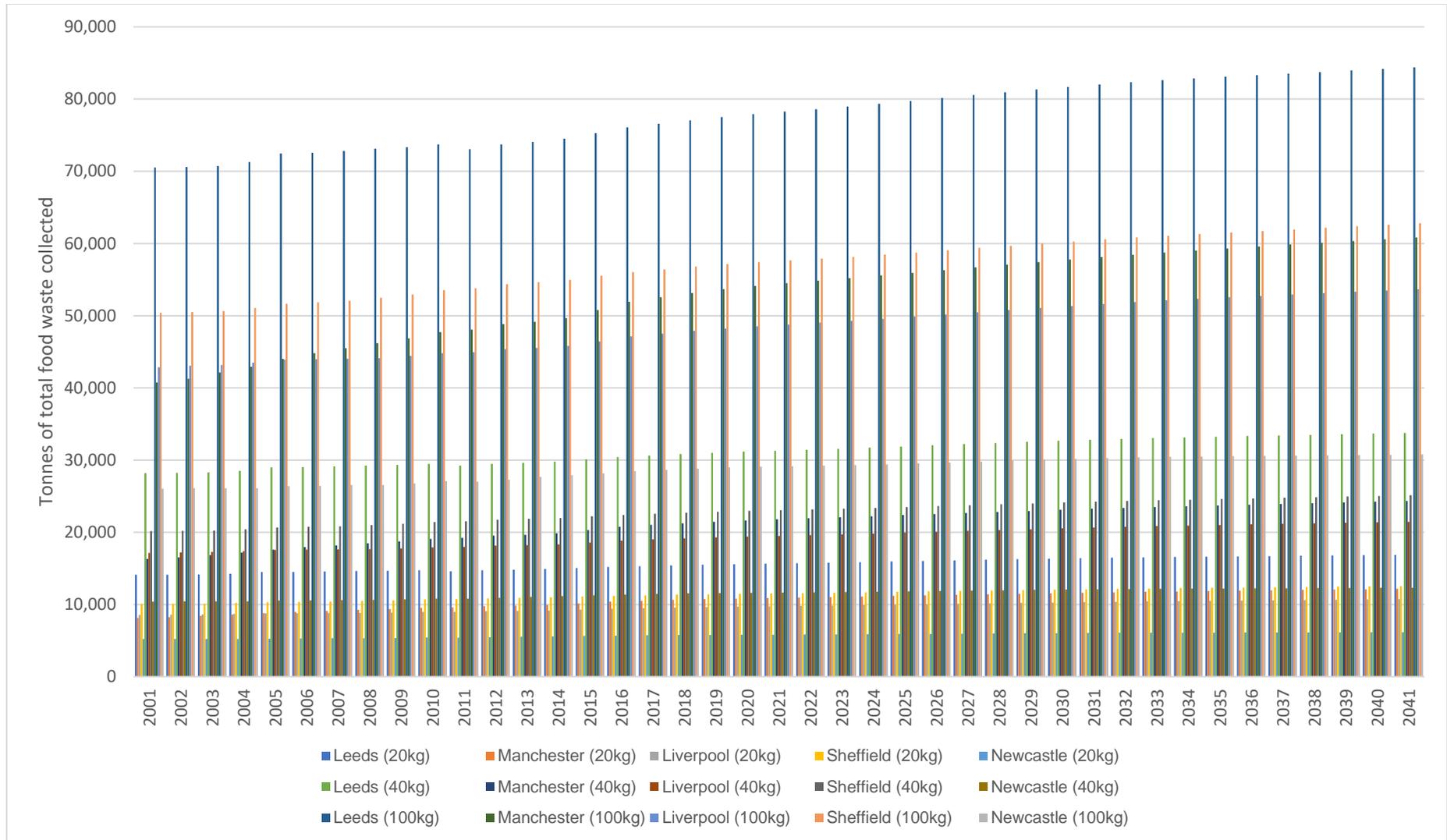


Figure 122. Summary of all total FW collected from all 5 NPH city region of Leeds, Manchester, Liverpool, Sheffield and Newcastle for the fixed FW collection data scenarios between 2001 and 2041 (under low, medium and high fixed FW collection scenarios of 20, 40 and 100 kg/person/year)

By contrast, estimation of total FW output using same ONS population data and time-adjusted FW output data from WRAP suggests an exponential decay in output value with a half-life of approximately 20 years across all NPH city and metropolitan county regions. A similar exponential decay trend in total time-adjusted FW output is observed using data from Waste Data Flow (WDF), albeit with a longer half-life of 30-35 years.

These are respectively outlined in the figures below, from which respectively shows dotted line which represents collected data, with dashed line representing a trendline curve of best fit across the collected data (shown in dots) created using excel's exponential best fit function, from which relevant equation is determined.

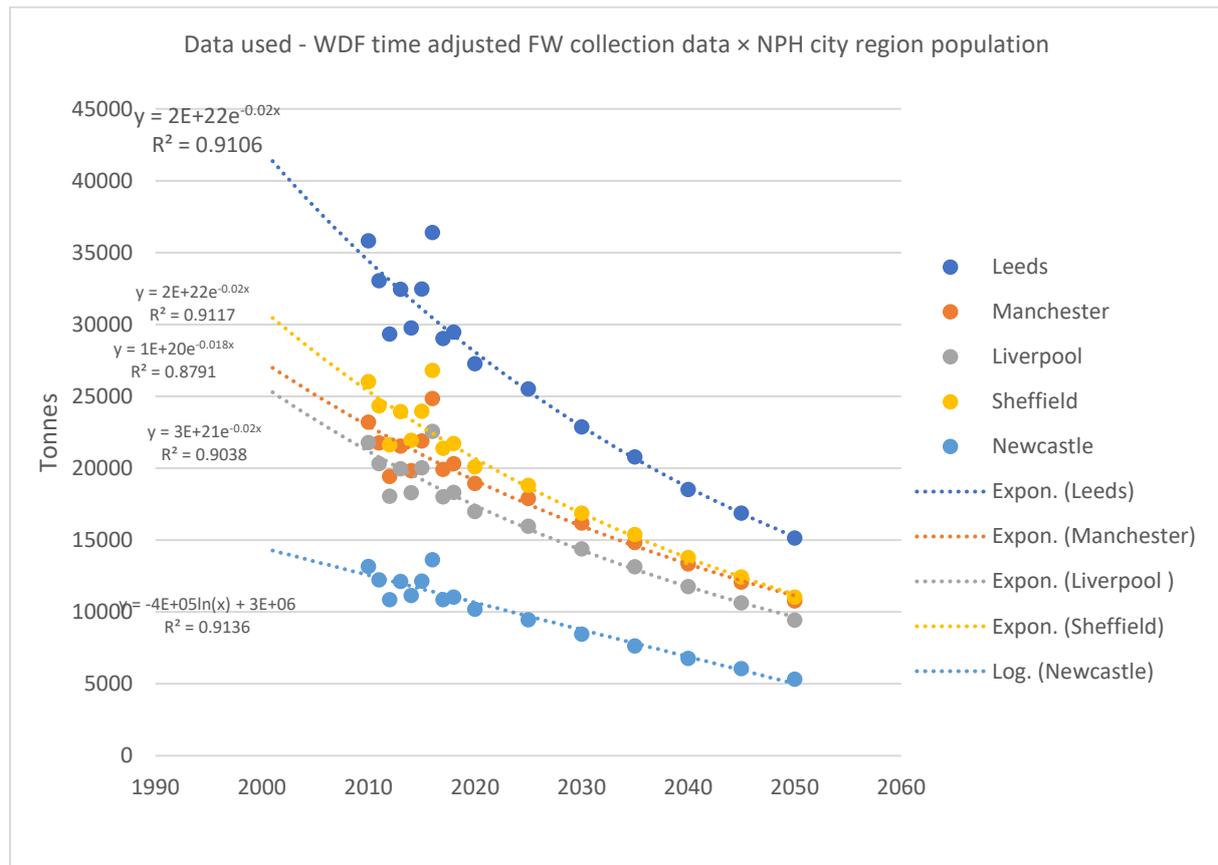


Figure 123. Total food waste outputs (tonnes) across all NPH city regions for time adjusted food waste collection scenarios using Waste Data Flow (WDF) FW collection trial data (for data used, please refer to Appendix table 9) (dotted line represents collected FW data, whilst dashed line represents best fit trendline created using Excel's regression trendline function, from which relevant equation and R² value is determined).

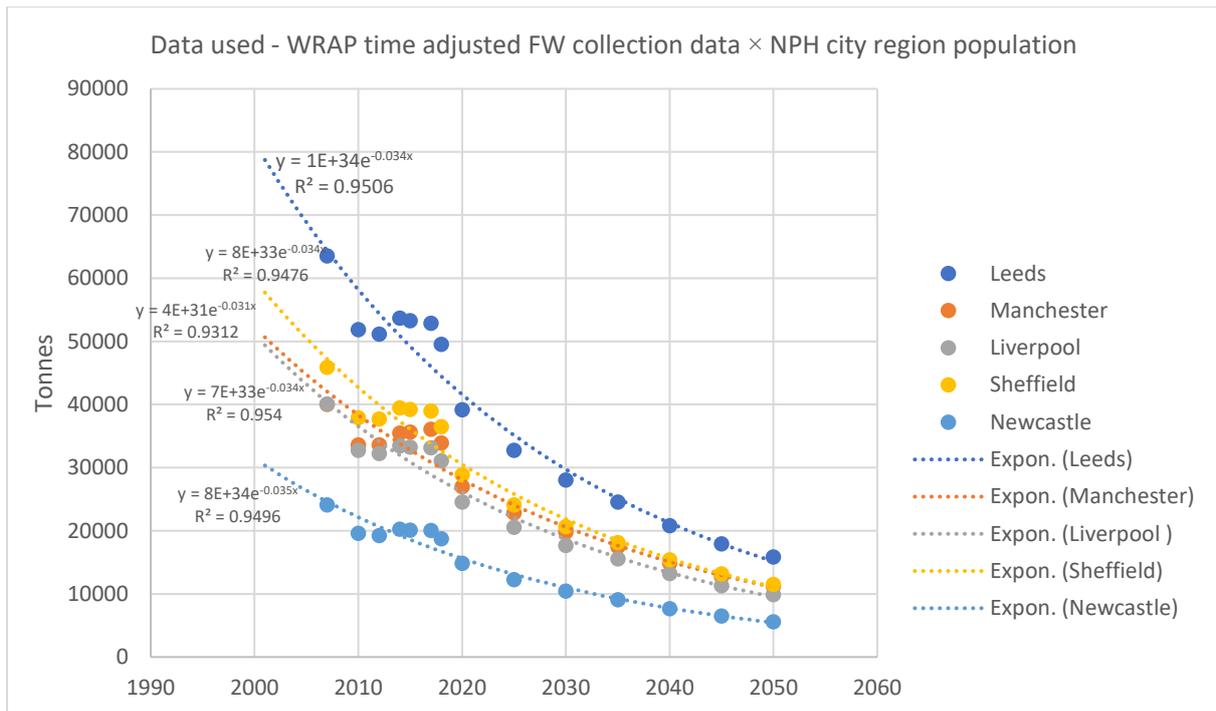


Figure 124. Total food waste outputs across all NPH city regions for time adjusted food waste collection scenarios using WRAP FW collection trial data (for data used, please refer to

Appendix table 8) (dotted line represents collected FW data, whilst dashed line represents best fit trendline created using Excel's regression trendline function, from which relevant equation and R² value is determined)

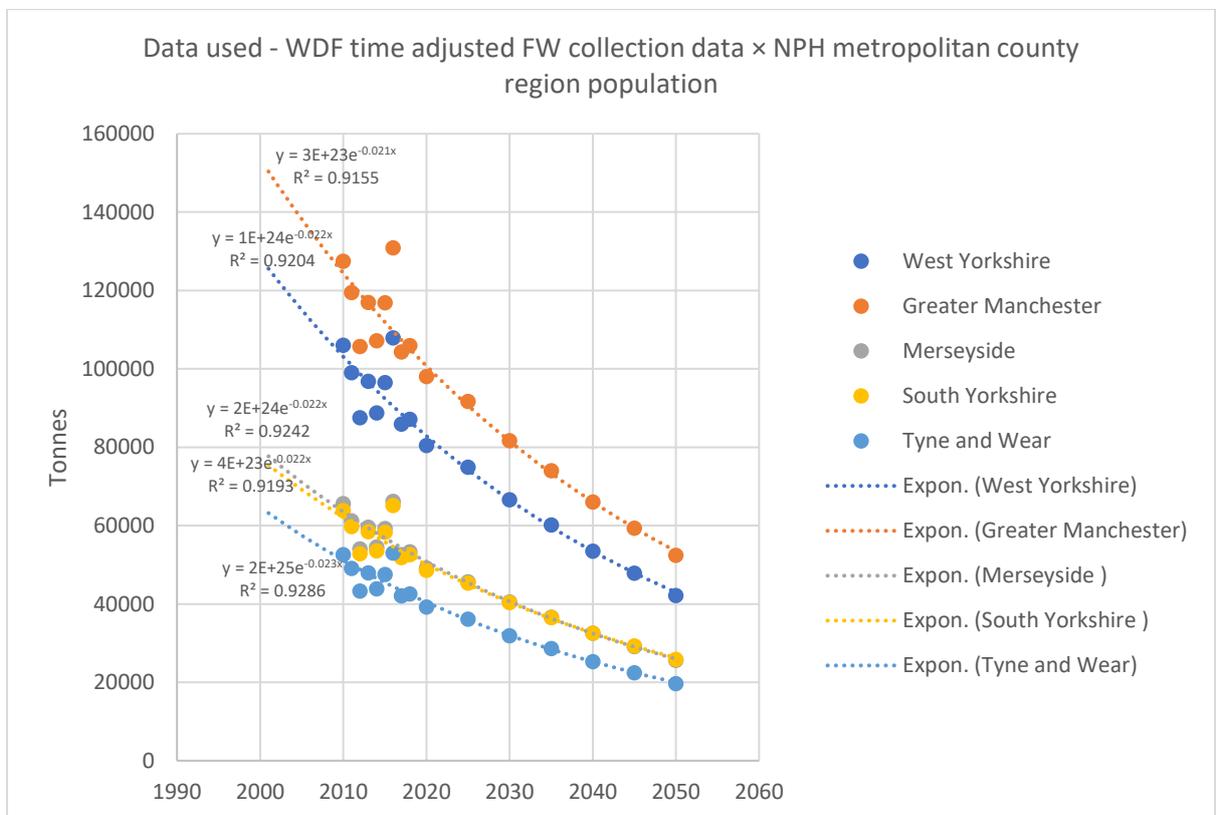


Figure 125. Total food waste outputs across all NPH metropolitan county region for time adjusted food waste collection scenarios using Waste Data Flow (WDF) FW collection trial data (for data used, please refer to Appendix table 11) (dotted line represents collected FW data, whilst dashed line represents best fit trendline created using Excel's regression trendline function, from which relevant equation and R² value is determined)

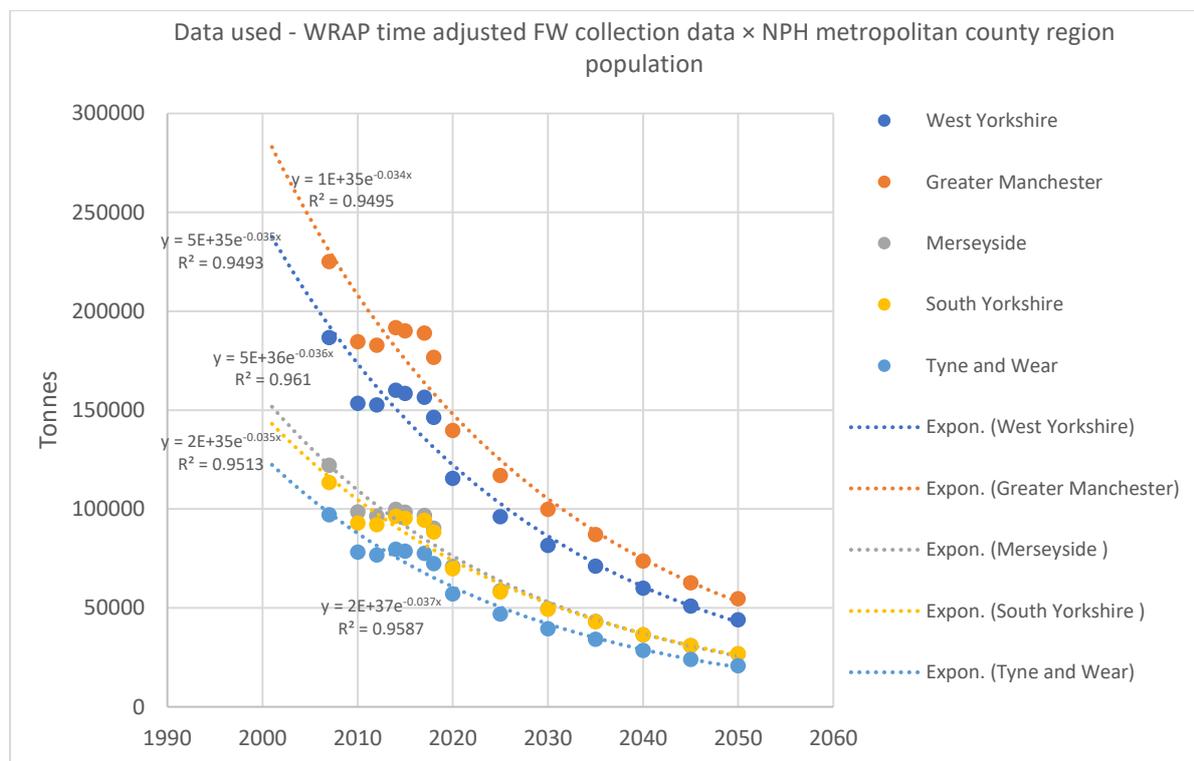


Figure 126. Total food waste outputs across all NPH metropolitan county region for time adjusted food waste collection scenarios using WRAP FW collection trial data (for data used, please refer to Appendix table 10) (dotted line represents collected FW data, whilst dashed line represents best fit trendline created using Excel's regression trendline function, from which relevant equation and R² value is determined).

Here it is important to note that the time-adjusted FW collection trendline demonstrates an exponential decline in household FW collection overtime, which is mainly attributed to the large decline in annual FW collection between 2001 and 2050 as seen in both WDF and WRAP scenarios, that is not sufficiently offset by the slower rate of population increase throughout the same period.

This finding appears to be robust based on the strong R² values of >0.90 for all exponential decay curves (Figure 123, Figure 124, Figure 125 and Figure 126) if they are to include the extrapolated data. Without inclusion of the extrapolated data however the R² value reverts to the same as those seen in the original exponential regression trendline for WDF and WRAP FW data collection (see Table 89 and Figure 112 respectively), with WRAP data to constitute a greater relative R² value over WDF data.

The findings from a material energy context ultimately suggest for there to be an inevitable future decline in the availability of total FW for collection, biomethane conversion and associated revenue generation (from energy sales, renewable tariff incentives and landfill diversion), thus again brings significant doubt in the longer term profitability and financial viability of any current and potential future FW recycling schemes.

Below outlines an alternative representation of total FW collected (tonnes per year) by clustering all findings on a region only basis for all NPH city regions, which are summarized

into 5-yearly intervals to demonstrate the relative annual decline in FW collection for each region.

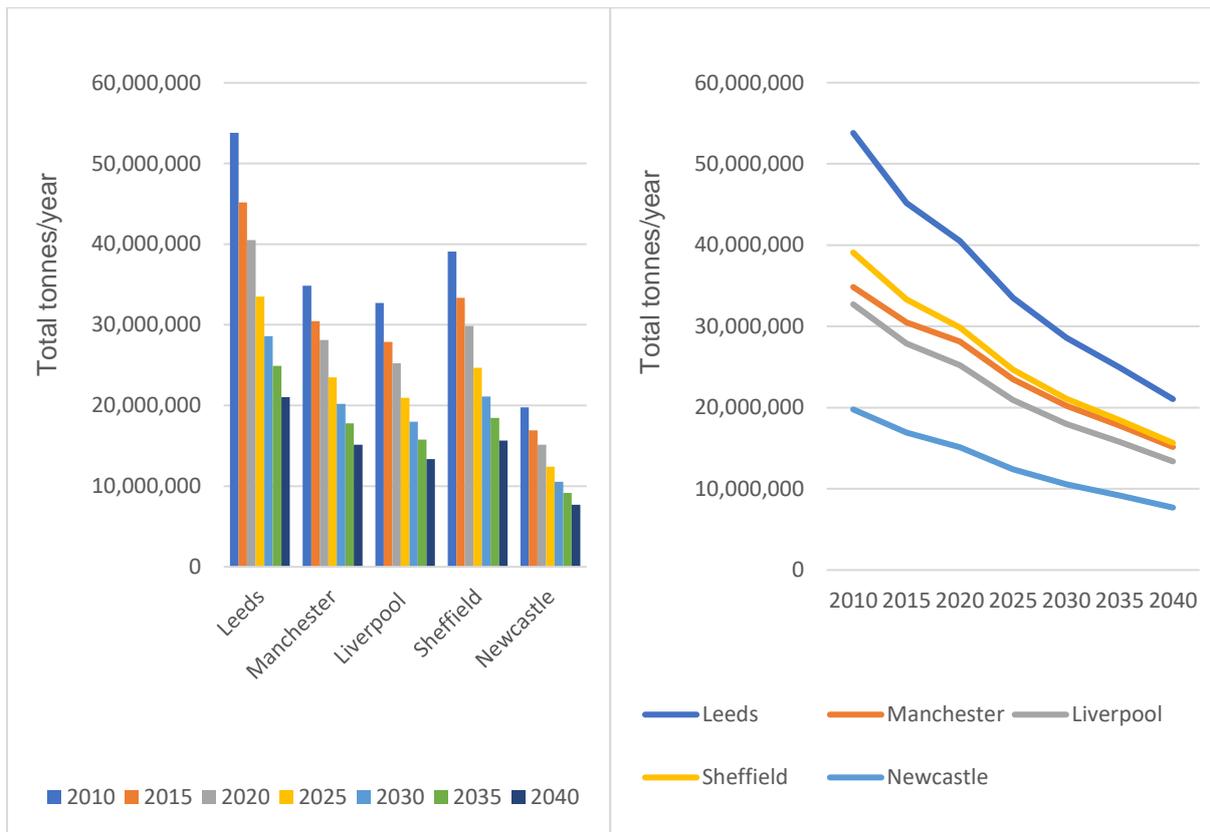


Figure 127. Total food waste data for each NPH region based on WRAP time-adjusted food waste collection data of 73 to 18 over relevant time durations of 2010 to 2050 (for data used, please see Appendix table 12)

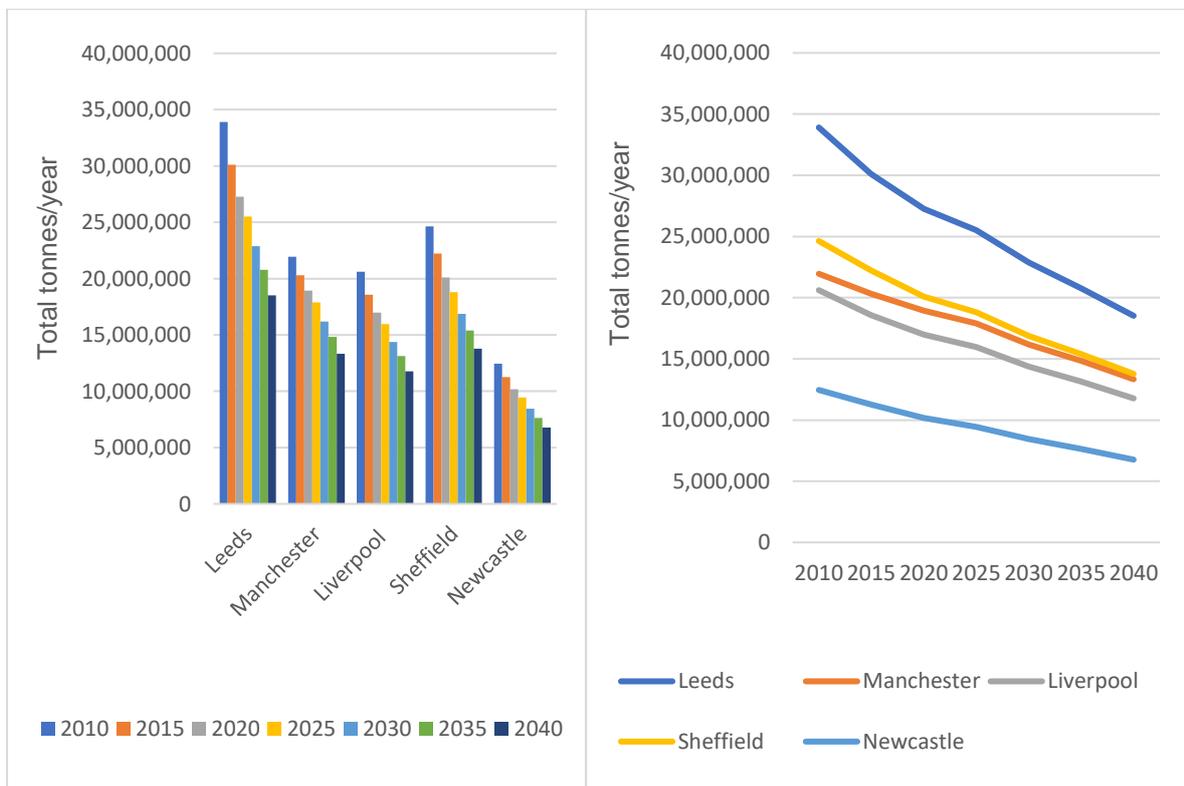


Figure 128. Total food waste data for each NPH city region based on Waste Data Flow (WDF) time-adjusted food waste collection data of 46 to 17 over relevant time durations of 2010 to 2050 (for data used, please see Appendix table 13)

This comparative illustration outlines the observations of there being a consistent notable decline in annual FW collection for all NPH cities in order of Leeds, Sheffield, Manchester, Liverpool and Newcastle from order of city with highest to lowest FW collection,

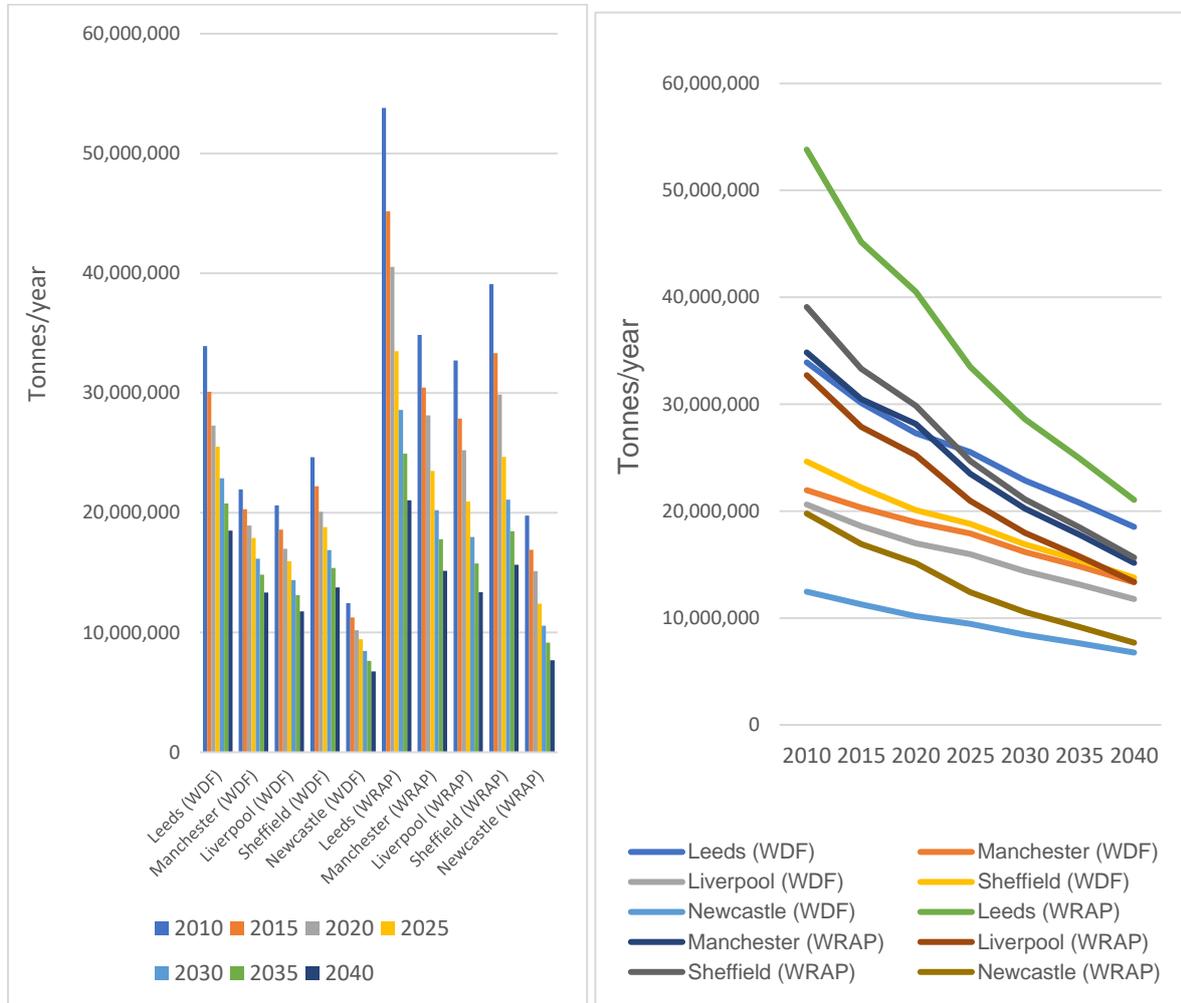


Figure 129. Total food waste data comparison of time-adjusted WRAP and Waste data flow food waste collection data for each NPH region over relevant time durations of 2010 to 2050 (for data used, please see Appendix table 14).

A comparison between time-adjusted WDF and WRAP household FW collection trial data projections for all NPH city regions illustrates a higher initial total FW collection for WRAP in 2010 coupled with a higher rate of exponential decay which leads to a similar level of estimated FW collection between both datasets in 2050. Here it is important to note that this convergence is attributed to the same trend in the convergence in per capita FW collection between the WDF and WRAP datasets as mentioned in the above section (see Figure 127, Figure 128 and Figure 129).

In context of FWtTBC pathway deployment, the above findings support the notion of there being a wide range of total biomethane generation scenarios across the NPH city region that will be elucidated and discussed in the subsequent relevant section (see Chapter 5.3.4)

following establishment of and subsequent integration of technical FW to biomethane conversion data derived from academic research literature.

5.3 Technical data findings on Biogas and Biomethane potential

5.3.1 Overview

This section presents technical findings on biogas and biomethane (and equivalent electricity generation) yield potential of relevant household food wastes, with output value governed by a number of technical factors, i.e., food waste category or outlet and AD type by operational temperature or system type as outlined in all relevant research papers (e.g. found by using online Boolean search method) and used for the analysis (findings 1).

Results are then cross evaluated with operational food waste to biogas and biomethane conversion data from existing AD plants as outlined by an official biogas Excel database (Biogas-info, 2017) to establish degree of real-world relevance of the technical research data used (finding 2).

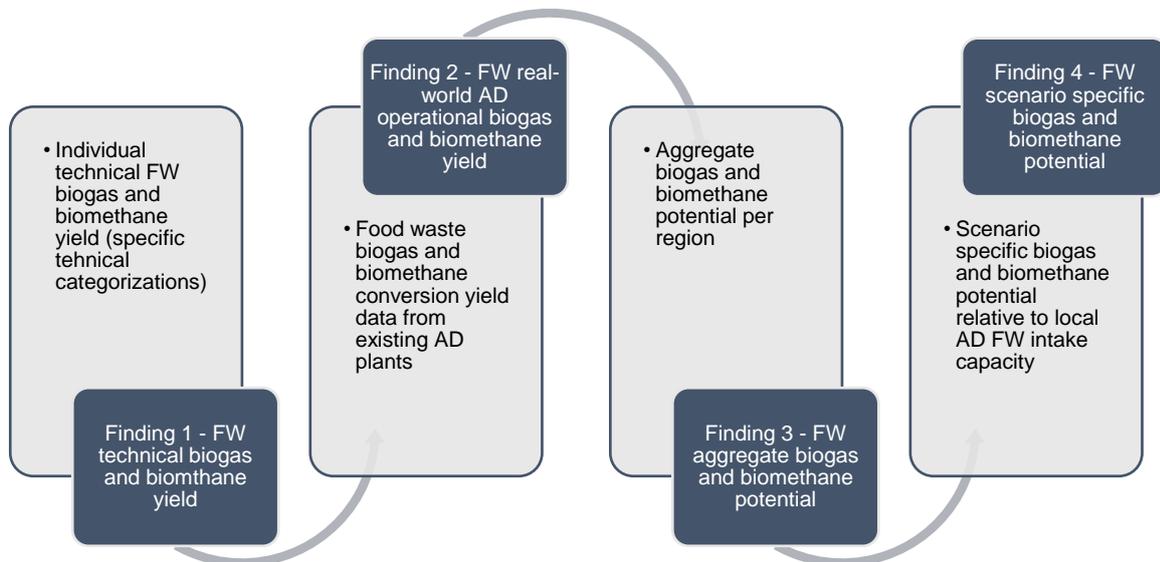


Figure 130. Summary of findings for biogas and biomethane data component of the FWtTBC pathway

The cross-verified results are then combined with findings on total food waste collection data for relevant NPH regions to establish total biogas, biomethane and electricity potential within the same regions (finding 3) for further analysis.

This includes estimating extent of real-world biogas and biomethane generation potential (finding 4) by factoring in infrastructure limitations such as local AD and refuel station capacity, from (see basic and advanced process operation diagrams in Methodologies 4.3.3 and 4.3.4 for details) (see Figure 130).

Here it is important to note the combined material energy losses (as alluded to in the original advanced process operation diagrams) are already accounted for in the findings from existing FW collection trials and FW anaerobic digestion experiments (for conversion to biomethane) for purpose of streamlining the modelling approach, to help re-consolidate focus towards deriving financial and whole-system calculations in the ensuing sections.

5.3.2 Finding 1 - Technical FW to biogas and biomethane conversion yield method overview

Findings on technical biogas and biomethane potential of FW are derived from a total of 30 FW to biogas and/or biomethane conversion academic research articles that were returned from use of Boolean keyword research across specified online search platforms (see Chapter 4.4: Methodology 3). These collectively include 161 individual experimental data points in context of technical parameters pertaining to food waste type and anaerobic digestion operational conditions (see Appendix table 1 for summary), with one example of data collected being outlined in Table 99 below.

Table 99. Technical process operations for outlining food waste biogas and biomethane yield potential pertaining to AD component of FWtTBC pathway deployment, with all technical fields included in the actual Excel model, accompanied by one dataset to illustrate model application, Please note the actual model has a total of 161 field inputs from which all subsequent analytical results are based (160 in addition to the one data entered here).

Related FWtTBC pathway component		Representation example 1 (Study 1)	
Source		Youn and H.-S. Shin, 2005	
Research article number (out of 29 literature sources)		3	
Results number (out of 167 total food waste anaerobic digestion results range)		25-30	
URL		https://journals.sagepub.com/doi/abs/10.1177/0734242X05049766	
Number of studies (for averaging experimental results)		6	
Food waste	FW categorization data	FW category	Commercial
		FW outlet	Dining Hall
		FW description	Fixed food waste
	Material input technical compositional data (individually sections for food waste / inoculum / substrate respectively, example results shown as presented)	Co-substrate	De-ionized water
		Food waste co-substrate ratio	1:2 Fresh weight
		Inoculum	Sewage sludge
		pH	5.5 / NA / 7.3
		Total solid (%)	20.10 / N/A / 2.36
		Volatile solid (%)	18.90 / NA / 1.41
		VS/TS	94.03 / NA / 59.75
C/N Ratio	16 / N/A / NR		
Anaerobic digestion	AD system technical info	AD system type	Standalone
		AD stage	Two-stage
		AD type by temperature	Mesophilic
		Reactor scale	Bench scale
		Reactor size (L)	15
		Reactor type	Continued Stirring tank reactor
		Reactor full description	Standalone Two stage mesophilic bench scale
	AD technical operational parameters	Operational Temp (°C) Lower	35
		Operational Temp (°C) Upper	35
		On-loading rate (OLR) (gVS/L/d)	5.67
		Hydraulic retention time (HRT)	25
		Solid Retention Time (SRT)	N/A
		AD process pH	5.5
	AD useful output data	Biogas output (m ³ /kml/VS)	0.96
		Food waste biogas yield (m ³ /t)	182.33
		Food waste Biogas yield	
		Biomethane output (m ³ /kml/VS)	0.64
		Food waste Biomethane yield (m ³ /t)	120.80
		Biogas methane yield	66%
		Equivalent electricity output (kWh)	

Example source is from [25] in the actual data collection process, with reference: J.-H. Youn and H.-S. Shin, "Comparative performance between temperature-phased and conventional mesophilic two-phased processes in terMSof anaerobically produced bioenergy from food waste," Waste Management and Research, vol. 23, no. 1, pp. 32–38, 2005.

Results surrounding food waste to biogas and biomethane conversion yields estimations are calculated using a subset of these specific technical parameters deemed to be both relevant and important in both driving FWtTBC pathway deployment and for informing suitable deployment strategies (see Table 100).

Table 100. Full terms and abbreviations for all technical findings on FW to biogas and biomethane conversion yield potential in context of their relative relevance and importance to overall research aims and objectives

Finding no.	Technical categories	Relevant section	Abbreviations	Full Technical terms (used for each findings section)	Relevance & Importance	Rationale for relevance and importance of the results
1.1	All	5.3.2.1	All Exp	All experiments	Strong / High	Large data points of Food waste data
1.2	Food waste outlet	5.3.2.2	HH-FW	Household FW	Very Strong / Very High	Most representative FW data to modelling pathway
1.3		5.3.2.3	HH&C-FW	Household & Commercial FW	Strong / High	Second most representative FW data
1.4		5.3.2.4	C-FW	Commercial FW	Moderate / Moderate	Somewhat relevant to household FW
1.5		5.3.2.5	C&I-FW	Commercial and Industrial FW	Moderate / Moderate	Somewhat relevant to household FW
1.6		5.3.2.6	I-FW	Industrial FW	Weak / Low	Less relevant to household FW
1.7		Food waste category	5.3.2.7	MFW	Mixed FW	Moderate / Moderate
1.8	5.3.2.8		MFVW	Mixed Food & Vegetable waste	Moderate / Moderate	Somewhat relevant to household FW
1.9	5.3.2.9		MFrVW	Mixed Fruit & Vegetable Waste	Weak / Low	Less relevant to household FW
1.10	5.3.2.10		MVW	Mixed Vegetable Waste	Weak / Low	Less relevant to household FW
1.11	AD type by temperature	5.3.2.11	MS-AD	Mesophilic AD	Strong / High	Typical AD used for anaerobic digestion of FW
1.12		5.3.2.12	TM-AD	Thermophilic AD	Strong / High	
1.13		5.3.2.13	All comparisons of above results			

For estimations of mean, median and interquartile range (Q1-Q3) values pertaining to each technical category of FW to biogas and biomethane conversion yield, 2 separate layers of averages (1st and 2nd order average) whose application is elaborated in Table 101 below.

Table 101. Elaboration of calculation method for 1st and 2nd average values for FWtTBC pathway deployment.

Average type		Description	Equation
1	1 st Order average	Step 1 - Divide sum of all individual experimental data points for all studies (S1) by corresponding number (n1) of experimental data points involved	$S1 / n1$, where n = 161 (total no. of data points)
2	2 nd Order average	Step 1 - Divide sum all individual experimental data points for each individual study (S2) by corresponding number (n2) of experimental data points involved	$S2 / n2$, where n = variable (equivalent to no. of data point used in each study)
		Step 2 – Sum all data points from each experimental study and divide sum total by total number (n2) of experimental studies	$S3 / n3$, where n = 30 (total number of studies)

All data are subsequently inputted into the Excel model by applying the above technical data collection metrics and are subsequently categorized and analysed with respect to both first and second order mean, median, and interquartile (first, second, third quartile) range values, with all returned results for different types of FW categories shown in the below section.

5.3.2.1 Finding 1.1 – All FW to biogas and biomethane conversion yield findings

This section outlines findings on all FW to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from all 161 data points (1st order average) and 30 experimental studies (2nd order average), with all results being outlined in Table 102 and Figure 131 below (see Table 100 for relevant full terms corresponding to abbreviations used).

Table 102. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original excel model) from all FW (Data Points = 161, Experimental Studies = 30)

Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
All Exp,1st Order, Mean	116.29	70.89	60.89%
All Exp, 2nd Order, Mean	130.06	80.22	62.97%
All Exp, 1st Order, Median	105.72	69.24	62.00%
All Exp, 2nd Order, Median	125.24	75.43	64.00%
All Exp, 1st Order, Q1 (25%),	59.73	38.85	57.00%
All Exp, 2nd Order, Q1 (25%),	77.08	48.78	57.71%
All Exp, 1st Order, Q2 (50%),	105.72	69.24	62.00%
All Exp, 2nd Order, Q2 (50%),	125.24	75.43	64.00%
All Exp, 1st Order, Q3 (75%),	166.24	97.52	67.00%
All Exp, 2nd Order, Q3 (75%),	157.81	91.27	70.00%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile ranges data respectively

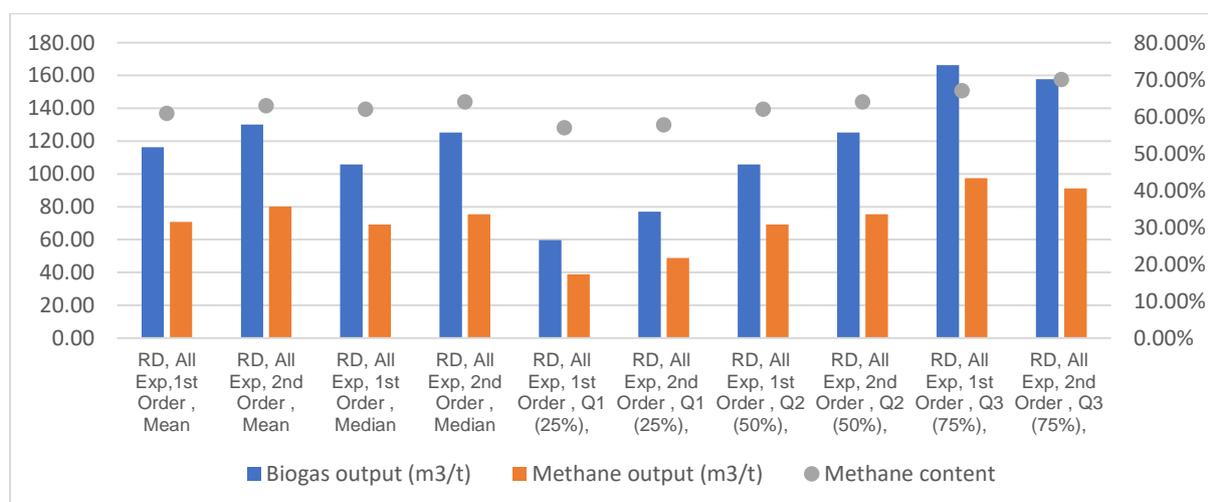


Figure 131. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from all food wastes (please note the m³/t as shown in the figure pertains to m³/t).

The results shows a mean FW to biogas conversion yield of approximately 116-130m³/t, followed by a median value range of 106-125m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 60-77m³/t, 106-125m³/t and 158-166m³/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 60.89-62.97%, 62-64%, 57-57.71%, 62-64% and 67-70%, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 70-80m³/t, 70-75m³/t, 39-49m³/t, 69-75m³/t and 91-97m³/t, respectively.

5.3.2.2 Finding 1.2 – Household FW to biogas and biomethane conversion yield findings

This section outlines findings on Household FW (HHFW) to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 11 data points (using 1st order average) and 3 experimental studies (using 2nd order average), with all results being outlined in Table 103 and Figure 132 below (see Table 100 for full terms corresponding to abbreviations used).

Table 103. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from household FW (Data Points = 11, Experimental Studies = 3)

Abbreviated names only	Biogas output (m ³ /t)	Methane output (m ³ /t)	Methane content
RD, HH-FW, 1st Order, Mean	74.07	45.83	64.18%
RD, HH-FW, 2nd Order, Mean	74.07	45.83	64.18%
RD, HH-FW, 1st Order, Median	59.08	41.35	66.35%
RD, HH-FW, 2nd Order, Median	74.07	45.83	64.18%
RD, HH-FW, 1st Order, 1st Quartile (25%),	55.69	38.99	59.44%
RD, HH-FW, 2nd Order, 1st Quartile (25%),	65.54	42.87	61.26%
RD, HH-FW, 1st Order, 2nd Quartile (50%),	59.08	41.35	66.35%
RD, HH-FW, 2nd Order, 2nd Quartile (50%),	74.07	45.83	64.18%
RD, HH-FW, 1st Order, 3rd Quartile (75%),	75.62	43.75	70.00%
RD, HH-FW, 2nd Order, 3rd Quartile (75%),	82.60	48.78	67.09%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

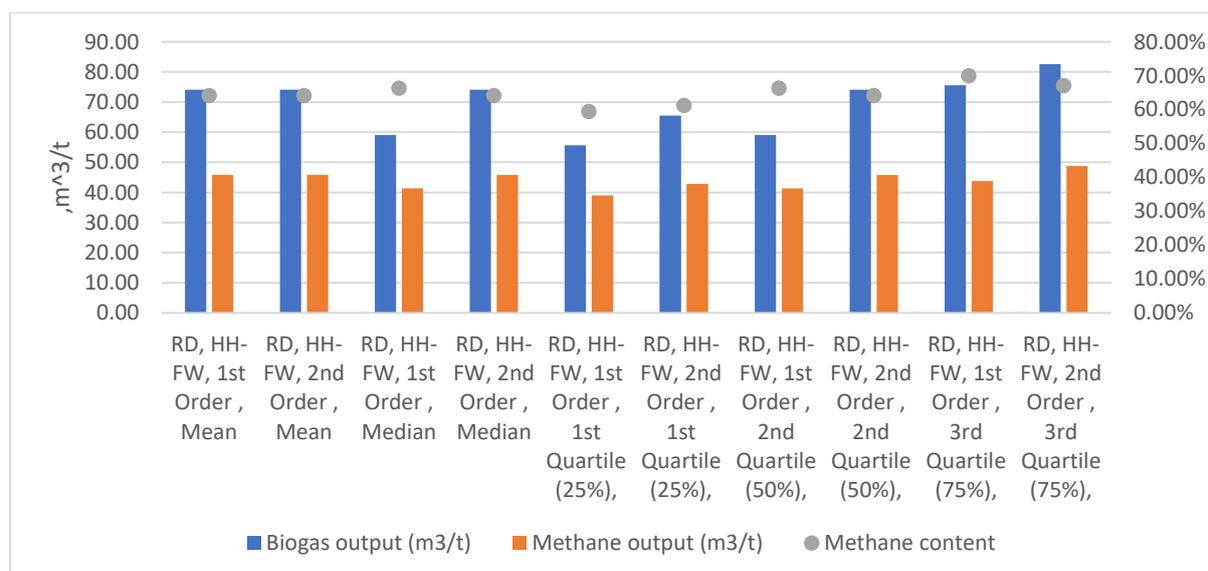


Figure 132. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from household (HH) food wastes (please note the m³/t as shown in the figure pertains to m³/t).

The results shows a mean FW to biogas conversion yield of approximately 74.07m³/t, followed by a median value range of 59-74m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 56-66m³/t, 59-74m³/t and 76-83m³/t respectively. These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 64.18%, 64.18-66.35%, 59.44-61.26%, 64.18-66.35%, 67.09-70.00%, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 46m³/t, 41-46m³/t, 39-43m³/t, 41-46m³/t and 44-49m³/t, respectively.

5.3.2.3 Finding 1.3 – Combined Household and Commercial FW biogas and biomethane conversion yield findings

This section outlines findings on Household and Commercial FW (HH&C-FW) to biogas and biomethane conversion yield on a per tonne FW (m^3/t) basis arising from 6 data points (using 1st order average) and 3 experimental studies (using 2nd order average), with all results being outlined in Table 121 and Figure 133 below (also see Table 100 for relevant full terms corresponding to abbreviations used).

Table 104. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from household and commercial FW (Data Points=11, Experimental Studies=3)

Abbreviated names only	Biogas output (m^3/t)	Methane output (m^3/t)	Methane content
RD, HH&C-FW, 1st Order, Mean	111.35	81.69	75.54%
RD, HH&C-FW, 2nd Order, Mean	116.80	81.02	70.31%
RD, HH&C-FW, 1st Order, Median	102.60	87.08	77.60%
RD, HH&C-FW, 2nd Order, Median	103.35	77.19	70.00%
RD, HH&C-FW, 1st Order, 1st Quartile (25%),	99.86	71.72	70.00%
RD, HH&C-FW, 2nd Order, 1st Quartile (25%),	102.53	71.77	68.00%
RD, HH&C-FW, 1st Order, 2nd Quartile (50%),	102.60	76.67	76.50%
RD, HH&C-FW, 2nd Order, 2nd Quartile (50%),	103.35	77.19	70.00%
RD, HH&C-FW, 1st Order, 3rd Quartile (75%),	129.52	97.79	79.20%
RD, HH&C-FW, 2nd Order, 3rd Quartile (75%),	117.62	86.45	72.23%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

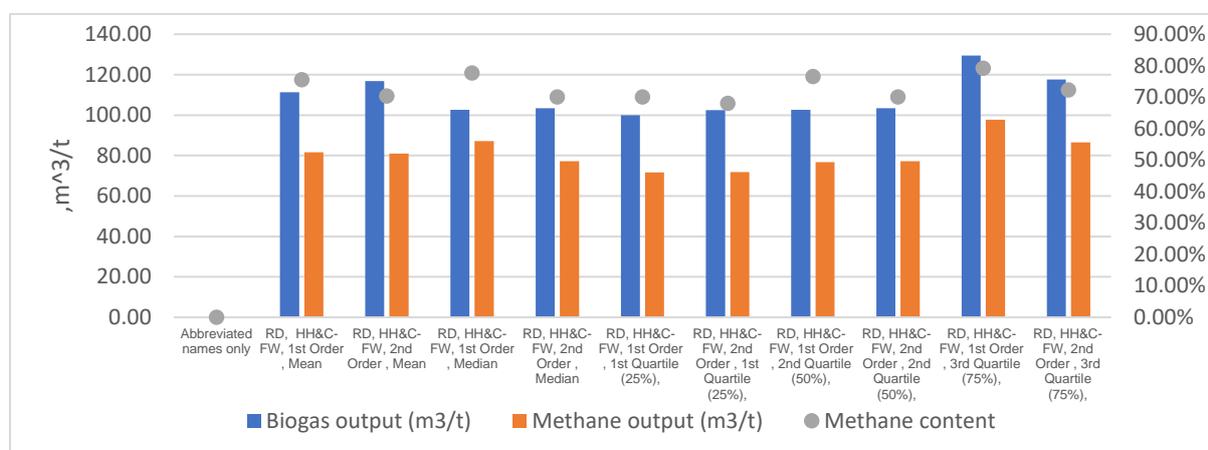


Figure 133. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from household and commercial (HH&C) food wastes (please note the m^3/t as shown in the figure pertains to m^3/t).

The results show a mean FW to biogas conversion yield of approximately 111-117 m^3/t , followed by a median value range of 103 m^3/t , and first, second, third quartile (Q1, Q2, and Q3) value range of 100-103 m^3/t , 103 m^3/t and 118-130 m^3/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 70-76%, 70-78%, 68-70%, 70-77% and 72-79%, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 81-82 m^3/t , 77-87 m^3/t , 72 m^3/t , 77 m^3/t and 86-98 m^3/t , respectively.

5.3.2.4 Finding 1.4 – Commercial FW to biogas and biomethane conversion yield findings

This section outlines findings on Commercial FW (CFW) to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 132 data points (using 1st order average) and 25 experimental studies (using 2nd order average), with all results being outlined in Table 105 and Figure 134 below (also see Table 100, for full terms corresponding to abbreviations used).

Table 105. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from commercial FW (Data Points = 132, Experimental Studies = 25)

Abbreviated names only	Biogas output (m ³ /t)	Methane output (m ³ /t)	Methane content
RD, C-FW, 1st Order, Mean	116.16	69.70	59.67%
RD, C-FW, 2nd Order, Mean	128.48	81.11	61.92%
RD, C-FW, 1st Order, Median	105.88	68.04	60.50%
RD, C-FW, 2nd Order, Median	123.33	73.64	62.71%
RD, C-FW, 1st Order, Q1 (25%),	59.34	33.76	56.00%
RD, C-FW, 2nd Order, Q1 (25%),	64.69	38.83	57.44%
RD, C-FW, 1st Order, Q2 (50%),	105.88	68.04	60.50%
RD, C-FW, 2nd Order, Q2 (50%),	123.33	73.64	62.71%
RD, C-FW, 1st Order, Q3 (75%),	167.10	94.62	66.02%
RD, C-FW, 2nd Order, Q3 (75%),	157.02	89.00	70.00%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

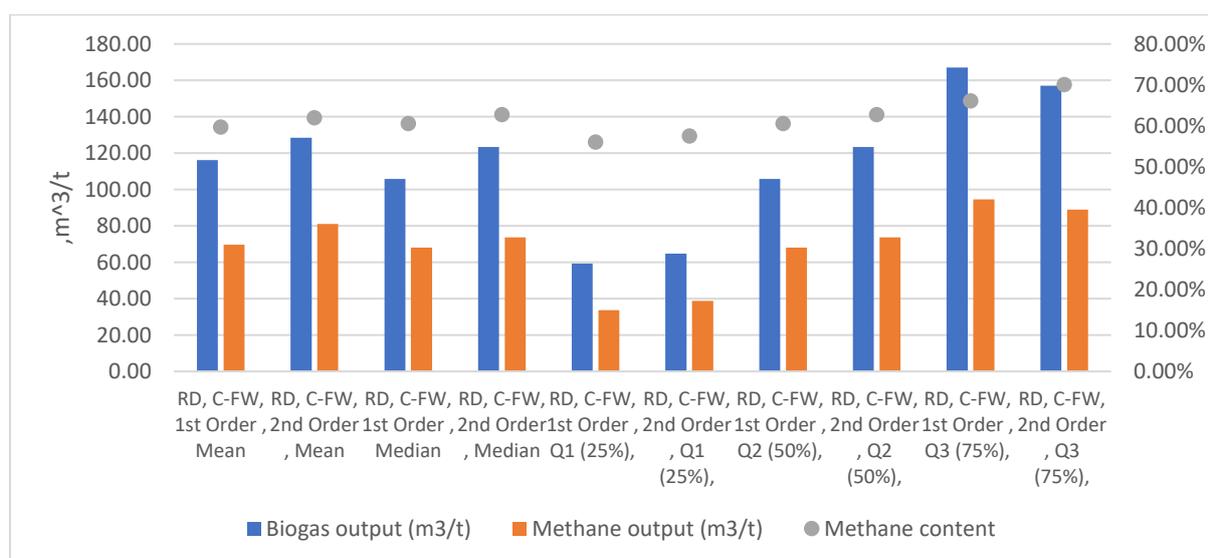


Figure 134. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from commercial (C) food wastes (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 116-128m³/t, followed by a median value range of 106-123m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 59-65m³/t, 106-123m³/t and 157-167m³/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 60-62%, 61-63%, 56-57%, 61-63% and 66-70%, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 70-81m³/t, 68-74m³/t, 34-39m³/t, 68-74m³/t and 89-95m³/t, respectively.

5.3.2.5 Finding 1.5 – Commercial and Industrial to FW biogas and biomethane conversion yield findings

This section outlines findings on Commercial and Industrial FW (CIFW) to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 7 data points (using 1st order average) and 2 experimental studies (using 2nd order average), with all results being outlined in Table 106 and **Error! Reference source not found.** below (also see Table 100 for relevant full terms corresponding to abbreviations used).

Table 106. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from commercial and industrial (C&I) FW (Data Points = 7, Experimental Studies = 2)

Abbreviated names only	Biogas output (m ³ /t)	Methane output (m ³ /t)	Methane content
RD, C&I-FW, 1st Order, Mean	169.69	107.02	64.64%
RD, C&I-FW, 2nd Order, Mean	169.52	107.57	64.37%
RD, C&I-FW, 1st Order, Median	186.92	119.20	63.77%
RD, C&I-FW, 2nd Order, Median	169.52	107.57	64.37%
RD, C&I-FW, 1st Order, 1st Quartile (25%),	127.98	86.89	61.19%
RD, C&I-FW, 2nd Order, 1st Quartile (25%),	169.40	107.18	64.19%
RD, C&I-FW, 1st Order, 2nd Quartile (50%),	186.92	119.20	63.77%
RD, C&I-FW, 2nd Order, 2nd Quartile (50%),	169.52	107.57	64.37%
RD, C&I-FW, 1st Order, 3rd Quartile (75%),	207.24	123.26	66.05%
RD, C&I-FW, 2nd Order, 3rd Quartile (75%),	169.64	107.95	64.56%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

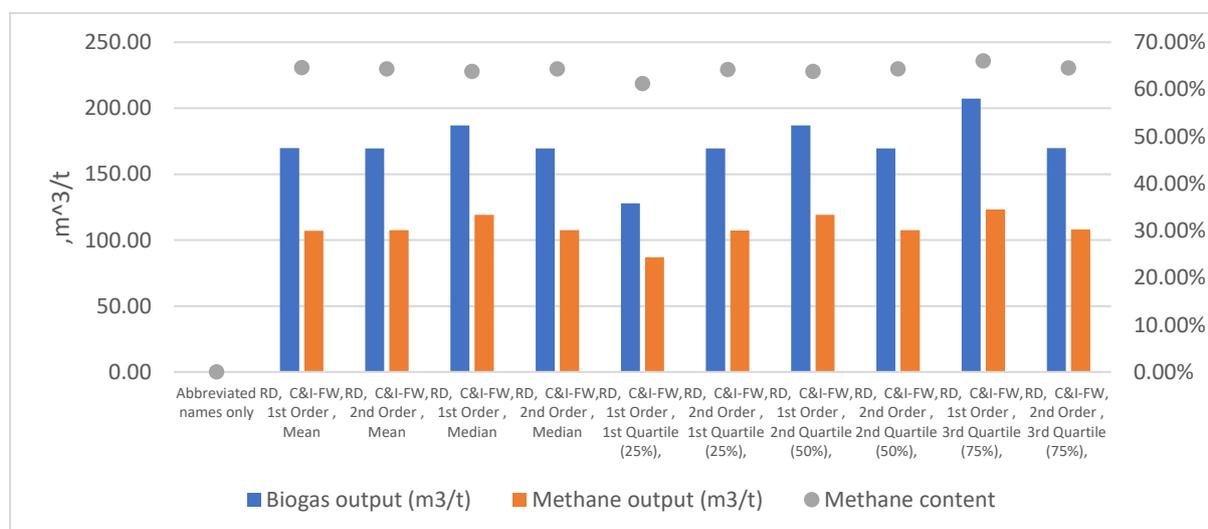


Figure 135. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from commercial and industrial (C&I) food wastes (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 170m³/t, followed by a median value range of 170-187m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 128-169m³/t, 170-187m³/t and 170-207m³/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 64.37-64.64%, to 63.77-64.37%, 61.49-64.19%, 63.77-64.37% and 64.56-66.05%, respectively. Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 107-108m³/t, 108-119m³/t, 87-107m³/t, 108-119m³/t and 108-123m³/t, respectively.

5.3.2.6 Finding 1.6 – Industrial FW to biogas and biomethane conversion yield findings

This section outlines findings on Industrial FW (IFW) to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 4 data points (using 1st order average) and 1 experimental study (using 2nd order average), with all results being outlined in Table 107 and Figure 136 below (also see Table 100 for relevant full terms corresponding to abbreviations used).

Table 107. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from industrial (I) FW (Data Points = 4, Experimental Studies = 1)

Abbreviated names only	Biogas output (m ³ /t)	Methane output (m ³ /t)	Methane content
RD, I-FW, 1st Order, Mean	141.35	90.46	64.00%
RD, I-FW, 2nd Order, Mean	141.35	90.46	64.00%
RD, I-FW, 1st Order, Median	141.62	90.63	64.00%
RD, I-FW, 2nd Order, Median	141.62	90.63	64.00%
RD, I-FW, 1st Order, 1st Quartile (25%),	125.69	80.44	64.00%
RD, I-FW, 2nd Order, 1st Quartile (25%),	125.69	80.44	64.00%
RD, I-FW, 1st Order, 2nd Quartile (50%),	141.62	90.63	64.00%
RD, I-FW, 2nd Order, 2nd Quartile (50%),	141.62	90.63	64.00%
RD, I-FW, 1st Order, 3rd Quartile (75%),	157.27	100.65	64.00%
RD, I-FW, 2nd Order, 3rd Quartile (75%),	157.27	100.65	64.00%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

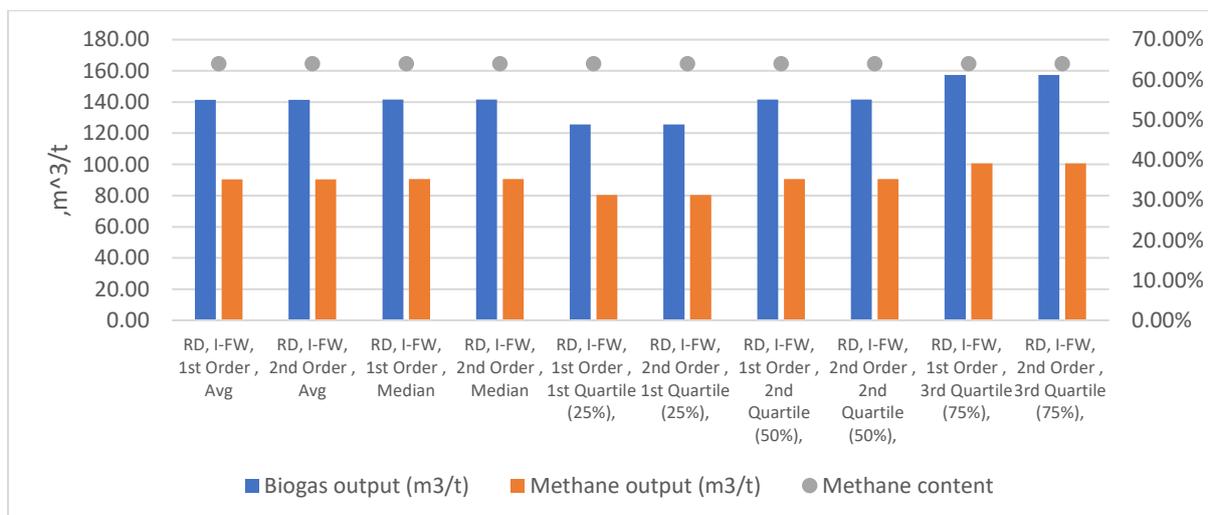


Figure 136. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from industrial (I) food wastes (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 141m³/t, followed by a median value range of 142m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 126m³/t, 142m³/t and 157m³/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content value of 64% throughout.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 90.46 m³/t, 90.63m³/t, 80.44m³/t, 90.63m³/t and 100.65 m³/t, respectively.

5.3.2.7 Finding 1.7 – Mixed Food Waste to biogas and biomethane conversion yield findings

This section outlines findings on Mixed FW (MFW) to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 116 data points (using 1st order average) and 23 experimental studies (using 2nd order average), with all results being outlined in Table 108 and Figure 137 below (also see Table 100, for relevant full terms corresponding to abbreviations used).

Table 108. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from mixed food waste (MFW) (Data Points = 116, Experimental Studies = 23)

Abbreviated names only	Biogas output (m ³ /t)	Methane output (m ³ /t)	Methane content
RD, MFW, 1st Order, Mean	125.35	78.74	62.89%
RD, MFW, 2nd Order, Mean	138.27	89.66	64.31%
RD, MFW, 1st Order, Median	122.38	71.86	63.94%
RD, MFW, 2nd Order, Median	127.14	77.70	65.35%
RD, MFW, 1st Order, 1st Quartile (25%),	71.00	42.99	58.36%
RD, MFW, 2nd Order, 1st Quartile (25%),	91.12	56.85	58.30%
RD, MFW, 1st Order, 2nd Quartile (50%),	122.38	71.86	63.94%
RD, MFW, 2nd Order, 2nd Quartile (50%),	127.14	77.70	65.35%
RD, MFW, 1st Order, 3rd Quartile (75%),	177.19	111.84	70.00%
RD, MFW, 2nd Order, 3rd Quartile (75%),	158.21	106.80	70.00%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

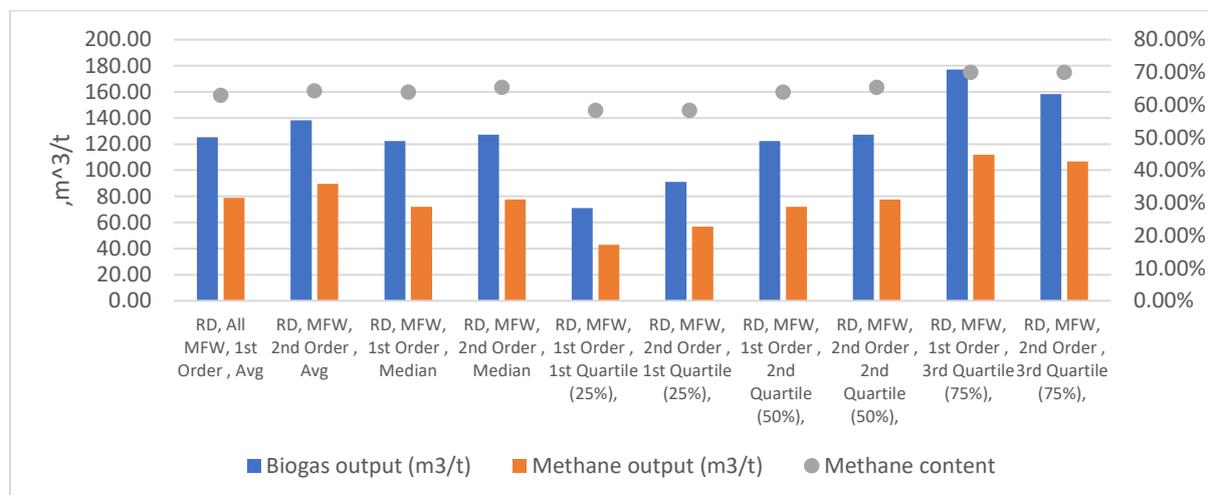


Figure 137. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from mixed food waste (MFW) (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 125-138m³/t, followed by a median value range of 122-127m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 71-91m³/t, 122-127m³/t and 158-177m³/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 62.89-64.31%, 63.94-65.35%, 58.30-58.36%, 63.94-65.35% and 70.00%, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 78-90m³/t, 72-78m³/t, 43-57m³/t, 72-78m³/t and 107-112m³/t, respectively.

5.3.2.8 Finding 1.8 – Mixed Food and Vegetable Waste to biogas and biomethane conversion yield findings

This section outlines findings on Mixed Food and Vegetable Waste (MFVW) to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 20 data points (using 1st order average) and 2 experimental studies (using 2nd order average), with all results being outlined in Table 109 and Figure 138 below (also see Table 100, for relevant full terms corresponding to abbreviations used).

Table 109. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from mixed food and vegetable waste (MFVW) (Data Points = 20, Experimental Studies = 2)

Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
RD, MFVW, 1st Order, Mean	104.35	57.71	56.33%
RD, MFVW, 2nd Order, Mean	104.35	57.71	53.30%
RD, MFVW, 1st Order, Median	104.15	58.78	56.00%
RD, MFVW, 2nd Order, Median	104.35	57.71	26.65%
RD, MFVW, 1st Order, Q1 (25%),	67.24	42.57	53.75%
RD, MFVW, 2nd Order, Q1 (25%),	84.52	48.27	13.33%
RD, MFVW, 1st Order, Q2 (50%),	104.15	58.78	56.00%
RD, MFVW, 2nd Order, Q2 (50%),	104.35	57.71	26.65%
RD, MFVW, 1st Order, Q3 (75%),	142.48	75.74	58.25%
RD, MFVW, 2nd Order, Q3 (75%),	124.17	67.15	39.98%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

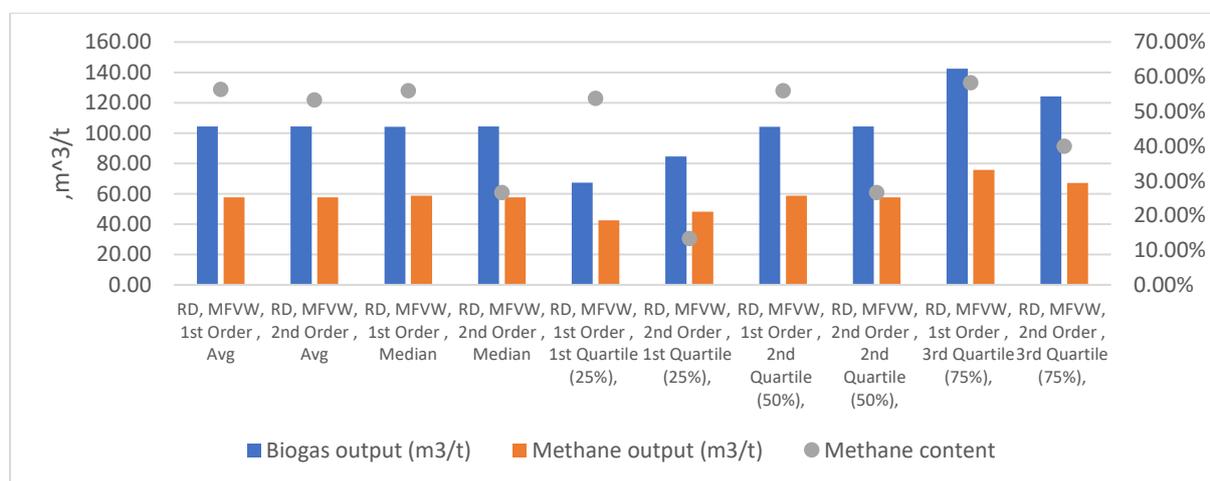


Figure 138. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from mixed food and vegetable waste (MFVW) (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 104m³/t, followed by a median value range of 104m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 67-85m³/t, 104m³/t and 124-142m³/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 53.30-56.33%, 26.65-56%, 13.33-53.75%, 26.65-56%, 39.98-58.25%, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 58m³/t, 58-59m³/t, 43-48m³/t, 58-59m³/t and 67-76m³/t, respectively.

5.3.2.9 Finding 1.9 – Mixed Fruit and vegetable waste to biogas and biomethane conversion yield findings

This section outlines findings on Mixed Fruit and Vegetable FW (MFrVFW) to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 19 data points (using 1st order average) and 4 experimental studies (using 2nd order average), with all results being outlined in Table 110 and Figure 139 below (also see Table 100, for relevant full terms corresponding to abbreviations used).

Table 110. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from mixed fruit and vegetable waste (MFrVFW) (Data Points = 3, Experimental Studies = 1)

Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
All Exp, 1st Order, Mean	84.34	42.65	52.18%
All Exp, 2nd Order, Mean	80.86	47.19	59.13%
All Exp, 1st Order, Median	54.11	29.93	58.00%
All Exp, 2nd Order, Median	79.16	46.28	61.13%
All Exp, 1st Order, Q1 (25%),	36.96	19.24	45.00%
All Exp, 2nd Order, Q1 (25%),	52.24	33.27	54.01%
All Exp, 1st Order, Q2 (50%),	55.73	32.54	58.00%
All Exp, 2nd Order, Q2 (50%),	79.16	46.28	61.13%
All Exp, 1st Order, Q3 (75%),	104.25	67.02	61.10%
All Exp, 2nd Order, Q3 (75%),	107.78	60.20	66.25%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

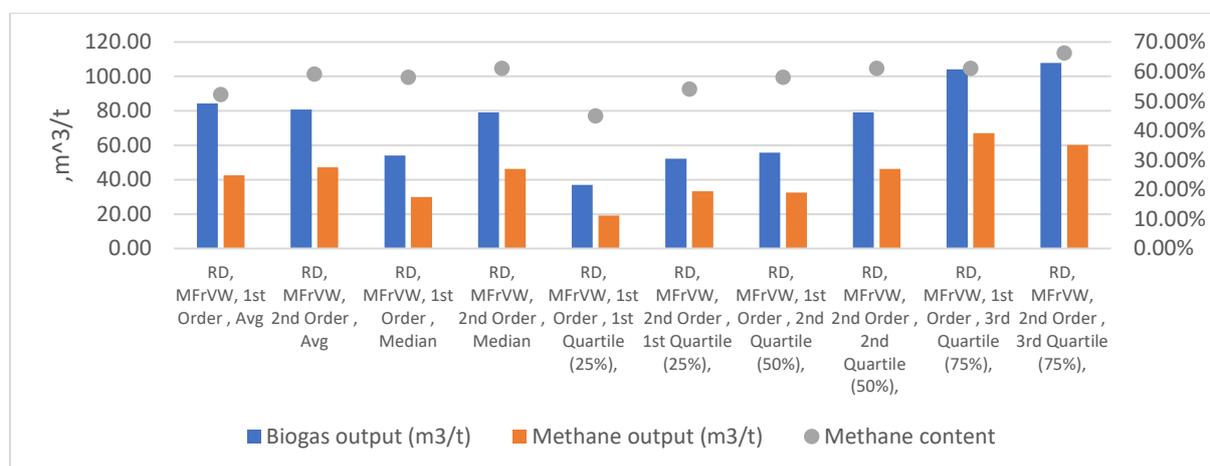


Figure 139. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from mixed fruit and vegetable waste (MFrVFW) (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 81-84m³/t, followed by a median value range of 54-79m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 37-52m³/t, 56-79m³/t and 104-108m³/t respectively.

These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 52.18-59.13%, 58-61.13%, 45-54.01%, 58-61.13%, 61.10-66.25, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 43-47m³/t, 30-46m³/t, 19-33m³/t, 33-46m³/t and 60-67m³/t, respectively.

5.3.2.10 Finding 1.10 – Mixed Vegetable Waste to biogas and biomethane conversion yield findings

This section outlines findings on household FW to biogas and biomethane conversion yield on a per tonne FW (m³/t) basis arising from 3 data points (using 1st order average) and 1 experimental studies (using 2nd order average), with all results being outlined in Table 111 and Figure 140 below (also see Table 100, for relevant full terms corresponding to abbreviations used).

Table 111. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from commercial FW (Data Points = 132, Experimental Studies = 25)

Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
All Exp,1st Order, Mean	20.64	13.21	64.00%
All Exp, 2nd Order, Mean	20.64	13.21	64.00%
All Exp, 1st Order, Median	18.18	11.64	64.00%
All Exp, 2nd Order, Median	20.64	13.21	64.00%
All Exp, 1st Order, Q1 (25%),	14.05	8.99	64.00%
All Exp, 2nd Order, Q1 (25%),	20.64	13.21	64.00%
All Exp, 1st Order, Q2 (50%),	18.18	11.64	64.00%
All Exp, 2nd Order, Q2 (50%),	20.64	13.21	64.00%
All Exp, 1st Order, Q3 (75%),	26.00	16.64	64.00%
All Exp, 2nd Order, Q3 (75%),	20.64	13.21	64.00%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

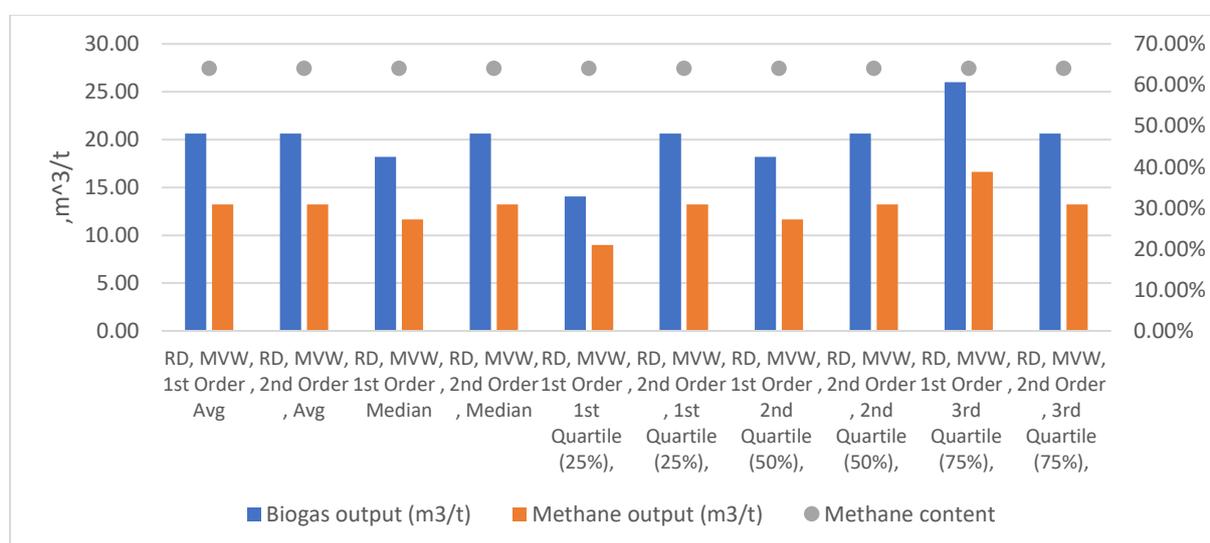


Figure 140. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from commercial and industrial (C&I) food wastes (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 21m³/t, followed by a median value range of 18-21m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 14-21m³/t, 18-21m³/t and 21-26m³/t respectively. These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 64% throughout.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 13m³/t, 12-13m³/t, 9-13m³/t, 12-13m³/t and 13-17m³/t, respectively.

5.3.2.11 Finding 1.11 – Mesophilic AD FW to biogas and biomethane conversion yield findings

This section outlines findings on biogas and biomethane conversion yield of all FW operated under mesophilic AD conditions on a per tonne FW (m³/t) basis arising from 108 data points (using 1st order average) and 19 experimental studies (using 2nd order average), with all results being outlined in Table 112 and Figure 141 below (also see Table 100, for relevant full terms corresponding to abbreviations used).

Table 112. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from all FW operated under mesophilic AD operational conditions (Data Points = 108, Experimental Studies = 19)

Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
RD, All FW, TM-AD, 1st Order, Mean	119.73	71.85	60.49%
RD, All FW, TM-AD, 2nd Order, Mean	117.57	72.18	62.07%
RD, All FW, TM-AD, 1st Order, Median	121.08	71.25	62.30%
RD, All FW, TM-AD, 2nd Order, Median	116.83	73.08	64.80%
RD, All FW, TM-AD, 1st Order, 1st Quartile (25%),	76.45	46.15	55.00%
RD, All FW, TM-AD, 2nd Order, 1st Quartile (25%),	84.97	51.91	58.01%
RD, All FW, TM-AD, 1st Order, 2nd Quartile (50%),	121.08	71.25	62.30%
RD, All FW, TM-AD, 2nd Order, 2nd Quartile (50%),	116.83	73.08	64.80%
RD, All FW, TM-AD, 1st Order, 3rd Quartile (75%),	164.04	95.43	68.07%
RD, All FW, TM-AD, 2nd Order, 3rd Quartile (75%),	153.65	84.35	70.00%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

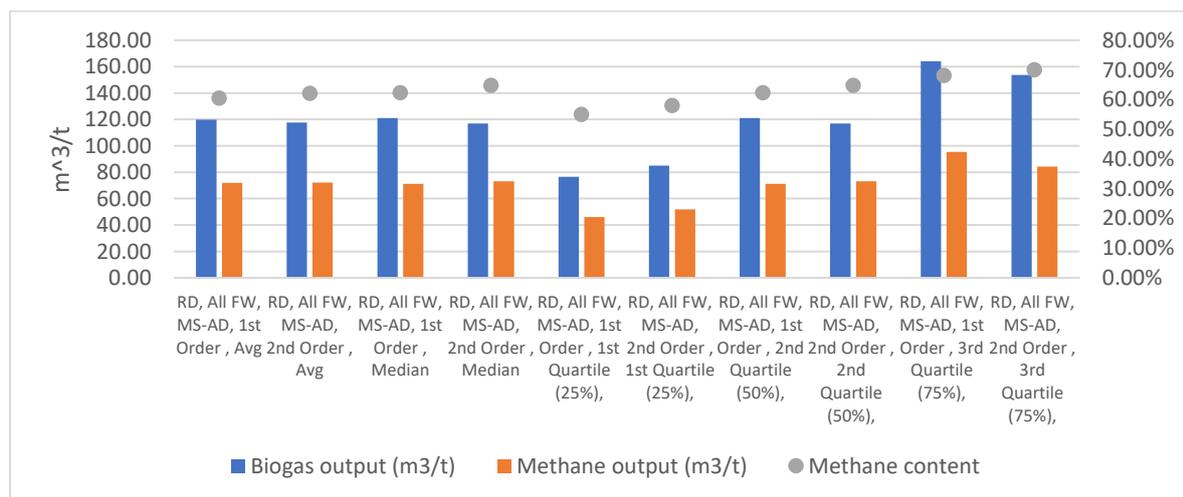


Figure 141. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from all FW operated under mesophilic AD operational conditions (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 118-120m³/t, followed by a median value range of 117-121m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 76-85m³/t, 117-121m³/t and 154-164m³/t respectively. These are

accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 60.49-62.07%, 62.30-64.80%, 55-58.01%, 62.30-64.80%, 68.07-70%, respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 72m³/t, 71-73m³/t, 46-52m³/t, 71-73m³/t and 84-95m³/t, respectively.

5.3.2.12 Finding 1.12 – Thermophilic AD FW to biogas and biomethane conversion yield

This section outlines findings on biogas and biomethane conversion yield of all FW operated under thermophilic AD conditions on a per tonne FW (m³/t) basis arising from 26 data points (using 1st order average) and 8 experimental studies (using 2nd order average), with all results being outlined in Table 113 and Figure 142 below (also see Table 100, for relevant full terms corresponding to abbreviations used).

Table 113. Table of data for all averages findings for food waste biogas and biomethane yield, and corresponding methane content (extracted from original Excel model) from all FW operated under thermophilic AD operational conditions (Data Points = 26, Experimental Studies = 8)

Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
RD, All FW, TM-AD, 1st Order, Mean	90.08	55.72	60.17%
RD, All FW, TM-AD, 2nd Order, Mean	100.46	63.19	62.54%
RD, All FW, TM-AD, 1st Order, Median	70.22	40.68	61.60%
RD, All FW, TM-AD, 2nd Order, Median	100.16	57.96	62.01%
RD, All FW, TM-AD, 1st Order, 1st Quartile (25%),	47.0859	27.64941	58.00%
RD, All FW, TM-AD, 2nd Order, 1st Quartile (25%),	50.25665	31.00611	58.59%
RD, All FW, TM-AD, 1st Order, 2nd Quartile (50%),	70.22466	40.67913	61.60%
RD, All FW, TM-AD, 2nd Order, 2nd Quartile (50%),	100.164	57.96068	62.01%
RD, All FW, TM-AD, 1st Order, 3rd Quartile (75%),	136.2683	72.22222	63.77%
RD, All FW, TM-AD, 2nd Order, 3rd Quartile (75%),	157.3145	102.2216	65.28%

*Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively

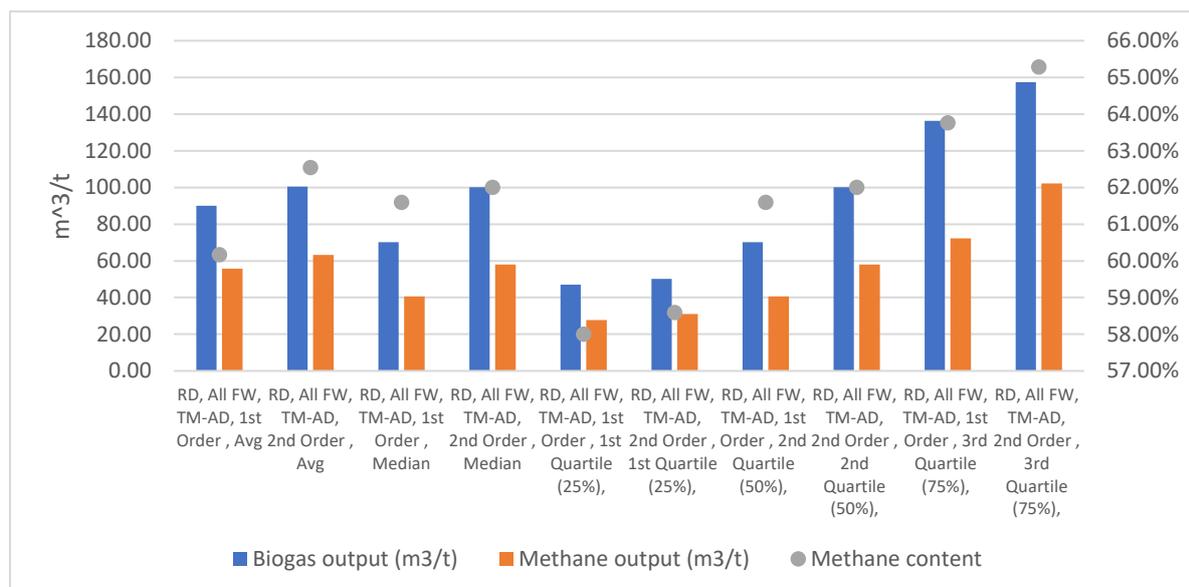


Figure 142. All averages findings for food waste biogas and biomethane yield, and corresponding methane content from all FW operated under mesophilic AD operational conditions (Data Points = 108, Experimental Studies = 19) (please note the m³/t as shown in the figure pertains to m³/t).

The results show a mean FW to biogas conversion yield of approximately 90-100m³/t, followed by a median value range of 70-100m³/t, and first, second, third quartile (Q1, Q2, and Q3) value range of 47-50m³/t, 70-100m³/t and 136-157m³/t respectively. These are accompanied by corresponding mean, median, Q1, Q2 and Q3 methane content ranges of 60.17-62.54%, 61.60-62.01%, 58-58.59%, 61.60-62.01%, 63.77-65.28% respectively.

Factor in the above two dataset consequently give rise to a respective mean, median, Q1, Q2 and Q3 FW to biomethane conversion yields range of approximately 56-63m³/t, 41-58m³/t, 28-31m³/t, 41-58m³/t and 72-102m³/t, respectively.

An alternative representation of results is shown below by grouping together all FW types using the same analytic metric, i.e. mean, median, and first to third interquartile range (Q1-3) for all FW types, as opposed to all analytical metrics for the same FW type as shown above.

5.3.2.13 Finding 1.13 – Thermophilic AD FW to biogas and biomethane conversion yield

The above results were further analysed and summarized using 7 most relevant technical categories as outlined in Table 114, Figure 143, Table 115 and Figure 144 below, which returned a 1st and 2nd order mean value range of 46-82m³/t and 46-90m³/t for food waste biogas and biomethane conversion yields respectively. These are also accompanied with a corresponding 1st and 2nd order methane content range of 59.67-75.54% and 61.92-70.31%, respectively.

Table 114. Summary of all 1st order mean FW to biogas and biomethane conversion yield data based on relevant technical data categories of FW type and AD operational temperature

	Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
1	All Exp,1st Order, Mean	116.29	70.89	60.89%
2	RD, HH-FW, 1st Order, Mean	74.07	45.83	64.18%
3	RD, HH&C-FW, 1st Order, Mean	111.35	81.69	75.54%
4	RD, C-FW, 1st Order, Mean	116.16	69.7	59.67%
5	RD, All MFW, 1st Order, Mean	125.35	78.74	62.89%
6	RD, All FW, MS-AD, 1st Order, Mean	119.73	71.85	60.49%
7	RD, All FW, TM-AD, 1st Order, Mean	90.08	55.72	60.17%
9	Mean (of all 1 st order mean results)	107.58	67.77	63.40%

*HH = household, HH&C = Household and commercial, C = Commercial,

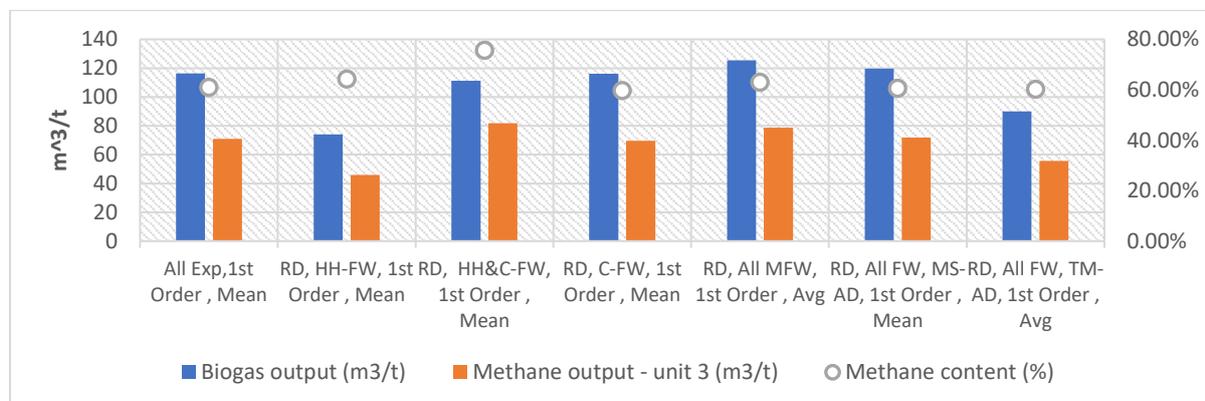


Figure 143. Graphical illustration of all 1st order mean FW to biogas and biomethane conversion yield data with biomethane yield based on relevant technical data categories of FW type and AD operational temperature (please note the m³/t as shown in the figure pertains to m³/t).

Table 115. Summary of all 2nd order mean FW to biogas and biomethane conversion yield data based on relevant technical data categories of FW type and AD operational temperature

	Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
1	All Exp, 2nd Order, Mean	130.06	80.22	62.97%
2	RD, HH-FW, 2nd Order, Mean	74.07	45.83	64.18%
3	RD, HH&C-FW, 2nd Order, Mean	116.8	81.02	70.31%
4	RD, C-FW, 2nd Order, Mean	128.48	81.11	61.92%
5	RD, MFW, 2nd Order, Mean	138.27	89.66	64.31%
6	RD, All FW, MS-AD, 2nd Order, Mean	117.57	72.18	62.07%
7	RD, All FW, TM-AD, 2nd Order, Mean	100.46	63.19	62.54%
8	Mean (of all 2 nd order mean results)	115.10	73.32	64.04%

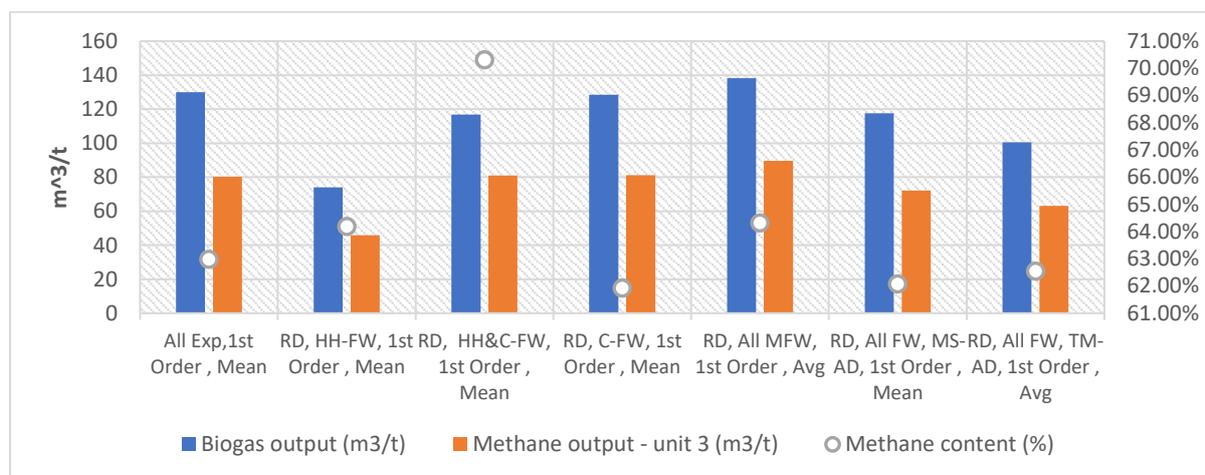


Figure 144. Graphical illustration of all 2nd order mean FW to biogas and biomethane conversion yield data with biomethane yield based on relevant technical data categories of FW type and AD operational temperature (please note the m³/t as shown in the figure pertains to m³/t).

Likewise, these findings also demonstrated a 1st and 2nd order median value range of 41-87m³/t and 46-82m³/t for food waste biogas and biomethane conversion yields based on the same 7 (most relevant) technical measurements (see Table 116, Figure 145, Table 117 and Figure 146). These are also accompanied with a corresponding 1st and 2nd order methane content range of 60.50-77.60% and 59.67-75.54%, respectively.

Table 116. Summary of all 1st order median FW to biogas and biomethane conversion yield data based on relevant technical data categories of FW type and AD operational temperature

	Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
1	All Exp, 1st Order, Median	105.72	69.24	62.00%
2	RD, HH-FW, 1st Order, Median	59.08	41.35	66.35%
3	RD, HH&C-FW, 1st Order, Median	102.6	87.08	77.60%
4	RD, C-FW, 1st Order, Median	105.88	68.04	60.50%
5	RD, MFW, 1st Order, Median	122.38	71.86	63.94%
6	RD, All FW, TM-AD, 1st Order, Median	121.08	71.25	62.30%
7	RD, All FW, TM-AD, 1st Order, Median	70.22	40.68	61.60%
8	Mean (of all 1 st order mean results)	98.14	64.21	64.90%

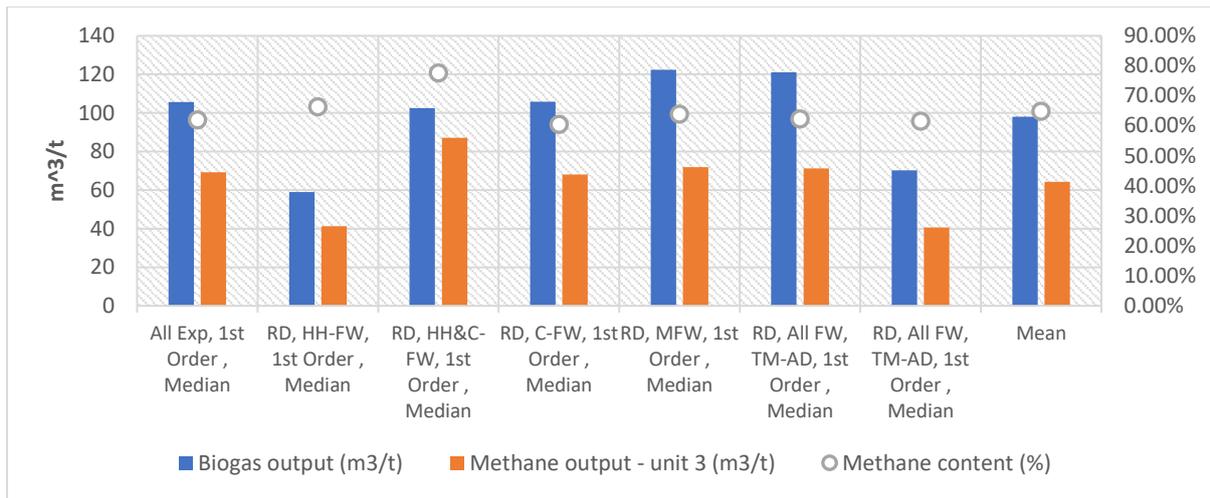


Figure 145. Graphical illustration of all 1st order median FW to biogas and biomethane conversion yield data with biomethane yield based on relevant technical data categories of FW type and AD operational temperature (please note the m³/t as shown in the figure pertains to m³/t).

Table 117. Summary of all 2nd order median FW to biogas and biomethane conversion yield data based on relevant technical data categories of FW type and AD operational temperature

	Abbreviated names only	Biogas output (m ³ /t)	Methane output - unit 3 (m ³ /t)	Methane content (%)
1	All Exp, 2nd Order, Median	116.29	70.89	60.89%
2	RD, HH-FW, 2nd Order, Median	74.07	45.83	64.18%
3	RD, HH&C-FW, 2nd Order, Median	111.35	81.69	75.54%
4	RD, C-FW, 2nd Order, Median	116.16	69.7	59.67%
5	RD, All MFW, 2nd Order, Median	125.35	78.74	62.89%
6	RD, All FW, MS-AD, 2nd Order, Median	119.73	71.85	60.49%
7	RD, All FW, TM-AD, 2nd Order, Median	90.08	55.72	60.17%
8	Mean (of all 2nd Order, mean results)	107.58	67.77	63.40%

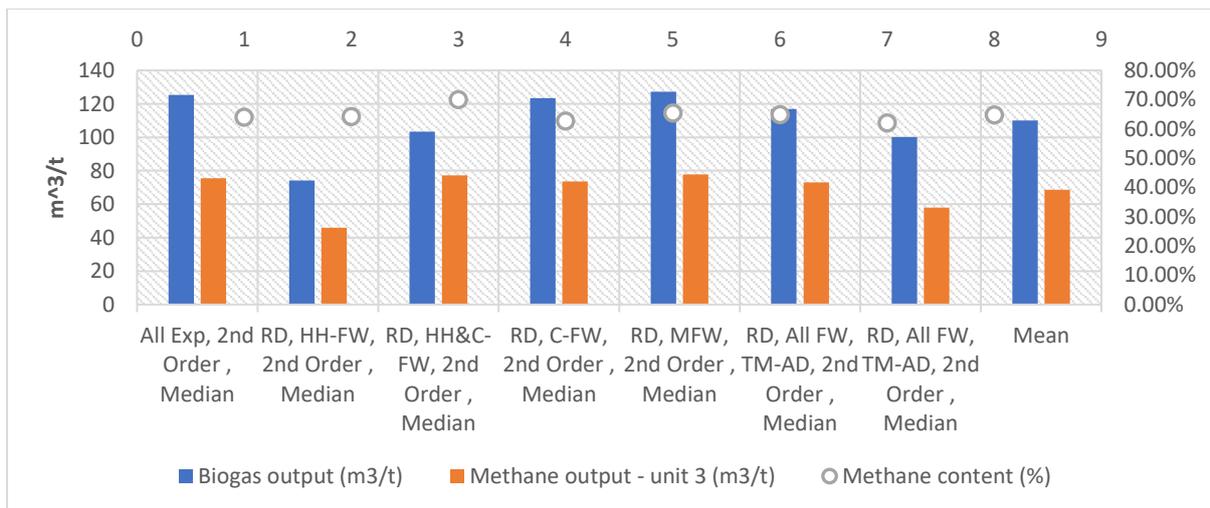


Figure 146. Graphical illustration of all 2nd order median FW to biogas and biomethane conversion yield data with biomethane yield based on relevant technical data categories of FW type and AD operational temperature (please note the m³/t as shown in the figure pertains to m³/t).

These findings constitute a preliminary acceptable FW to biogas and biomethane conversion data range of 45-90m³/t (and methane content range of 60-76%) for use in estimating total

biogas and biomethane potential for each NPH scenario region between 2010 and 2050 as defined by aforementioned pathway deployment boundary conditions. The final conversion value chosen will be pending on outcome of further cross-evaluation with NFCCC’s real-world AD operational data outlined in the next section (see Chapter 5.3.3 - findings 2).

Here it is worth noting that the FW to biomethane energy conversion potential has a multiplier potential effect of 2x (45-90m³/t FW) on basis of FW used. Interestingly, where commercial FW is used either alone or with household FW, the overall biomethane yield appears to be much higher than if household FW is used alone, as will be further elaborated in the next section.

A separate comparative analysis of all FW types using the same respective analytical measurements of mean, median, and interquartile ranges (Q1, Q2 and Q3) is conducted below with aim to establish further insight on FWtTBC pathway deployment strategies and relevant supporting policies.

5.3.2.14 Finding 1.14 – All FW to biogas and biomethane conversion yield, all mean values

Table 118. Comparison of all mean values (1st and 2nd order) for all FW types derived from experimental studies used for Excel modelling

	Food Waste (FW) type (1-10) or AD type (11-12)	Abbreviation	1 st Order Mean			2 nd Order Mean		
			Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)	Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)
1	All FW	AFW	116.29	70.89	60.89%	130.06	80.22	62.97%
2	Household FW	HHFW	74.07	45.83	64.18%	74.07	45.83	64.18%
3	Household and Commercial FW	HH&C-FW	111.35	81.69	75.54%	116.80	81.02	70.31%
4	Commercial FW	CFW	116.16	69.70	59.67%	128.48	81.11	61.92%
5	Commercial and Industrial FW	C&I-FW	169.69	107.02	64.64%	169.52	107.57	64.37%
6	Industrial FW	IFW	141.35	90.46	64.00%	141.35	90.46	64.00%
7	Mixed FW	MFW	125.35	78.74	62.89%	138.27	89.66	64.31%
8	Mixed Food and Vegetable Waste	MFVW	104.35	57.71	56.33%	104.35	57.71	53.30%
9	Mixed Fruit and Vegetable Waste	MFrVW	84.34	42.65	52.18%	80.86	47.19	59.13%
10	Mixed Vegetable Waste	MVW	20.64	13.21	64.00%	20.64	13.21	64.00%
11	Mesophilic AD FW	M-AD-FW	119.73	71.85	60.49%	117.57	72.18	62.07%
12	Thermophilic AD FW	T-AD-FW	90.08	55.72	60.17%	100.46	63.19	62.54%

Mean values findings shows C&I-FW to yield the greatest methane content (107m³/t), followed by IFW (90m³/t), HH&C-FW (81 and 82m³/t), MFW (79 and 90m³/t), AFW (80m³/t), CFW (70 and 81m³/t), MFVW (58m³/t). Interestingly HHFW (46m³/t) yields relatively lower methane content, followed by MFrVW (43 and 47m³/t) and MVW (13m³/t) (see Table 118).

Table 119. Comparison of all median values (1st and 2nd order) for all FW types derived from experimental studies used for Excel modelling

	Food Waste (FW) type (1-10) or AD type (11-12)	Abbreviation	1 st Order Median			2 nd Order Median		
			Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)	Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)
1	All FW	AFW	105.72	69.24	62.00%	125.24	75.43	64.00%
2	Household FW	HHFW	59.08	41.35	66.35%	74.07	45.83	64.18%
3	Household and Commercial FW	HH&C-FW	102.60	87.08	77.60%	103.35	77.19	70.00%
4	Commercial FW	CFW	105.88	68.04	60.50%	123.33	73.64	62.71%
5	Commercial and Industrial FW	C&I-FW	186.92	119.20	63.77%	169.52	107.57	64.37%
6	Industrial FW	IFW	141.62	90.63	64.00%	141.62	90.63	64.00%
7	Mixed FW	MFW	122.38	71.86	63.94%	127.14	77.70	65.35%
8	Mixed Food and Vegetable Waste	MFVW	104.15	58.78	56.00%	104.35	57.71	26.65%
9	Mixed Fruit and Vegetable Waste	MFrVW	54.11	29.93	58.00%	79.16	46.28	61.13%
10	Mixed Vegetable Waste	MVW	18.18	11.64	64.00%	20.64	13.21	64.00%
11	Mesophilic AD FW	M-AD-FW	121.08	71.25	62.30%	116.83	73.08	64.80%
12	Thermophilic AD FW	T-AD-FW	70.22	40.68	61.60%	100.16	57.96	62.01%

Median values findings show C&I-FW to yield the greatest methane content (119 and 108m³/t), followed by IFW (91m³/t), HH&C-FW (87 and 77m³/t), MFW (72 and 78m³/t), AFW (69 and 75m³/t), CFW (68 and 74m³/t), MFVW (59 and 58 m³/t). Again, HHFW (41 and 46m³/t) yields relatively lower methane content, followed by MFrVW (30 and 46m³/t) and MVW (12 and 13m³/t) (see Table 119).

5.3.2.15 Finding 1.15 – All FW to biogas and biomethane conversion yield, all interquartile (first, second third or Q1, Q3 and Q3 interquartile) values

Table 120. Comparison of all Interquartile (1st Quartile or Q1) values (1st and 2nd order) for all FW types derived from experimental studies used for Excel modelling

	Food Waste (FW) type (1-10) or AD type (11-12)	Abbreviation	1 st Order First quartile (Q1)			2 nd Order First quartile (Q1)		
			Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)	Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)
1	All FW	AFW	59.73	38.85	57.00%	77.08	48.78	57.71%
2	Household FW	HHFW	55.69	38.99	59.44%	65.54	42.87	61.26%
3	Household and Commercial FW	HH&C-FW	99.86	71.72	70.00%	102.53	71.77	68.00%
4	Commercial FW	CFW	59.34	33.76	56.00%	64.69	38.83	57.44%
5	Commercial and Industrial FW	C&I-FW	127.98	86.89	61.19%	169.40	107.18	64.19%
6	Industrial FW	IFW	125.69	80.44	64.00%	125.69	80.44	64.00%
7	Mixed FW	MFW	71.00	42.99	58.36%	91.12	56.85	58.30%
8	Mixed Food and Vegetable Waste	MFVW	67.24	42.57	53.75%	84.52	48.27	13.33%
9	Mixed Fruit and Vegetable Waste	MFrVW	36.96	19.24	45.00%	52.24	33.27	54.01%
10	Mixed Vegetable Waste	MVW	14.05	8.99	64.00%	20.64	13.21	64.00%
11	Mesophilic AD FW	M-AD-FW	76.45	46.15	55.00%	84.97	51.91	58.01%
12	Thermophilic AD FW	T-AD-FW	47.0859	27.64941	58.00%	50.25665	31.00611	58.59%

First quartile (Q1 Interquartile) values findings shows C&I-FW to yield the greatest methane content (87 and 107m³/t), followed by IFW (80m³/t), HH&C-FW (72m³/t), MFW (43 and 57m³/t),

AFW (39 and 49m³/t), HHFW (39 and 43m³/t), CFW (34 and 39m³/t), MFVW (19 and 33m³/t), MFrVW (19 and 33m³/t) and MVW (9 and 13m³/t). Here it is interesting to note HHFW possess a higher Q1 relative to its mean and median methane content value (see

Table 120).

Table 121. Comparison of all Interquartile (2nd Quartile or Q2) values (1st and 2nd order) for all FW types derived from experimental studies used for Excel modelling

	Food Waste (FW) type (1-10) or AD type (11-12)	Abbreviation	1 st Order Second quartile (Q2)			2 nd Order Second quartile (Q2)		
			Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)	Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)
1	All FW	AFW	105.72	69.24	62.00%	125.24	75.43	64.00%
2	Household FW	HHFW	59.08	41.35	66.35%	74.07	45.83	64.18%
3	Household and Commercial FW	HH&C-FW	102.60	76.67	76.50%	103.35	77.19	70.00%
4	Commercial FW	CFW	105.88	68.04	60.50%	123.33	73.64	62.71%
5	Commercial and Industrial FW	C&I-FW	186.92	119.20	63.77%	169.52	107.57	64.37%
6	Industrial FW	IFW	141.62	90.63	64.00%	141.62	90.63	64.00%
7	Mixed FW	MFW	122.38	71.86	63.94%	127.14	77.70	65.35%
8	Mixed Food and Vegetable Waste	MFVW	104.15	58.78	56.00%	104.35	57.71	26.65%
9	Mixed Fruit and Vegetable Waste	MFrVW	55.73	32.54	58.00%	79.16	46.28	61.13%
10	Mixed Vegetable Waste	MVW	18.18	11.64	64.00%	20.64	13.21	64.00%
11	Mesophilic AD FW	M-AD-FW	121.08	71.25	62.30%	116.83	73.08	64.80%
12	Thermophilic AD FW	T-AD-FW	70.22466	40.67913	61.60%	100.164	57.96068	62.01%

Second quartile (Q2 Interquartile) values findings show C&I-FW to yield the greatest methane content (123 and 108m³/t), followed by MFW (112 and 107m³/t), IFW (101m³/t), AFW (98 and 91m³/t), HH&C-FW (98 and 86m³/t), CFW (95 and 89m³/t), MFVW (76 and 67m³/t), MFrVW (67 and 60m³/t), HHFW (44 and 49m³/t) and MVW (17 and 13m³/t). Here it is interesting to note HHFW possess a slightly lower Q2 relative to its mean and median methane content value (in stark contrast compared to Q1 results) (see Table 121).

Table 122. Comparison of all Interquartile (3rd Quartile or Q3) values (1st and 2nd order) for all FW types derived from experimental studies used for Excel modelling

	Food Waste (FW) type (1-10) or AD type (11-12)	Abbreviation	1 st Order Third quartile (Q3)			2 nd Order Third quartile (Q3)		
			Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)	Biogas yield (m ³ /t)	Methane yield (m ³ /t)	Methane content (%)
1	All FW	AFW	166.24	97.52	67.00%	157.81	91.27	70.00%
2	Household FW	HHFW	75.62	43.75	70.00%	82.60	48.78	67.09%
3	Household and Commercial FW	HH&C-FW	129.52	97.79	79.20%	117.62	86.45	72.23%
4	Commercial FW	CFW	167.10	94.62	66.02%	157.02	89.00	70.00%
5	Commercial and Industrial FW	C&I-FW	207.24	123.26	66.05%	169.64	107.95	64.56%
6	Industrial FW	IFW	157.27	100.65	64.00%	157.27	100.65	64.00%
7	Mixed FW	MFW	177.19	111.84	70.00%	158.21	106.80	70.00%
8	Mixed Food and Vegetable Waste	MFVW	142.48	75.74	58.25%	124.17	67.15	39.98%
9	Mixed Fruit and Vegetable Waste	MFrVW	104.25	67.02	61.10%	107.78	60.20	66.25%
10	Mixed Vegetable Waste	MVW	26.00	16.64	64.00%	20.64	13.21	64.00%
11	Mesophilic AD FW	M-AD-FW	164.04	95.43	68.07%	153.65	84.35	70.00%
12	Thermophilic AD FW	T-AD-FW	136.2683	72.22222	63.77%	157.3145	102.2216	65.28%

Third quartile (Q3 Interquartile) values findings show C&I-FW to yield the greatest methane content (123 and 170m³/t), followed by MFW (112 and 107m³/t), IFW (101m³/t), AFW (98 and

91m³/t), HH&C-FW (98 and 86m³/t), CFW (95 and 89m³/t), MFVW (76 and 67m³/t), MFrVW (76 and 67m³/t), HHFW (44 and 49m³/t) and MVW (17 and 13m³/t). Here it is interesting to note HHFW possess a slightly lower Q3 (same as Q2 results) relative to its mean and median methane content value (in stark contrast compared to Q1 results) (see Table 122).

5.3.2.16 Finding 1.16 – Discussion of all results in form of combined data findings

Analysis of results relating to findings 1.13 to findings 1.15 showing a comparative analysis of all FW types using key metrics (mean, median and Q1-Q3 Interquartile ranges) interestingly demonstrates greatest biomethane yield appear to be from commercial and industrial FW (C&I-FW), followed by industrial FW (IFW), household and commercial FW (HH&C-FW), mixed FW (MFW) and all FW (AFW) types. In contrast, mixed vegetable waste (MVW), mixed fruit and vegetable waste (MFrVW), mixed food and vegetable waste (MFVW) and household FW (HHFW) has shown to give rise to relatively low biomethane content.

The general rationale accounting for such differences is likely due to the different composition that constitutes each waste type, with commercial and industrial waste typically contain higher energy content due to use of more oil and grease as opposed to other waste types. Likewise, given the general eating habits of many households and UK’s diet, it would be reasonable to assume that household FW would typically include greater quantities of vegetables and fruits that are typically lower in their energy contents, with significantly lower biomethane conversion potential (as observed in the MVW category). Verifications of these however will require accurate data documenting the specific composition of the collected FW, which could be conducted as part of future research.

It is important to note that the biomethane content of household FW (HHFW) can be greatly increased through mixture with commercial FW (CFW) and also possibly industrial FW (IFW), translating to the potential need to bridge FW collection between households and other commercial or industrial outlets to favour real world FWtTBC pathway deployment.

Based on these available data and insight, further research should focus on integration of HHFW with CFW and IFW collection, with other sources of FW being supplementary but not essential to the process. Relevant supporting policies should consequently at least explore if not actively promote the integration of FW collection from household with commercial and industrial sources (Table 123).

Table 123. General policy support to promote suitable FW collection strategies and good practices across relevant regions of interest

General policy support		Goals
1	Offer intra-city, city and county level financial incentives (investments, loans) and non-financial support (networking) to explore integration of FW collection schemes across key outlets including from household, businesses and industry	Support and Promote FWtTBC pathway deployment in a manner which bridges FW collection from household with other commercial and industrial sources of FW
2	Offer additional incentive to participating regions that demonstrate excellent data collection and insight gathering practices during implementing of relevant FW schemes	
3	Offer incentives to participating households and businesses in the scheme in a manner that promotes data and insight gathering	

It is hoped that the effective implementation of these policies would support the deployment of FWtTBC pathway in a manner that collectively reduces both household and non-household (commercial and industrial) FW in light of the above findings, by ensure that the downstream benefits of FW landfill diversion and revenue generation from higher biomethane generation (sale, tariff incentives, avoided landfilled costs) would sufficiently outweigh perceived costs and risks of pathway deployment.

5.3.3 Finding 2 – Operational FW to Biogas and Biomethane data from AD plant operations

This section outlines all data findings on real-world AD operational FW to biogas and biomethane conversion yield attained from an official technical data spreadsheet collated by NFCCC (an officially recognized organisation for provision of AD related data) found using the Boolean search method (see

Table 34,

Table 35 and Figure 87 for details on relevant process operational metrics and calculations).

The dataset collectively includes details for 104 AD plants, with all general and operational details outlined in Table 124 below using 3 example AD plants.

Table 124. General and technical details for existing AD plant operations based on NFCCC AD plant Excel data used for establishing official AD map, contains key AD feedstock capacity, and food waste to biogas and biomethane yield conversion data

		Example 1	Example 2	Example 3
General details	Region	YH	NE	NE
	County	North Yorkshire	North Yorkshire	Durham
	Developer	AB Agri	BF Biogas	Emerald Biogas
	Site name	Maltings Organic Treatment Facility	Teeside Green Energy Plant	Newton Aycliffe Industrial
	Postcode	LS25 5DN	TS2 1UT	DL5 6AB
	Capacity (kWe)	2400	6250	1560
Operational and technical	Biomethane generation capacity (Nm ³ /hr biomethane)	550	495	660
	Energy output Capacity adjusted for Biogas Energy - BtG plants only (kWe)	7900	11200	8160
	Output energy	BtG & CHP	BtG & CHP	BtG & CHP
	Completion	2016	2015	2013
	Type	Waste-fed	Waste-fed	Waste-fed
	Feedstock capacity (tonnes/year)	Food waste & green waste	Green waste, animal slurry & food waste	C&I Food Waste
	Total feedstock capacity (tonnes/year)	82,500	40,000	73,000
	Food Waste input (tonnes/year)	50,000	16,000	73,000
	2ndary waste input (tonnes/year)	32,500	24,000	0
	Financial data	Costs ('000,000)	15	10.5
kWe/M		160	595	134
Capital £/kW - Un-Adjusted Biogas		6,250	1,680	7,487

	Capital £/kW - Adjusted Biogas	1,899	938	1,431
	Capital £/tFW	182	263	160

These 3 examples indicate plants of different scales can differ in their total waste capacity, annual waste input, biomethane or electricity generation capacity, total capital cost and cost per unit energy production.

The full results surrounding FW to biogas and biomethane conversion yields estimations will be calculated using the same subset of specific technical FW and AD parameters outlined above, with findings used for comparison of technical food waste to biogas and biomethane data arising from scientific literature data in finding 1 (see section on finding 1 and 2 comparison) (Table 125).

Table 125. Full terms and abbreviations for AD general and technical operational details pertaining to FW to biogas and biomethane conversion yield potential in context of their relative relevance and importance to overall research aims and objectives

Finding no.	Full Technical comparison	Relevant section	Details (feedstock, plant type, capacity or combination thereof)	Data points	Relevance & Importance	Rationale for relevance and importance of the results
2.1	Biogas to Grid (BtG) AD plant – All general feedstocks	5.3.3.1	All Feedstock, Biogas to Grid (BtG)	16	Very Strong / Very High	Representative feedstock and AD plant type
			FW-Only, BtG	9	Very Strong / Very High	
			FW + Other, BtG	7	Very Strong / Very High	
2.2	Combined Heat and Power (CHP) AD plant – All general feedstocks	5.3.3.2	All feedstock, CHP	63	Moderate / Moderate	Representative feedstock but not AD plant type
			FW-only, CHP	36	Moderate / Moderate	
			FW + Others, CHP	27	Moderate / Moderate	
2.3	Food waste + Additional (secondary) waste feedstock	5.3.2.3	All, FW + Animal Waste	1	High / Strong	Representative feedstock with mix (representative and non-representative) AD plant types
			All, FW + Crop	7	Strong / High	
			All, FW + Animal Processing Waste	8	Strong / High	
			All, FW + Green Waste	3	High / Strong	
2.4	AD capacity size	5.3.2.4	<250kWe	4	Weak / Low	AD plant scale unsuitable for large scale deployment

			250-500kWe	1	Moderate / Moderate	AD plant scale moderately suitable for large scale deployment
			>500kWe	3	High / Strong	AD plant scale strongly suitable for large scale deployment

Here it is important to note a few key limitations and corresponding calculation assumptions to the datasets used, relating mainly to AD operational efficiency and interpretation of FW to biomethane conversion data for both BtG and CHP plants.

For AD operational efficiency, there exist no specific details on whether if original CHP electricity and biomethane generation values correspond to either the maximum outputs attainable if AD plant operates at 100% capacity or a lesser output that is more representative of real world AD operations. For purpose of calculations, the biomethane production values observed is assumed to be representative of those attained from typical real-world AD operations based on the, with operational efficiency to range of 50% to 90% which would represents the minimally acceptable to maximally achievable operational levels for suitable AD plants. Here it is important to note that the specific operational efficiency of each AD plant included in the dataset (which may likely differ) is both unknown and becomes irrelevant for attaining any quantitative findings in this section given that the biomethane production values are primarily used, but should constitute an area of future research focusing on how improvements in operational efficiencies (if data exist) would affect the overall increased production of biomethane and associated financial metrics. Conversely, it is also possible for these reported values to be higher than the usual AD operational values, i.e. in case of AD operators themselves reporting on the data figures, which tend often lead to over than under reporting, though this possibility is deemed to be less likely and therefore ruled out given that all data comes from an industry recognised official and reputable source (NCPMP) that would have done their data due diligence prior to the reporting of such data.

The dataset also assumes that presented CHP electricity and biomethane generation values do not overlap and are generated separately from each other, and that CHP only plants derives most of their energy from combustion of biogas, the biogas quantities of which can be retrospectively estimated from the plant's overall generation capacity.

These assumptions consequently allow for the estimation of FW biomethane conversion yield from:

- (i) BtG plants by dividing annual biomethane generation capacity by annual FW input capacity,
- (ii) CHP plants, by dividing total electricity output (kWh) by biogas energy density (and assume a biogas to biomethane yield of 66%), then dividing results by annual FW input capacity.

Here it is also worth noting the added limitation in lack of data point for findings 2.3 and 2.4, and thus corresponding result should be open to reasonable interpretation.

Notwithstanding, this dataset on AD plant process operations does demonstrate moderate robustness in value and is used on basis of it being the most readily available data found using

Boolean data collection search method, that is applicable for cross-verifying real-world representativeness of research literature derived food waste to biogas and biomethane conversion yields.

5.3.3.1 Finding 2.1 – Biogas-to-Grid (BtG) AD plant biogas, biomethane and electricity conversion yields (All feedstocks)

Results for Biogas-to-Grid (BtG) AD plants demonstrate a mean and median FW feedstock to biomethane conversion yield of approximately 83.49m³/t and 87.66 m³/t, 104.69m³/t and 84.01m³/t, 121.18m³/t and 80.36m³/t for FW+Other, all substrates and FW-only feedstocks, respectively.

With regard to the mean values, these findings show good agreements with C&I-FW (107m³/t), IFW (90m³/t), HH&C-FW (81 and 82m³/t), MFW (79 and 90m³/t), AFW (80m³/t) and CFW (70 and 81m³/t) (see Table 118). Likewise, the median values show good agreements with HH&C-FW (87 and 77m³/t) and MFW (72 and 78m³/t) (see Table 119).

Interestingly, all BtG FW to biomethane conversion yield findings are greater than biomethane yield of household FW from academic literature data (approx. 46m³/t for mean and 41-46m³/t for median), likely due to the nature of feedstocks being a heterogenous mix of different FW derived from a wide variety of sources, i.e. household, commercial, industrial, etc. (see Table 126 and Figure 147).

Table 126. Table of data for AD operational feedstock to biogas, biomethane and electricity conversion yield for biogas-to-grid (BtGs) AD plants only (32 data points)

Abbreviated names only	Biogas output** (m ³ /tonne FW)	Methane output - (m ³ /tonne FW)	kWh output (kWh/tonne FW)
1 AD, All Substrates, BtG ADP, Mean	158.63	104.69	307.67
2 AD, All Substrates BtG ADP, Median	127.28	84.01	170.67
3 AD, All Substrates BtG ADP, Q1 (25%)	94.99	62.69	86.10
4 AD, All Substrates BtG ADP, Q2 (50%)	127.28	84.01	170.67
5 AD, All Substrates BtG ADP, Q3 (75%)	177.13	116.90	358.98
6 AD, FW-Only BtG ADP, Mean	183.61	121.18	184.49
7 AD, FW-Only BtG ADP, Median	121.75	80.36	154.01
8 AD, FW-Only BtG ADP, Q1 (25%)	101.46	66.96	87.14
9 AD, FW-Only BtG ADP, Q2 (50%)	121.75	80.36	154.01
10 AD, FW-Only BtG ADP, Q3 (75%)	214.85	141.80	247.38
11 AD, FW+Other BtG ADP, Mean	126.50	83.49	466.03
12 AD, FW+Other BtG ADP, Median	132.82	87.66	255.01
13 AD, FW+Other BtG ADP, Q1 (25%)	92.38	60.97	90.18
14 AD, FW+Other BtG ADP, Q2 (50%)	132.82	87.66	255.01
15 AD, FW+Other BtG ADP, Q3 (75%)	163.35	107.81	688.74

*AD stands for anaerobic digestion data, Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively; **Biomethane content of biogas is assumed to be at the generic value of 66%.

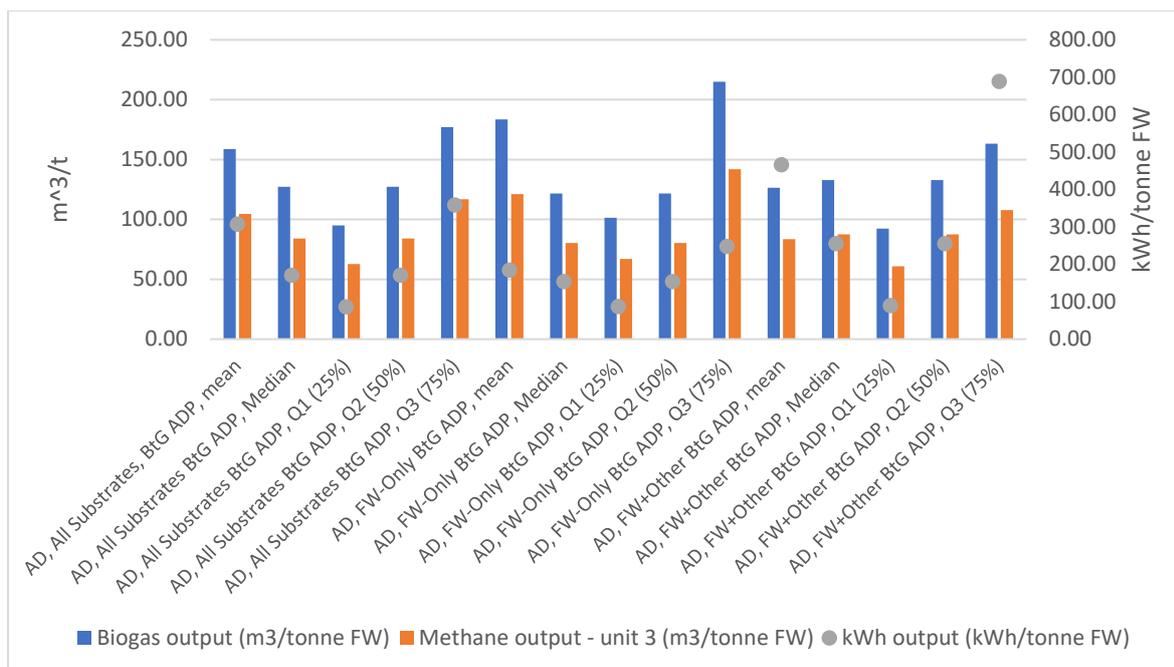


Figure 147. Figure of comparison for AD operational feedstock to biogas, biomethane and electricity conversion yield for biogas-to-grid (BtGs) AD plants only (please note the m3/t as shown in the figure pertains to m³/t).

5.3.3.2 Finding 2.2 – Combined Heat and Power (CHP) AD plant biogas, biomethane and electricity conversion yields (All feedstocks)

Results for Combined Heat and Power (CHP) AD plants demonstrate a mean and median feedstock to biomethane conversion yield of approximately 38.15m³/t and 36.90m³/t, 65.35m³/t and 59.09m³/t, 69.63m³/t and 30.64m³/t for FW+Other, all substrates and FW-only feedstocks, respectively (see Table 127).

Table 127. Table of data for AD operational feedstock to biogas, biomethane and electricity conversion yield for biogas-to-grid (CHP) AD plants only (126 data points)

	Abbreviated names only	Biogas output** (m³/tonne FW)	Methane output - (m³/tonne FW)	kWh output (kWh/tonne FW)
1	AD, All CHP ADP, mean	57.81	38.15	381.53
2	AD, All CHP ADP, Median	55.90	36.90	368.95
3	AD, All CHP ADP, Q1 (25%)	41.34	27.28	272.84
4	AD, All CHP ADP, Q2 (50%)	55.90	36.90	368.95
5	AD, All CHP ADP, Q3 (75%)	65.57	43.28	432.78
6	AD, FW-only, CHP ADP, mean	99.02	65.35	437.86
7	AD, FW-only, CHP ADP, Median	89.53	59.09	395.91
8	AD, FW-only, CHP ADP, Q1 (25%)	75.99	50.15	336.03
9	AD, FW-only, CHP ADP, Q2 (50%)	89.53	59.09	395.91
10	AD, FW-only, CHP ADP, Q3 (75%)	105.51	69.63	466.55
11	AD, FW+Others, CHP ADP, mean	46.43	30.64	306.43
12	AD, FW+Others, CHP ADP, Median	49.42	32.62	326.18
13	AD, FW+Others, CHP ADP, Q1 (25%)	31.72	20.94	209.37
14	AD, FW+Others, CHP ADP, Q2 (50%)	49.42	32.62	326.18
15	AD, FW+Others, CHP ADP, Q3 (75%)	59.70	39.40	394.00

*AD stands for anaerobic digestion data, Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively; **Biomethane content of biogas is assumed to be at the generic value of 66%.

With regard to the mean values, these findings show good agreements with MFVW (58m³/t), HHFW (46m³/t) and MFrVW (43 and 47m³/t) (see Table 118). Likewise, the median values show good agreements with MFVW (59 and 58 m³/t), HHFW (41 and 46m³/t) and MFrVW (30 and 46m³/t) from academic research literature data (see Table 119).

In contrast findings from BtG plants, CHP FW to biomethane conversion yield findings demonstrates a much stronger agreement with biomethane conversion yield of household FW from academic literature data (approx. 46m³/t for mean and 41-46m³/t for median, see (see Table 127 and Figure 148). This is likely due to use of representative HHFW feedstocks or a balance of feedstocks such as MFrVW, MVW, HHFW and MVW which when placed together yielded a FW to biomethane conversion yield that is similar to that of HHFW alone.

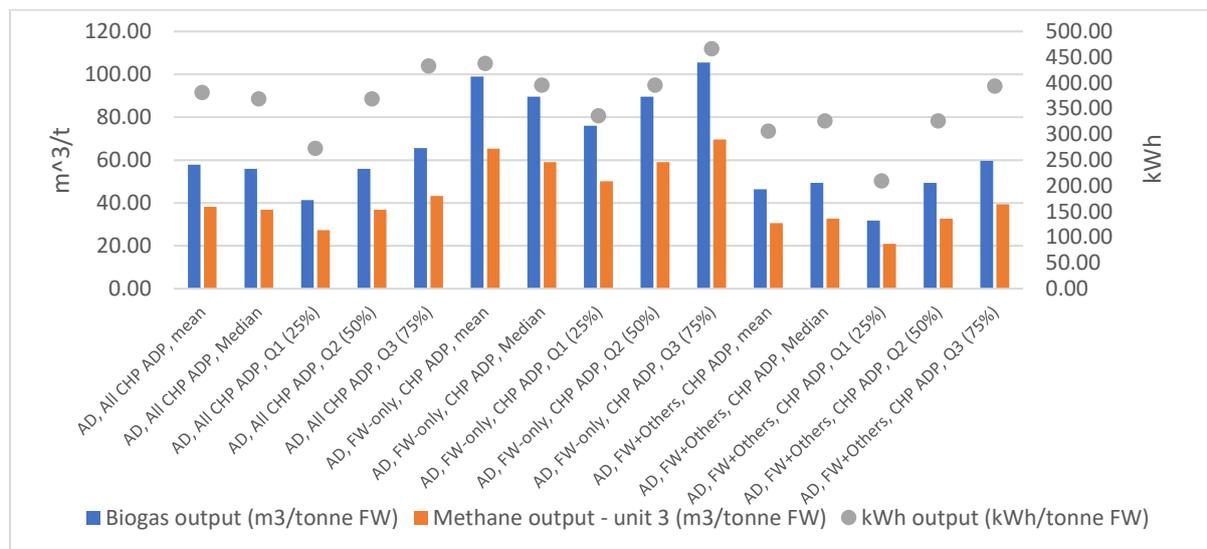


Figure 148. Figure of comparison for AD operational feedstock to biogas, biomethane and electricity conversion yield for biogas-to-grid (CHP) AD plants only (please note the m³/t as shown in the figure pertains to m³/t).

5.3.3.3 Finding 2.3 – Food waste & other secondary waste feedstocks for All AD plant types

Here the analysis takes a different approach by assessing the impact of 5 different FW on FW to biomethane conversion yields. The results interestingly demonstrates a mean and median feedstock to biomethane conversion yield of 112.15m³/t and 108.48m³/t for FW and Animal Waste (FW+AW), 87.90m³/t and 95.46m³/t for FW and Crop, 148.28m³/t for FW and Animal Processing Waste (FW+APW), 105.07m³/t and 108.48m³/t for FW and Green Waste (FW+GW), 128.28m³/t and 121.18m³/t for FW (see Table 128 and Figure 149).

Here both mean and median values are on average slightly higher than food waste to biomethane conversion yield data derived from literature research data (i.e. highest mean and median value would be for C&I-FW at 107m³/t and 108-119m³/t respectively) which are of 70-90 m³/t for most FW outputs (see Table 118 and Table 119) though their interpretation may need further evaluation given the small number of data points used in this section.

Table 128. Table of data for AD operational food waste (standalone or with co-substrate) to biogas, biomethane and electricity conversion yield for all (both BtG and CHP) AD plants (19 data points)

Abbreviated names only**		Biogas output** (m ³ /tonne FW)	Methane output - (m ³ /tonne FW)	kWh output (kWh/tonne FW)
1	AD, All ADP, FW+AW, Mean	169.92	112.15	420.49
2	AD, All ADP, FW+AW, Median	164.36	108.48	319.45
3	AD, All ADP, FW+AW, Q1 (25%)	142.55	94.09	234.13
4	AD, All ADP, FW+AW, Q2 (50%)	164.36	108.48	319.45
5	AD, All ADP, FW+AW, Q3 (75%)	194.52	128.38	372.56
6	AD, All ADP, FW+Crop, mean	133.18	87.90	299.47
7	AD, All ADP, FW+Crop, Median	144.64	95.46	274.67
8	AD, All ADP, FW+Crop, Q1 (25%)	95.25	62.86	126.49
9	AD, All ADP, FW+Crop, Q2 (50%)	144.64	95.46	274.67
10	AD, All ADP, FW+Crop, Q3 (75%)	182.57	120.49	365.88
11	AD, All ADP, FW+APW, mean	224.67	148.28	441.28
12	AD, All ADP, FW+APW, Median	224.67	148.28	418.21
13	AD, All ADP, FW+APW, Q1 (25%)	224.67	148.28	337.18
14	AD, All ADP, FW+APW, Q2 (50%)	224.67	148.28	418.21
15	AD, All ADP, FW+APW, Q3 (75%)	224.67	148.28	517.19
16	AD, All ADP, FW+GW, mean	159.19	105.07	710.06
17	AD, All ADP, FW+GW, Median	164.36	108.48	624.25
18	AD, All ADP, FW+GW, Q1 (25%)	126.45	83.46	246.78
19	AD, All ADP, FW+GW, Q2 (50%)	164.36	108.48	624.25
20	AD, All ADP, FW+GW, Q3 (75%)	194.52	128.38	1,087.53
21	AD, All ADP, FW, mean	183.61	121.18	184.49
22	AD, All ADP, FW, Median	121.75	80.36	154.01
23	AD, All ADP, FW, Q1 (25%)	96.39	63.61	61.83
24	AD, All ADP, FW, Q2 (50%)	121.75	80.36	154.01
25	AD, All ADP, FW, Q3 (75%)	238.92	157.68	299.01

*AD stands for anaerobic digestion data, Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively; **Biomethane content of biogas is assumed to be at the generic value of 66%; **AW = Animal waste, APW = Animal processing waste, GW = Green waste

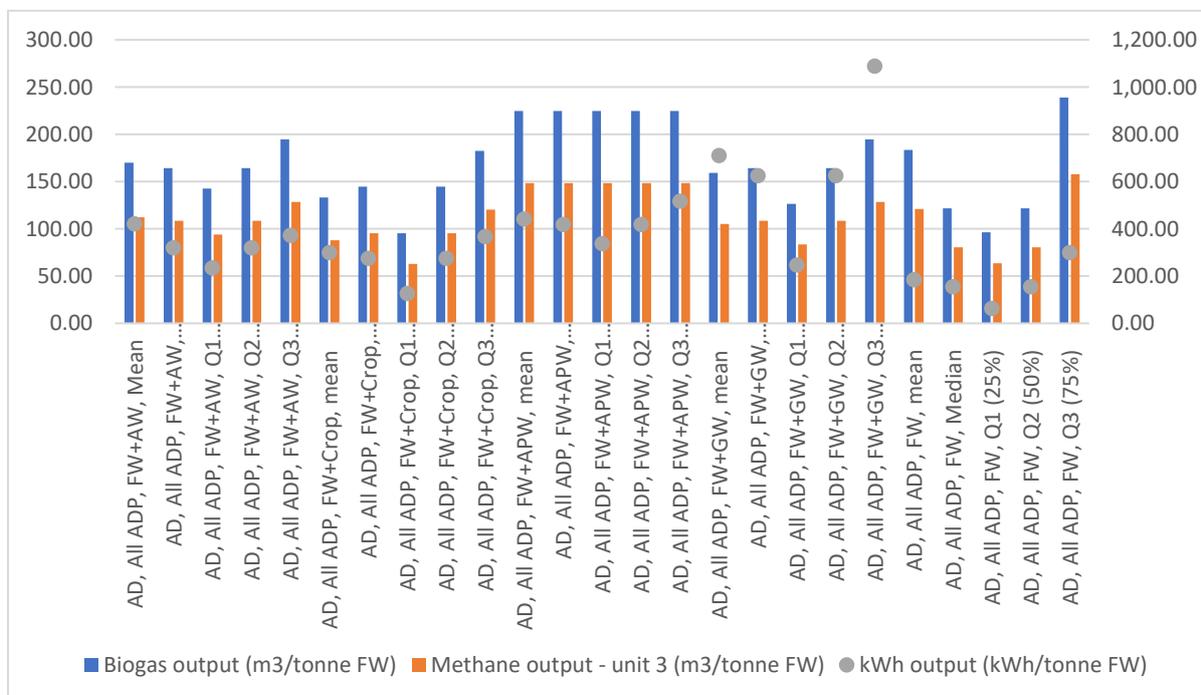


Figure 149. Figure of comparison for AD operational feedstock to biogas, biomethane and electricity conversion yield for all AD plants only based on different food waste feedstock input used (AW = Animal waste, APW = Animal processing waste, GW = Green waste) (please note the m³/t as shown in the figure pertains to m³/t).

Although more data is required to understand with greater certainty of the underlying reasons for this, it is generally thought that optimization of AD operations, i.e. via use of additives and optimal temperature, loading rate and other technical parameters is largely helpful in enabling achievement of greater FW to biomethane yields not observed from academic literature data. This constitute a notable point of gap in knowledge which should be further explored and bridged through future dedicated research to ensure the translation of results from academic research, i.e. those explored as part of this study, for industrial application, i.e. FW to biomethane conversion results in this section.

5.3.3.4 Finding 2.4 – AD plant capacity size against FW to biomethane conversion yield

From perspective of infrastructure development, the relative correlation between AD plant size and FW to biomethane conversion yield is also explored using all available data (8 data points). The results demonstrate a positive correlation between AD plant size or generation capacity and waste feedstock to biomethane conversion yield, with larger AD plants demonstrating higher FW to biomethane conversion yields. This is outlined in Table 129 and Figure 150 where mean and median values for AD plants with generation capacity of >500kWe, 250-500kWe and <250kWe to be 118.54m³/t and 93.20m³/t, 75.71m³/t and 82.96m³/t, 48m³/t and 48.00m³/t, respectively.

Here it is important to emphasise that these findings are derived from a small number of data points and should be interpreted with caution, although preliminary results do suggest it is more economic for establishing and operating AD plants with greater generation capacity given the greater FW feedstock to biomethane or electricity conversion values observed.

Table 129. Table of data for AD operational waste feedstock to biogas, biomethane and electricity conversion yield for all (both BtG and CHP) (8 data points), separated on basis of electricity generation capacity

	Abbreviated names only	Biogas output** (m ³ /tonne FW)	Methane output - (m ³ /tonne FW)	kWh output (kWh/tonne FW)
1	<250kWe, All ADP, mean	80.00	48.00	243.86
2	<250kWe, All ADP, Median	80.00	48.00	292.20
3	<250kWe, All ADP, Q1 (25%)	80.00	48.00	130.46
4	<250kWe, All ADP, Q2 (50%)	80.00	48.00	292.20
5	<250kWe, All ADP, Q3 (75%)	80.00	48.00	366.93
6	250-500kWe, All ADP, mean	126.18	75.71	282.37
7	250-500kWe, All ADP, Median	138.26	82.96	134.94
8	250-500kWe, All ADP, Q1 (25%)	96.85	58.11	89.71
9	250-500kWe, All ADP, Q2 (50%)	138.26	82.96	134.94
10	250-500kWe, All ADP, Q3 (75%)	153.79	92.27	203.39
11	>500kWe, All ADP, mean	197.57	118.54	409.59
12	>500kWe, All ADP, Median	155.33	93.20	386.98
13	>500kWe, All ADP, Q1 (25%)	108.05	64.83	319.45
14	>500kWe, All ADP, Q2 (50%)	155.33	93.20	386.98
15	>500kWe, All ADP, Q3 (75%)	207.92	124.75	444.75

*AD stands for anaerobic digestion data, Q1, Q2 and Q3 represents first (25%), second (50%) and third (75%) quartile data respectively; **Biomethane content of biogas is assumed to be at the generic value of 66%.

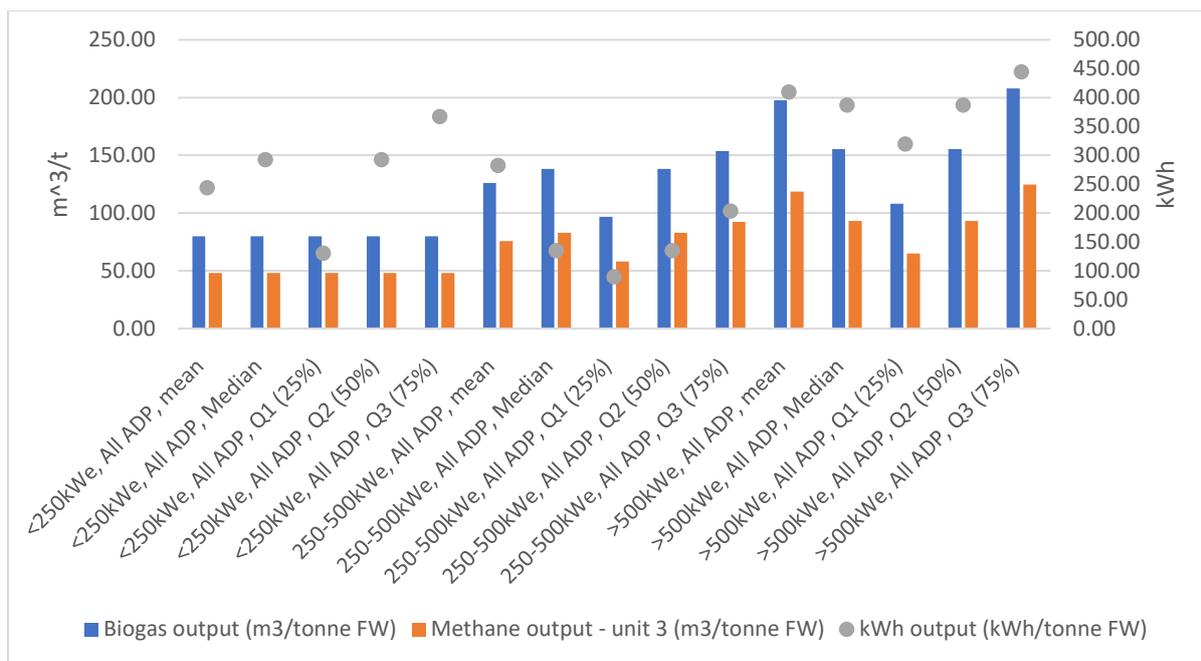


Figure 150. Figure of comparison for AD operational feedstock to biogas, biomethane and electricity conversion yield for all AD plants of 3 separate electricity generation capacity (please note the m³/t as shown in the figure pertains to m³/t).

Other possible explanations for this could be a purely coincidental occurrence or to do with specific design considerations arising at the level of FW feedstock, technical operations and combination thereof. At the feedstock level, it can be assumed that larger AD general commands the use of greater energy richer FW contents overall, i.e. commercial and industrial FW is occurring in larger AD plants, either coincidentally or due to their specialized design and intended purpose of taking in such wastes. At the operational level, this could translate to more stringent control of optimal conditions used for FW to biomethane conversion (where more optimal on loading rate, temperature, time of FW incubation, plant design affecting biomethane conversion efficient and capture and use of other additives could come into significant play towards ensuring a greater FW to biomethane production is achieved).

Future studies should endeavour to both collect more data points whilst also to collaborate with relevant AD operators to establish more accurate insight of the above observation in the positive correlation between AD plant size or capacity and FW to biomethane conversion yield. This could certainly achieved either through joint ground-up projects between universities and independent AD operators, or through local or central government incentives, i.e. funding and additional support to be made available to promote the establishment of such research projects as part of UK's renewable energy strategic growth plan.

5.3.3.5 Findings Summary – real world AD operational FW to biomethane conversion values.

A summary comparison of values for evaluation metrics across all findings (1-4) is outlined in Table 130 below, with key results showing modest to strong agreement with (FW to biogas and biomethane conversion yield) findings from academic research literature (see finding 1.13).

Table 130. Summary comparison for all waste feedstock to biomethane conversion yields using NFCCC AD plant operational data.

	Biogas-to-Grid (BtG) AD plant only	Combined Heat and Power (CHP) AD plant only	Food waste related feedstock only (All AD plants)*	AD plant capacity and size
Technical category variables	Feedstock Waste type			Electricity generation capacity
Technical category details	All wastes, FW only, FW+Others		FW+AW, FW+APW, FW+Crop, FW+GW	<250kWe, 250-500kWe, >500kWe
Mean Range	83-105m ³ /t	31-65m ³ /t	88-148m ³ /t	48-119m ³ /t
Median Range	80-88 m ³ /t	33-59m ³ /t	80-148m ³ /t	48-93m ³ /t
Q1 Range	61-67m ³ /t	21-50m ³ /t	63-148m ³ /t	48-65m ³ /t
Q2 Range	80-88m ³ /t	33-59m ³ /t	80-148m ³ /t	48-93m ³ /t
Q3 Range	108-142m ³ /t	39-70m ³ /t	120-158m ³ /t	48-125m ³ /t

*AW = Animal waste, APW = Animal processing waste, GW = Green waste

The above summarized findings on FW biomethane conversion yield have demonstrated a strong agreement between (i) NFCCC data on all AD plants types and capacity sizes (small to large generation capacity) and (ii) research literature data on anaerobic digestion of household, commercial, household & commercial, and mixed food wastes, which respectively exhibits a mean conversion value range of 48-119m³/t (for i) and 45-90 m³/t (for ii) (see finding 1.13 for latter). These findings are similarly true for median FW to biomethane conversion values of 48-93m³/t and 41-87m³/t for these respective datasets.

Here stronger correlations and agreements in mean FW to biomethane conversion yield data can be observed between (i) NFCCC data on BtG only AD plants (of 83-105m³/t) and (ii) research literature data on anaerobic digestion of all experimental, commercial, household & commercial, and mixed food wastes (approximately 70-90m³/t), with the mutual agreement value to be between 83-90m³/t.

These findings collectively establish a sufficient degree of confidence in the technical FW to biogas and biomethane yield research literature data being both real-world relevant and representative. For specific calculations on total biogas and biomethane potential across all relevant NPH regions and timeframes (2010-2050) (see finding 3), 3 separate values of 45, 70 and 90 are established in context of using mutually agreed data ranges for both NFCCC and research literature datasets (see Table 131).

Table 131. Mean low, medium and high household FW to biogas and biomethane conversion values attainable from typical AD plant operations

	Conversion value type	FW Biogas yield* (m ³ /t)	FW Biomethane yield (m ³ /t)	Rationale for biomethane value chosen
1	Low	60	45	Lowest attainable mean conversion value for Anaerobic digestion of FW only from research literature review
2	Moderate	106	67.50	Moderate value between low and high conversion yield values
3	High	152	90	Highest achievable mean value from anaerobic digestion of all mixed FW

*Assuming for biogas to possess 66% biomethane content

5.3.4 Finding 3 - Total biogas and biomethane output per NPH region

This section outlines total biogas and biomethane potential for each NPH region by combining findings in all previous sections, i.e. of food waste collection data, FW to biogas, ONS population data and biomethane conversion yield, for estimating total biogas and biomethane potential within each NPH region for relevant time periods of 2010-2050 (see findings 1-2).

All calculations thus this takes account of 3 sets of data findings elucidated so far, arising from (i) 1 time-adjusted population data for each of the 5 NPH city and county regions (1 ONS data scenario), (ii) 5 established food waste collection scenario data and (iii) 3 FW biogas and biomethane conversion yield scenarios data (see Table 132).

Table 132. Summary of datasets used for calculating total FW biogas and biomethane yields across NPH regions

No.	ONS population data (no unit)	FW collection data (kg/person/year)	FW to biogas and biomethane conversion yield value (m ³ /t)
1	Only set	Low fixed value – 20	Low yield – 45
2		Medium fixed value - 40	Medium yield – 67.50
3		High fixed value - 100	High yield – 90
4		WRAP variable value –18-73	
5		WDF variable value – 17-46	

*Each finding section corresponds to each different category of FW to biogas and biomethane conversion yield (m³/t)

These collectively give rises to 30 different scenarios of total FW output across all NPH city regions (15 dataset) and metropolitan county regions (15 dataset), as elaborated in respective sections below using relevant calculation methods for each scenario is outlined in in

Table 35 (Chapter 4.3.3) and the equation of (for each NPH region):

Total Projected Population (adjusted for time) × Food waste collection per capita × Biomethane yield per kg of FW collected (with all corresponding results shown below).

5.3.4.1 Finding 3.1 – All fixed FW collection scenarios (for all biomethane production scenario across all NPH city and county regions)

This section highlights all findings for fixed FW collection scenarios for all 5 NPH city and county regions by using findings outlined in Table 132 above. The configuration of comparisons focuses on comparing each level of biomethane conversion yield (low, medium, high) against each level of estimated fixed FW collection scenario (low, medium, high) and is outlined in the 18 graphs below.

Table 133 further clarifies the precise breakdown of configuration of the below graphs with respect to the relevant figure and graphs (2 per figure) with comments on key points of comparison.

Table 133. Configuration of arrangement of figures for the upcoming section showing total biomethane generation from all fixed FW scenarios across the NPH city and metropolitan county region

Section	Section number heading	Figure number	FW to biomethane conversion yield	Fixed FW waste collection scenario	Time period & population data
A	5.3.4.1a	Figure 151	Low	Low	2010-2050 & ONS population
	5.3.4.1b	Figure 152	Low	Medium	
	5.3.4.1c	Figure 153	Low	High	
	5.3.4.1d	N/A – Sub-Section summary of Figure 151-153			
B	5.3.4.1e	Figure 154	Medium	Low	
	5.3.4.1f	Figure 155	Medium	Medium	
	5.3.4.1g	Figure 156	Medium	High	
	5.3.4.1h	N/A – Sub-Section summary of Figure 154-156			
C	5.3.4.1i	Figure 157	High	Low	
	5.3.4.1j	Figure 158	High	Medium	
	5.3.4.1k	Figure 159	High	High	
	5.3.4.1l	N/A – Sub-Section summary of Figure 157-159			
D	5.3.4.1m	Main section summary of all 3 sub-sections (5.3.4.1d, 5.3.4.1h and 5.3.4.1l)			

The table also categorises Low, Medium and High FW to biomethane conversion yield scenarios into section A, B and C respectively for ease of subsequent discussion on comparison in findings both within each section and between these sections.

The first 3 graphs below (section A in table xx) outlines the trend in total FW production across NPH city and metropolitan county regions between 2001-2051 based on low FW to biomethane conversion yields against low, medium and high fixed FW output respectively (see Figure 151, Figure 152 and Figure 153)

5.3.4.1a Low fixed FW collection (20 kg/pp/yr) × Low biomethane FW to biomethane conversion yield (45m³/t) scenario

Figure 151 outlines total biomethane production potential from 2001 to 2050 under low fixed FW collection (Low-FWC) and low biomethane FW to biomethane conversion (Low-BMC) yield scenario for all 5 NPH city (left) and metropolitan county regions (right).

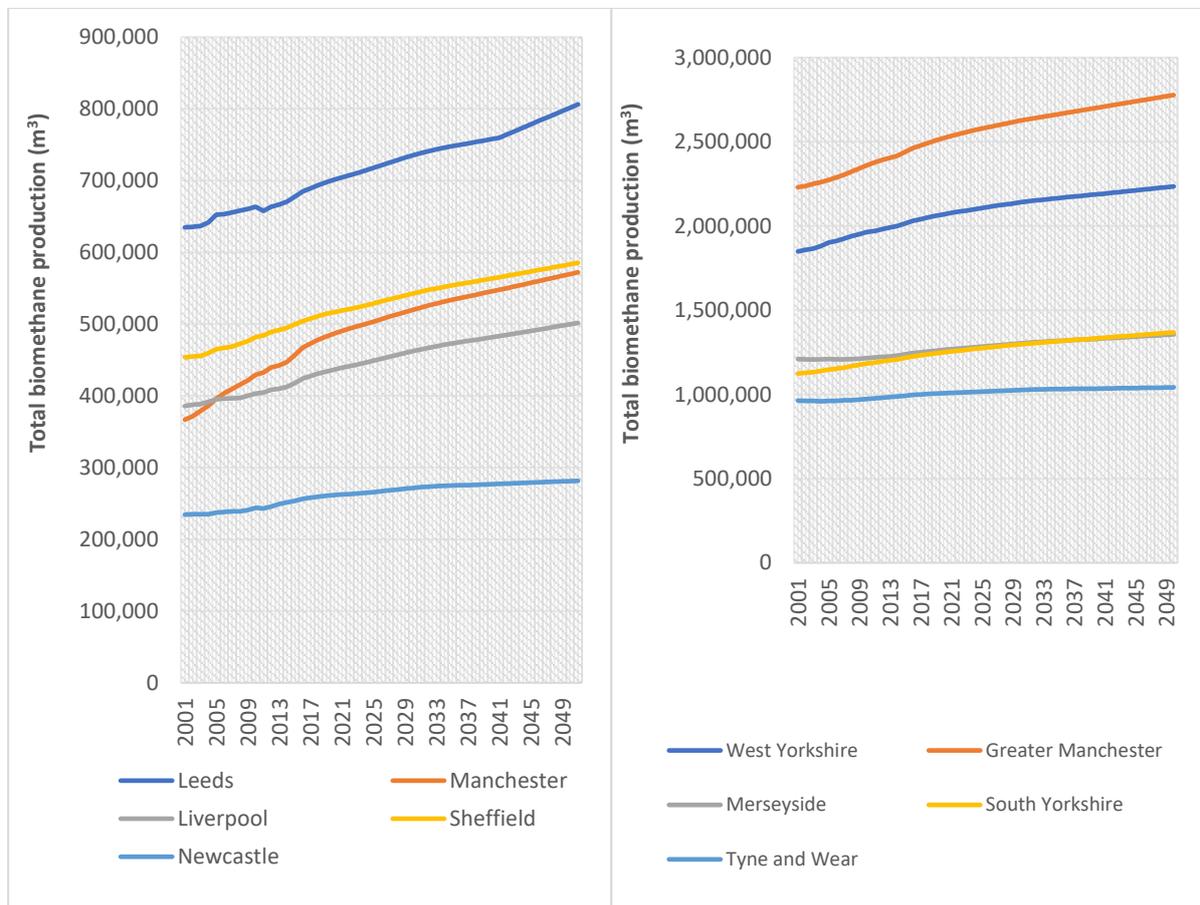


Figure 151. Low Fixed FW collection and low biomethane FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, please see Appendix table 16 and Appendix table 17)

For the Low-FWC and Low-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 250,000-300,000m³ for Newcastle, 390,000-490,000m³ for Liverpool, 360,000-570,000m³ for Manchester, 440,000-575,000m³ for Sheffield and 640,000-790,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan county regions from order of lowest to highest is shown to be approximately 1,000,000-1,100,000m³ for Tyne and Wear, 1,150,000-1,300,000m³ for South Yorkshire, 1,200,000-1,300,000m³ for Merseyside, 1,850,000-2,200,000m³ for West Yorkshire and 2,200,000-2,750,000m³ for Greater Manchester.

5.3.4.1b Medium fixed FW collection (40 kg/pp/yr) × Low biomethane FW to biomethane conversion yield (45m³/t) scenario

Figure 152 outlines total biomethane production potential from 2001 to 2050 under medium fixed FW collection (Medium-FWC) and low biomethane FW to biomethane conversion yield (Low-BMC) scenario for all 5 NPH cities (left) and metropolitan county regions (right).

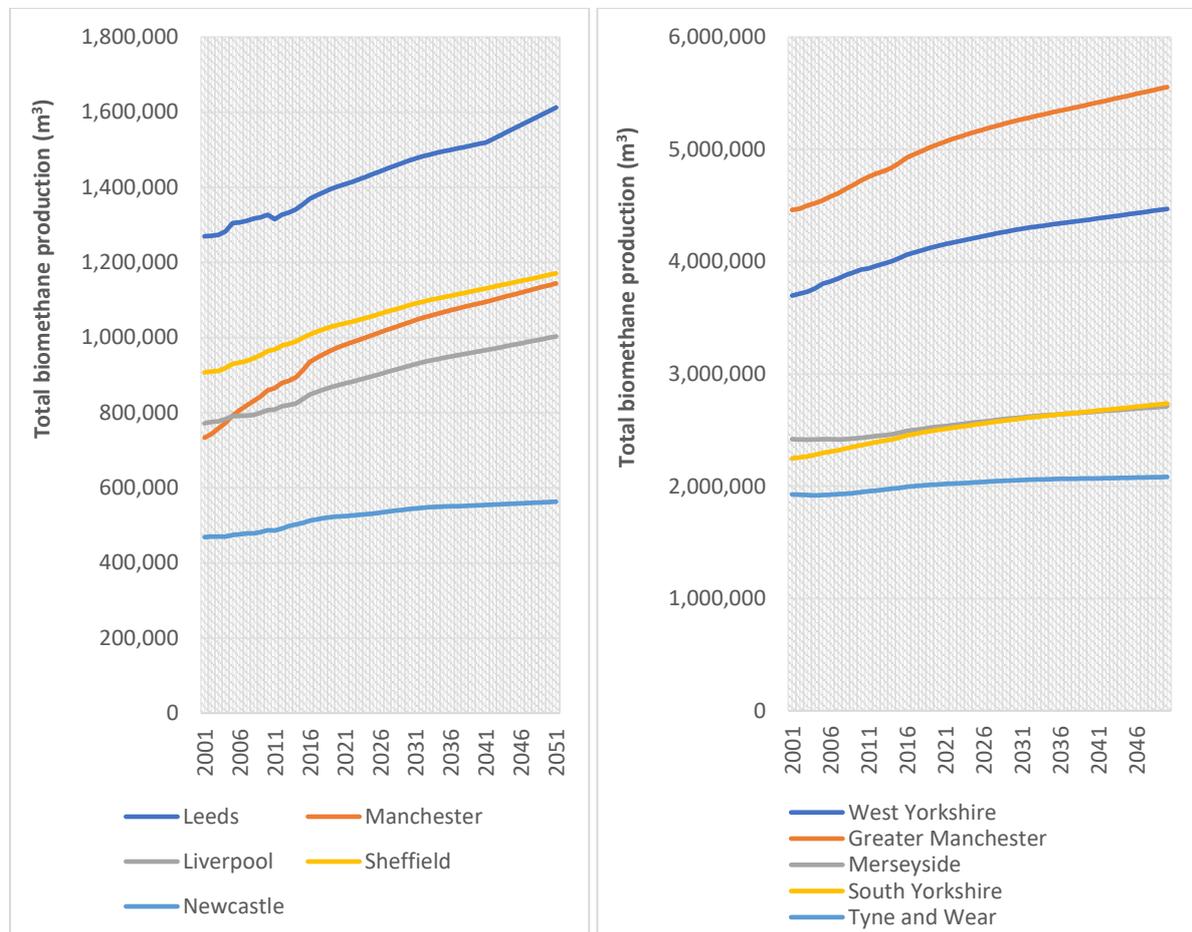


Figure 152. Medium Fixed FW collection and low biomethane FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, please see Appendix table 18 and Appendix table 19)

For the Medium-FWC and Low-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 500,000-600,000m³ for Newcastle, 780,000-980,000m³ for Liverpool, 720,000-1,140,000m³ for Manchester, 880,000-1,150,000m³ for Sheffield and 1,280,000-1,580,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan county regions from order of lowest to highest is shown to be approximately 2,000,000-2,200,000m³ for Tyne and Wear, 2,300,000-2,600,000m³ for South Yorkshire, 2,400,000-2,600,000m³ for Merseyside, 3,700,000-4,400,000m³ for West Yorkshire and 4,400,000-5,500,000m³ for Greater Manchester.

5.3.4.1c High fixed FW collection (100 kg/person/yr) × Low biomethane FW to biomethane conversion yield (45m³/t) scenario

Figure 153 outlines total biomethane production potential from 2001 to 2050 under high fixed FW collection (High-FWC) and low biomethane FW to biomethane conversion yield (Low-BMC) scenario for all 5 NPH cities (left) and metropolitan county regions (right).

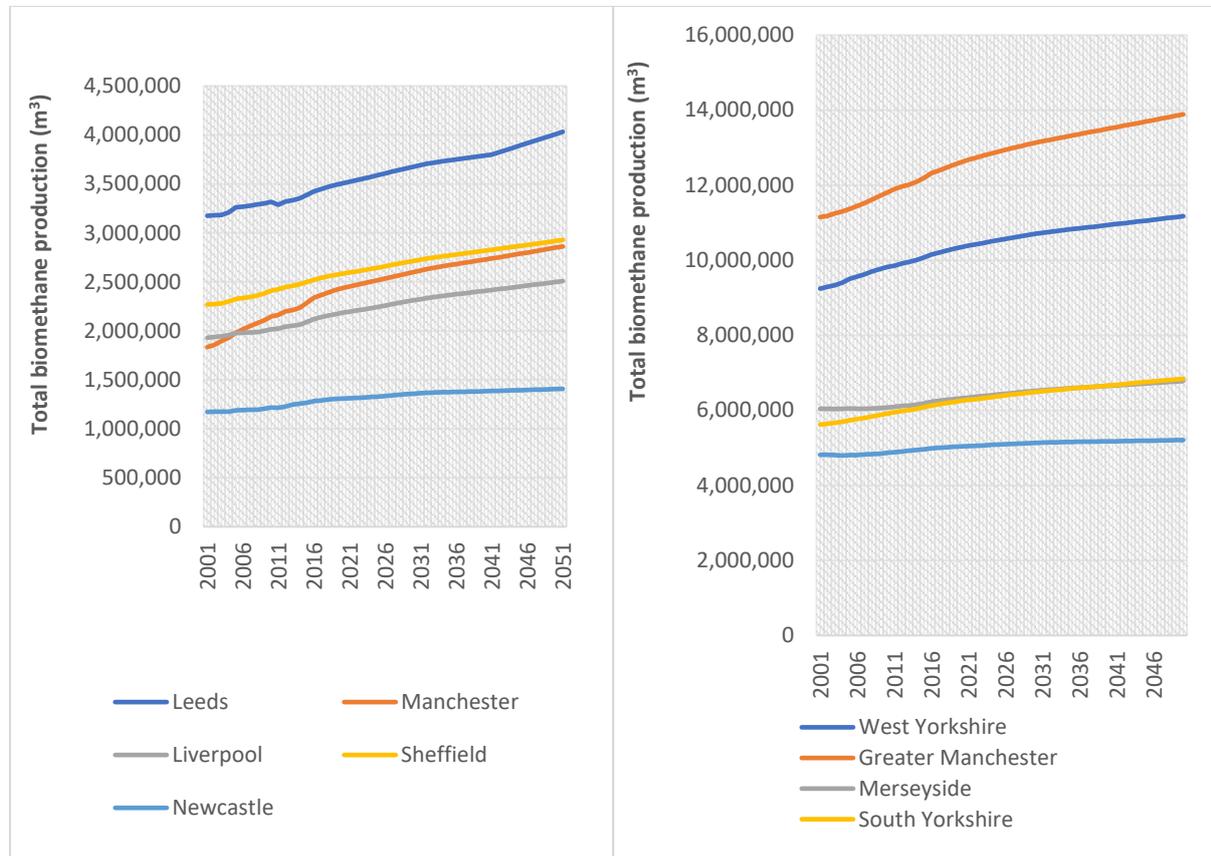


Figure 153. High Fixed FW collection and low biomethane FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, see Appendix table 20 and Appendix table 21).

For the High-FWC and Low-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 1,250,000-1,500,000m³ for Newcastle, 1,950,000-2,450,000m³ for Liverpool, 1,800,000-2,850,000m³ for Manchester, 2,200,000-2,875,000m³ for Sheffield and 1,280,000-1,580,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan county regions from order of lowest to highest is shown to be approximately 5,000,000-6,000,000m³ for Tyne and Wear, 5,750,000-6,500,000m³ for South Yorkshire, 6,000,000-6,500,000m³ for Merseyside, 9,250,000-11,000,000m³ for West Yorkshire and 11,000,000-13,750,000m³ for Greater Manchester.

5.3.4.1d Low biomethane FW to biomethane conversion yield (45m³/t) scenario sub-section summary (for Low, medium and high FW collection data inputs)

This section findings of all Low FW to Biomethane conversion yield scenarios for all three (Low, Medium, and High) scenarios of household FW collection data. This is underpinned by three different levels of FW output per person (20, 40 and 100 kg/person/year) has returned a lowest and highest 2001-2049 BMP value of 250,000-300,000m³ (Newcastle, Low-FMC and Low-BMC) and 1,280,000-1,580,000m³ (Leeds, High-FMC and Low-BMC) respectively. Here the same comparison for metropolitan county regions has returned a lowest and highest 2001-2049 BMP value of 1,000,000-1,100,000m³ (Tyne and Wear, Low-FWC and Low-BMC) and 11,000,000-13,750,000m³ (Greater Manchester, High-FWC and Low-BMC), respectively, which constitutes to approximately 11 times difference between the two values.

Here it is worth noting that these findings constitute the most modest estimations of BMP across all NPH city and metropolitan county regions as it applies the lowest household FW to biomethane conversion factor of 45m³/t FW.

This finding will also be compared with other sub-section summary (see sections 5.3.4.1h and 5.3.4.1i) in the main section summary in 5.3.4.1m for outlining differences in the BMP across all 9 BMP scenarios presented in this section.

The below sub-section of 3 graphs outlines the trend in FW potential across all 5 NPH city and metropolitan county regions where FW to biomethane conversion yield remains to be at the medium level against low, medium and high assumed fixed FW collection scenarios.

5.3.4.1e Low fixed FW collection (20kg/pp/yr) × Medium FW to biomethane conversion yield (67.50m³/t) scenario

Figure 154 displays total biomethane production from 2001 to 2050 under low fixed FW collection and medium biomethane FW to biomethane conversion yield scenario for all 5 NPH cities (left) and metropolitan county regions (right).

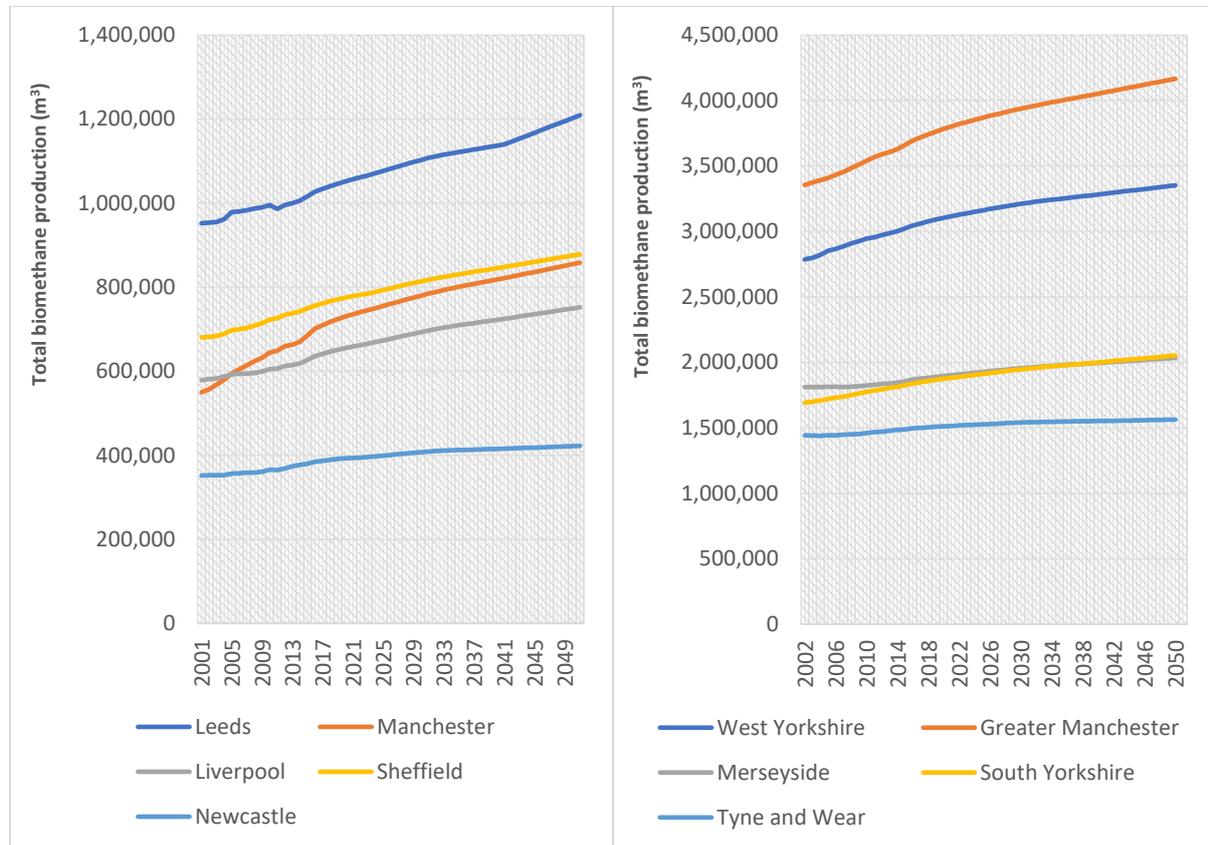


Figure 154. Low Fixed FW collection and medium biomethane FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, see Appendix table 22 and Appendix table 23).

For the Low-FWC and Medium-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 375,000-450,000m³ for Newcastle, 585,000-735,000m³ for Liverpool, 540,000-855,000m³ for Manchester, 660,000-863,000m³ for Sheffield and 960,000-1,190,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan county regions from order of lowest to highest is shown to be approximately 1,500,000-1,650,000m³ for Tyne and Wear, 1,650,000-1,950,000m³ for South Yorkshire, 1,800,000-1,950,000m³ for Merseyside, 2,780,000-3,300,000m³ for West Yorkshire and 3,300,000-4,130,000m³ for Greater Manchester.

5.3.4.1f Medium fixed FW collection scenario (40kg/pp/yr) × Medium biomethane conversion yield (67.50m³/t) scenario

Figure 155 displays total biomethane production from 2001 to 2050 under medium fixed FW collection and medium biomethane FW to biomethane conversion yield scenario for all 5 NPH cities (left) and metropolitan county regions (right).

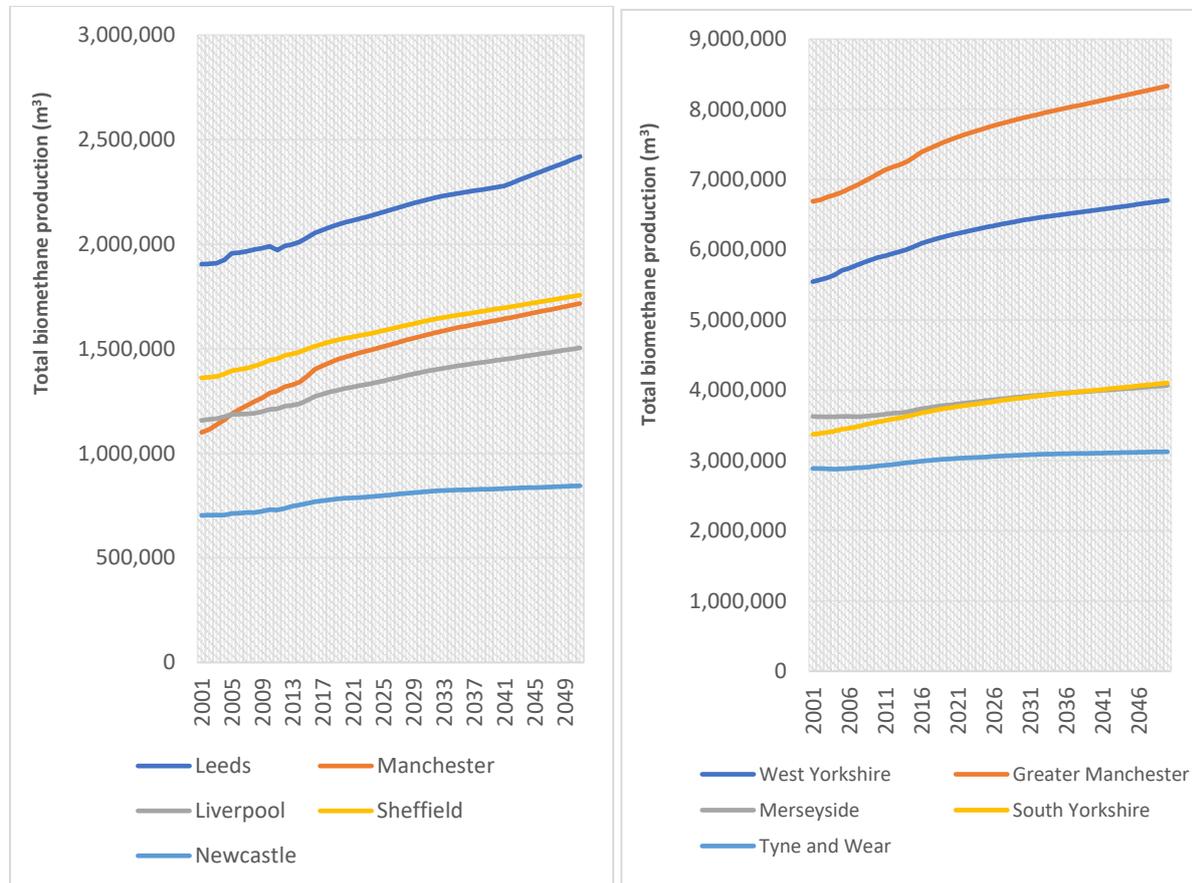


Figure 155. Medium Fixed FW collection and medium FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, please see Appendix table 24 and Appendix table 25).

For the Medium-FWC and Medium-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 750,000-900,000m³ for Newcastle, 1,170,000-1,470,000m³ for Liverpool, 1,080,000-1,710,000m³ for Manchester, 1,320,000-1,720,000m³ for Sheffield and 1,920,000-2,370,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan country regions from order of lowest to highest is shown to be approximately 3,000,000-3,300,000m³ for Tyne and Wear, 3,450,000-3,900,000m³ for South Yorkshire, 3,600,000-3,900,000m³ for Merseyside, 5,550,000-6,600,000m³ for West Yorkshire and 6,600,000-8,250,000m³ for Greater Manchester.

5.3.4.1g High fixed FW collection scenario (40kg/pp/yr) × Medium biomethane FW to biomethane conversion yield (67.50m³/t) scenario

Figure 156 displays total biomethane production from 2001 to 2050 under high fixed FW collection and medium biomethane FW to biomethane conversion yield scenario for all 5 NPH cities (left) and metropolitan county regions (right).

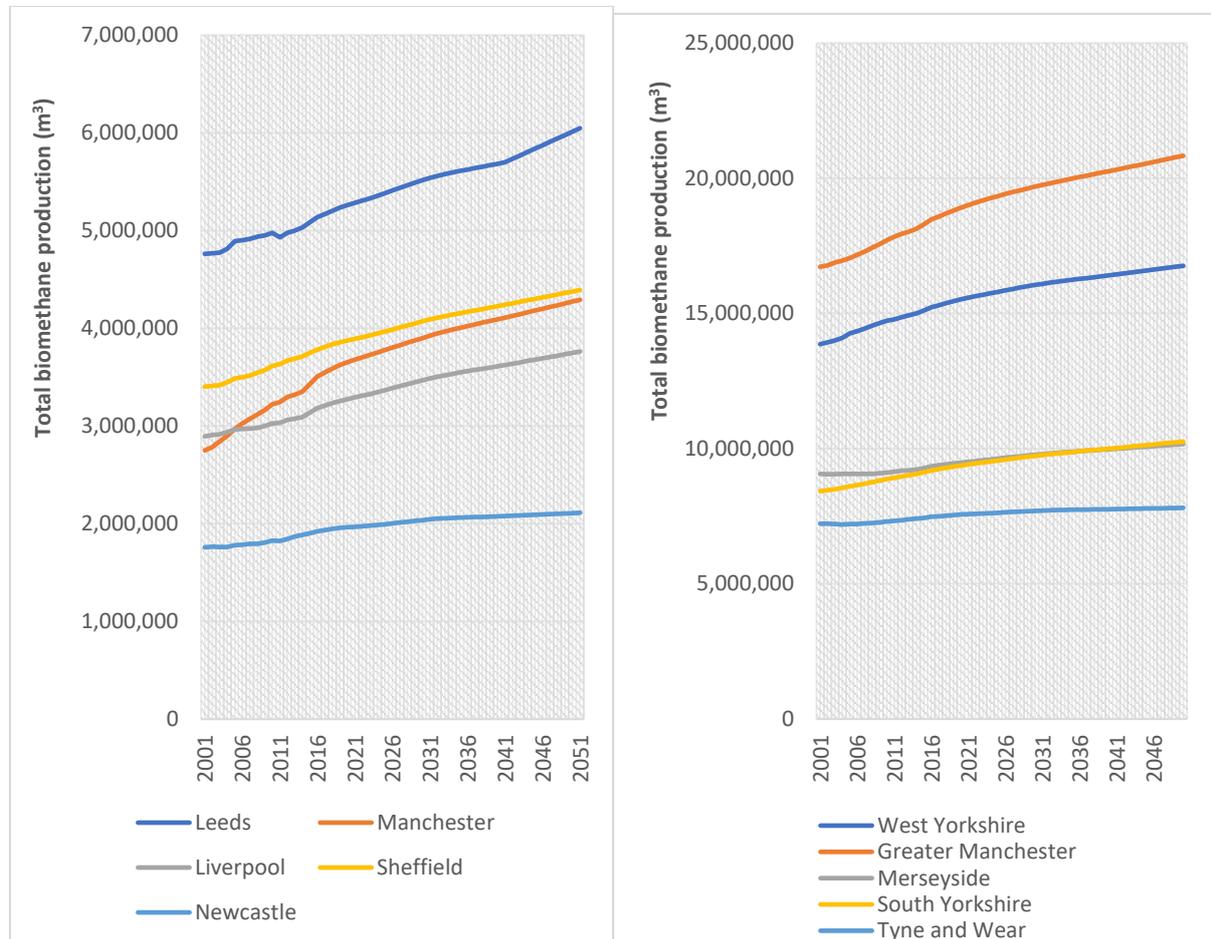


Figure 156. High Fixed FW collection and medium FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, please see Appendix table 26 and Appendix table 27).

For the High-FWC and Medium-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 1,875,000-2,250,000m³ for Newcastle, 2,925,000-3,675,000m³ for Liverpool, 2,700,000-4,275,000m³ for Manchester, 3,300,000-4,313,000m³ for Sheffield and 1,920,000-2,370,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan country regions from order of lowest to highest is shown to be approximately 7,500,000-9,000,000m³ for Tyne and Wear, 8,625,000-9,750,000m³ for South Yorkshire, 9,000,000-9,750,000m³ for Merseyside, 13,875,000-16,500,000m³ for West Yorkshire and 16,500,000-20,625,000m³ for Greater Manchester.

5.3.4.1h Medium biomethane FW to biomethane conversion yield ($67.5\text{m}^3/\text{t}$) scenario section summary (for Low, medium and high FW collection data inputs)

This section findings of all Medium FW to Biomethane conversion yield scenarios for all three (Low, Medium, and High) scenarios of household FW collection data. This is underpinned by three different levels of FW output per person (20, 40 and 100 kg/person/year) has returned a lowest and highest 2001-2049 BMP value of $375,000\text{-}450,000\text{m}^3$ (Newcastle, Low-FMC and Low-BMC) and $1,920,000\text{-}2,370,000\text{m}^3$ (Leeds, High-FMC and Low-BMC) respectively. Here the same comparison for metropolitan county regions has returned a lowest and highest 2001-2049 BMP value of $1,500,000\text{-}1,650,000\text{m}^3$ (Tyne and Wear, Low-FWC and Low-BMC) and $16,500,000\text{-}20,625,000\text{m}^3$ (Greater Manchester, High-FWC and Low-BMC), respectively, which constitutes to approximately 11 times difference between the two values.

Here it is worth noting that these findings constitute mid-level (between highest and lowest) estimations of BMP across all NPH city and metropolitan county regions as it applies the medium household FW to biomethane conversion factor of $67.5\text{m}^3/\text{t}$ FW.

This findings will also be compared with other sub-section summary (see sections 5.3.4.1d and 5.3.4.1l) in the main section summary in 5.3.4.1m for outlining differences in the BMP across all 9 BMP scenarios presented in this section.

The below sub-section of 3 graphs outlines the trend in FW potential across all 5 NPH city and metropolitan county regions where FW to biomethane conversion yield remains to be at the medium level against low, medium and high assumed fixed FW collection scenarios.

5.3.4.1i Low fixed FW collection scenario × High biomethane conversion yield (90m³/t) scenario

Figure 157 displays the tendency of the total biomethane production from 2001 to 2050 under low fixed FW collection and high biomethane FW to biomethane conversion yield scenario for all 5 NPH cities (left) and metropolitan county regions (right).

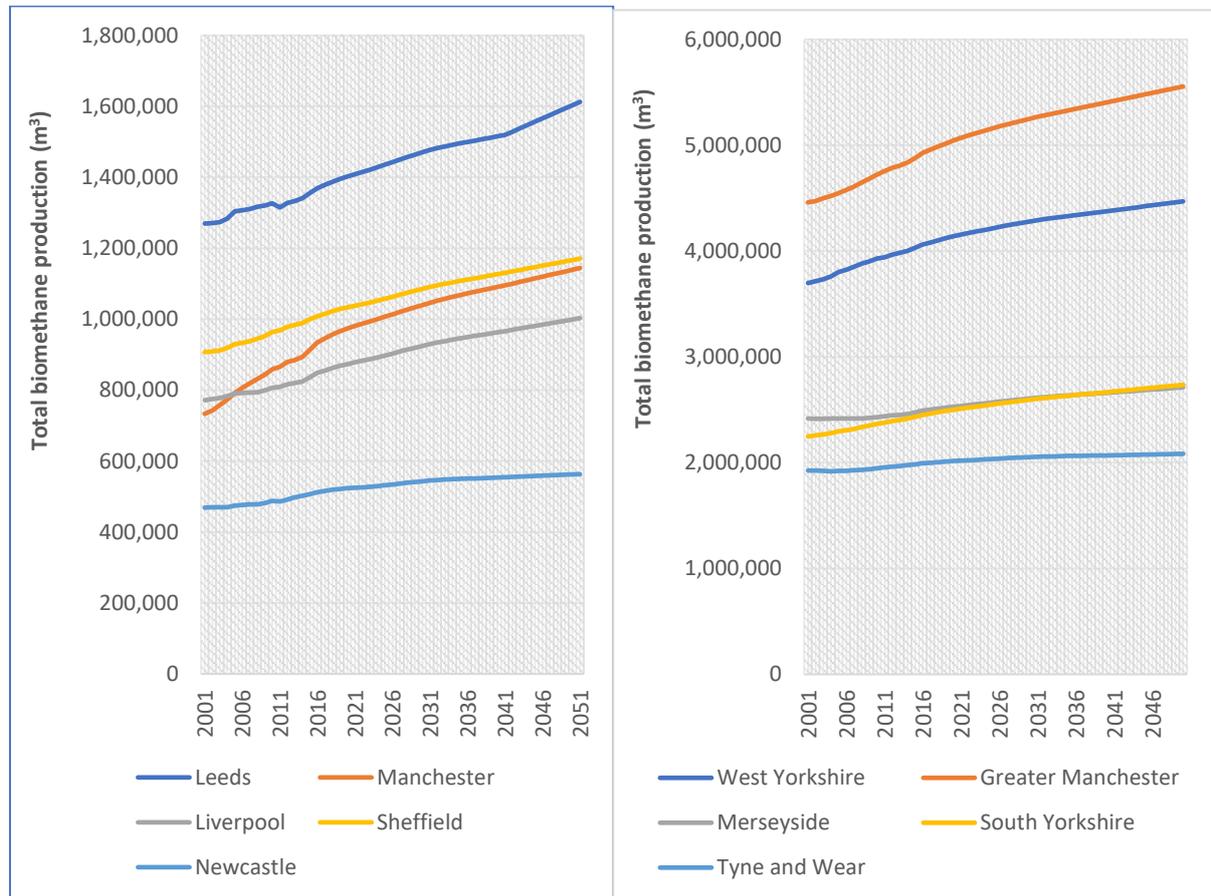


Figure 157. Low Fixed FW collection and high FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, please see Appendix table 28 and Appendix table 29)

For the Low-FWC and High-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 500,000-600,000m³ for Newcastle, 780,000-980,000m³ for Liverpool, 720,000-1,140,000m³ for Manchester 880,000-1,150,000m³ for Sheffield and 1,280,000-1,580,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan country regions from order of lowest to highest is shown to be approximately 2,000,000-2,200,000m³ for Tyne and Wear, 2,300,000-2,600,000m³ for South Yorkshire, 2,400,000-2,600,000m³ for Merseyside, 3,700,000-4,400,000m³ for West Yorkshire and 4,400,000-5,500,000m³ for Greater Manchester.

5.3.4.1j Medium fixed FW collection scenario × High biomethane conversion yield (90m³/t) scenario

Figure 158 displays the tendency of the total biomethane production from 2001 to 2050 under medium fixed FW collection and high biomethane FW to biomethane conversion yield scenario for all 5 NPH cities (left) and metropolitan county regions (right).

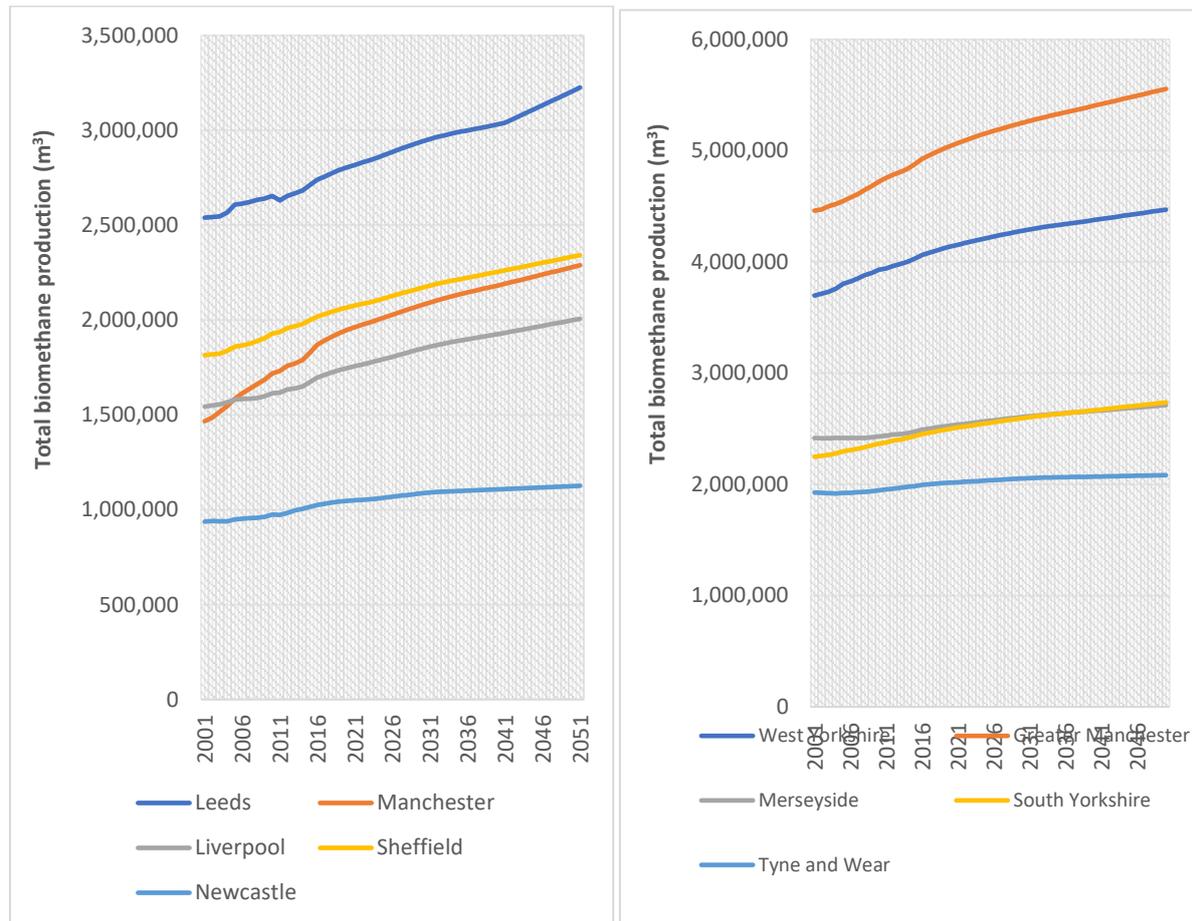


Figure 158. Medium Fixed FW collection and high FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, please see Appendix table 30 and Appendix table 31)

For the Medium-FWC and High-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 1,000,000-1,200,000m³ for Newcastle, 1,560,000-1,960,000m³ for Liverpool, 1,440,000-2,280,000m³ for Manchester, 1,760,000-2,300,000m³ for Sheffield and 2,560,000-3,160,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan country regions from order of lowest to highest is shown to be approximately 4,000,000-4,400,000m³ for Tyne and Wear, 4,600,000-5,200,000m³ for South Yorkshire, 4,800,000-5,200,000m³ for Merseyside, 7,400,000-8,800,000m³ for West Yorkshire and 8,800,000-11,000,000m³ for Greater Manchester.

5.3.4.1k High fixed FW collection scenario × High biomethane conversion yield (90m³/t) scenario

Figure 159 displays the tendency of the total biomethane production from 2001 to 2050 under high fixed FW collection and high biomethane FW to biomethane conversion yield scenario for all 5 NPH cities (left) and metropolitan county regions (right).

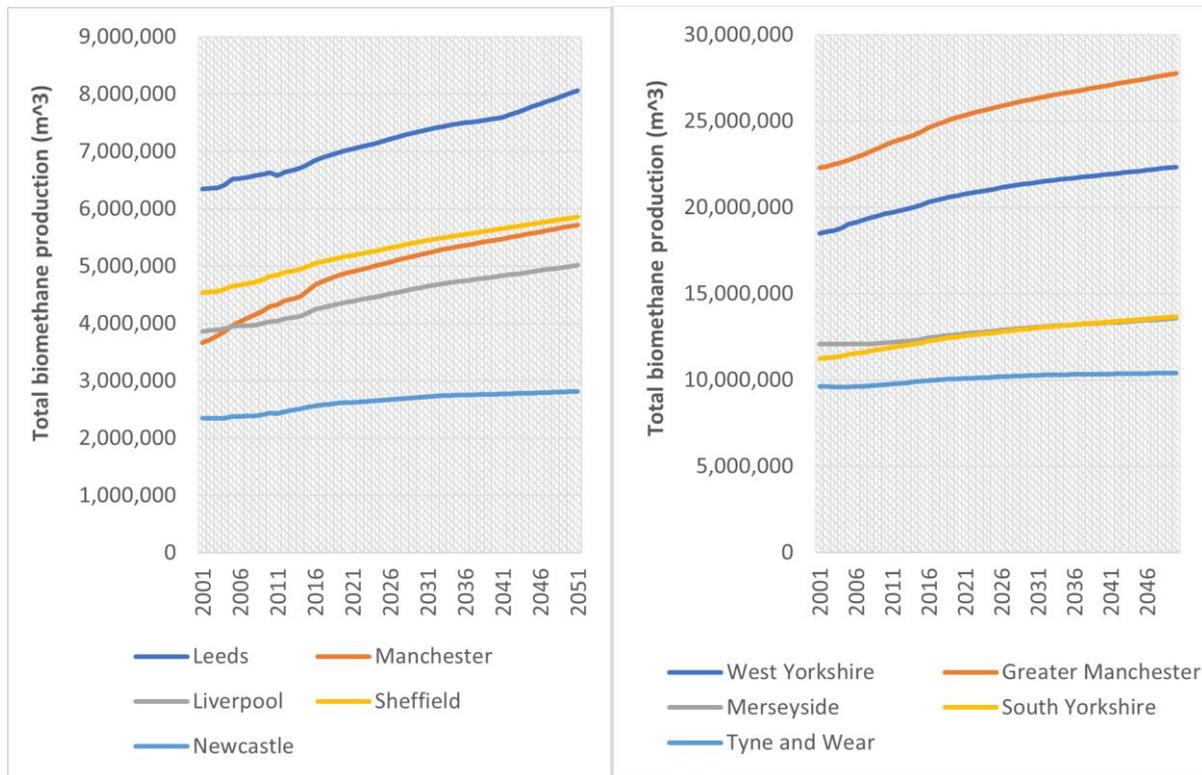


Figure 159. High Fixed FW collection and high FW to biomethane conversion yield scenario for all 5 NPH city (left) and metropolitan county (right) regions for 2010-2050 (for data used, please see Appendix table 32 and Appendix table 33)

For the High-FWC and High-BMC scenario, total biomethane production potential from 2001 to 2049 for all NPH city regions from order of lowest to highest is shown to be approximately 2,500,000-3,000,000m³ for Newcastle, 3,900,000-4,900,000m³ for Liverpool, 3,600,000-5,700,000m³ for Manchester, 4,400,000-5,750,000m³ for Sheffield and 2,560,000-3,160,000m³ for Leeds.

Interestingly, the total biomethane production potential from 2001 to 2049 for all NPH metropolitan country regions from order of lowest to highest is shown to be approximately 10,000,000-12,000,000m³ for Tyne and Wear, 11,500,000-13,000,000m³ for South Yorkshire, 12,000,000-13,000,000m³ for Merseyside, 18,500,000-22,000,000m³ for West Yorkshire and 22,000,000-27,500,000m³ for Greater Manchester.

5.3.4.1l High biomethane FW to biomethane conversion yield (45m³/t) scenario section summary (for Low, medium and high FW collection data inputs)

This section findings of all High FW to Biomethane conversion yield scenarios for all three (Low, Medium, and High) scenarios of household FW collection data. This is underpinned by three different levels of FW output per person (20, 40 and 100 kg/person/year) has returned a lowest and highest 2001-2049 BMP value of 500,000-600,000m³ (Newcastle, Low-FMC and Low-BMC) and 2,560,000-3,160,000m³ (Leeds, High-FMC and Low-BMC) respectively. Here the same comparison for metropolitan county regions has returned a lowest and highest 2001-2049 BMP value of 2,000,000-2,200,000m³ (Tyne and Wear, Low-FWC and Low-BMC) and 22,000,000-27,500,000m³ (Greater Manchester, High-FWC and Low-BMC), respectively, which constitutes to approximately 11 times difference between the two values.

Here it is worth noting that these findings constitute the highest estimations of BMP across all NPH city and metropolitan county regions as it applies the highest household FW to biomethane conversion factor of 90m³/t FW.

This finding will also be compared with other sub-section summary (see sections 5.3.4.1d and 5.3.4.1h) in the main section summary in 5.3.4.1m for outlining differences in the BMP across all 9 BMP scenarios presented in this section.

5.3.4.1m Section summary of all 9 scenario results comparisons

A summary comparison of total biomethane production across all NPH city regions (see Figure 160) shows extremely modest year on year increase, attributed solely to annual population changes, and with huge discrepancies attributable (and also with biomethane production being sensitive) to different scenarios of FW collection (FWC) and FW to biomethane conversion (BMC) yield.

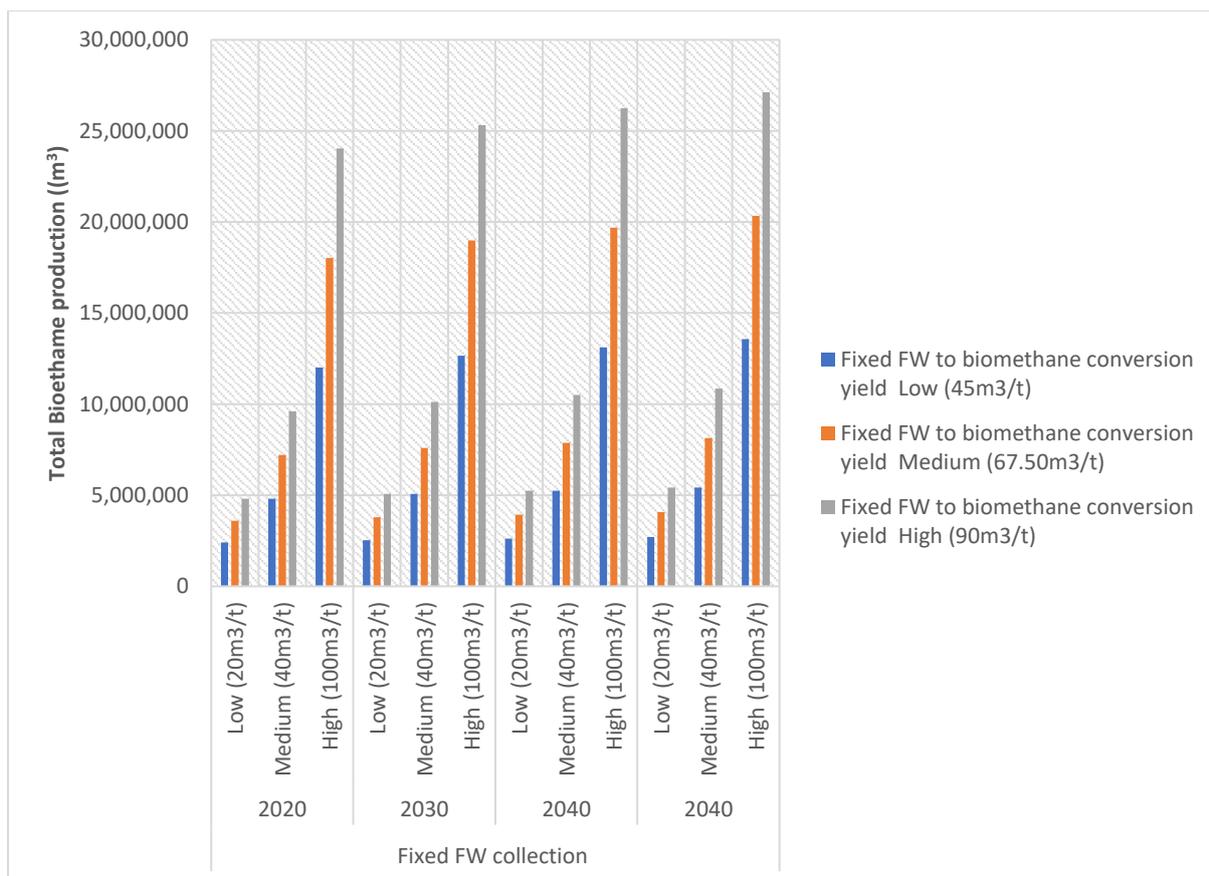


Figure 160. Total Biomethane production potential for 2020, 2030, 2040 and 2050 (as key timeline milestones) across all NPH city regions (for data used, see Appendix table 34)

To elaborate, the 9 scenarios and 3 sub-section summaries presented above outlined a few key trends in the overall BMP potential underpinned by 3 different levels (Low, Medium and High) FW collection (FWC) quantity per household (20, 40 and 100 kg/person/year) and Household FW to Biomethane conversion yields (BMC) (45, 67.5 and 90m³/t FW). Here it is important to note that general increase in BMP across all NPH city and metropolitan county regions from 2001 up to 2050 across all 9 scenarios attributed to the increase population across these regions with other factors for determining total BMP, i.e. FWC and BMC, to remain the same.

The first general trend findings in context of NPH geographical regions would be that Leeds and Greater Manchester respectively represent the NPH city and metropolitan county region with the greatest BMP potential due to having the greatest population base (based on ONS data projections). Conversely, Newcastle city and Tyne and Wear metropolitan county region yields the lowest BMP potential for the same given reasons.

The second general trend findings for each sub section involving low, medium and high levels of FWC (20, 40 and 100 kg/pp/year), which give rise to 5 times difference in total biomethane potential for the same region given that all other variables, i.e. BMC and year of comparison remain the same.

The third general trend findings for each sub section involving low, medium and high levels of BMC (45, 67.5 and 90m³/t FW), which give rise to 2 times difference in total biomethane potential for the same region given that all other variables, i.e. FWC and year of comparison remain the same.

When accounting for lower and upper ranges in both FWC (20, 40 and 100 kg/pp/year) and BMP (45, 67.50 and 90m³/t FW), the total difference in output BMP value between upper and lower values would be around 10 times for the same region given that all other variables, i.e. FWC and year of comparison remain the same (see Table 134).

Table 134. Multiplier table for all scenarios, showing multiplier number relative to scenario with base minimum value (FW collection and FW to biomethane conversion).

Fixed FW to biomethane conversion yield				
		Low (45m ³ /t)	Medium (67.50m ³ /t)	High (90m ³ /t)
Fixed FW collection	Low (20m ³ /t)	1	1.5	2
	Medium (40m ³ /t)	2	3	4
	High (100m ³ /t)	5	7.5	10

Here it is important to summarize that the order for biomethane potential (BMP) for all 5 NPH cities and metropolitan country regions from the highest to lowest would be Leeds > Sheffield > Manchester > Liverpool > Newcastle and Great Manchester > Wets Yorkshire > South Yorkshire = Merseyside > Tyne and Wear, respectively.

These findings are consequently important in situations where high level strategizing of where to implement FW collection schemes is to occur, as they would inevitably further affect values of downstream drivers of FWtTBC pathway, i.e., revenue and quantity of landfill FW diverted. Here based solely on the data for example it would be much enticing to implement FWtTBC pathways in Leeds city and Greater Manchester metropolitan country region, where the greatest perceived availability of BMP exists, and are directly proportional to the population difference.

Finally, it is critical to re-iterate that these findings are estimated by using both ONS and WDF data findings outlined in the preceding sections, and is consequently dependent on the accuracy and real world representativeness of these datasets (which is assumed to be adequate for purpose of this research).

5.3.4.1o Fixed biomethane generation potential findings summary – Limitations and proposal for future study

Key limitations to the above findings include a limited scenario coverage of the results (of only 9 scenarios) across the specified time period (2001-2050) using specific data i.e. for the WDF FW collection, FW to Biomethane Conversion (BMC) and ONS data, arising from previous findings for estimating total Biomethane Methane Potential (BMP) for each NPH city and metropolitan county region. Consequently, whilst the results clearly highlights the upper and lower bound BMP across each region, it cannot conclusively outline the most likely scenario that would occur for the foreseeable future. Rather, these findings are more useful for conducting assessment of theoretical available BMP across each region given certain conditions are met, i.e. in case of Low, Medium or high FWC or BMC across each specified region, rather than predicting real world BMP.

To this end, these outcomes suggest that policy, investment and deployment strategies pertaining to FWtTBC pathway deployment that could promote or facilitate (i) high FW capture

and participation rate, alongside (ii) FW to biomethane conversion yields, i.e. from technical AD operational parameters, FW type, or other factors such as presence of co-substrate, would be critical in affecting final biomethane output (see Findings on Whole systems analysis for specific recommendations).

The key weakness of these findings however would be that they assume no changes in FW collection yield (kg/person/year) overtime, for which limited dataset is available (arising from previous findings) from both WRAP and Waste Data Flow (WDF) sources. Consequently, these will be comparatively evaluated with findings in the next section which outlines an alternative total biomethane generation potential that accounts for time-adjusted FW collection data derived from WRAP and WDF FW collection trial datasets, which is reasonable assumed to be more real world representative (see finding 5.3.4.2).

5.3.4.2 Finding 3.2 – All time-adjusted variable FW collection scenarios (for all biomethane production scenario across all NPH city and county regions)

This section highlights all findings for time-adjusted variable food waste collection scenarios for NPH city and county regions, with 12 graphs in total (2 variable FW collection × 3 fixed biomethane production scenarios for 2 NPH regions of city and metropolitan county region, see relevant appendix section for corresponding data). These include total biomethane data estimated from both time adjusted FW collection data from both (i) WRAP (5.3.4.2a-f) and (ii) Waste Data Flow (WDF) (5.3.4.2g-l), as outlined in respective sections below.

5.3.4.2a Time-adjusted variable WRAP FW collection data × Low biomethane generation potential (45m³/t FW) scenario for NPH city regions

Figure 161 illustrates total biomethane generation potential (45m³) using time adjusted variable WRAP FW data collection in context of low FW to biomethane conversion yield (45m³/FW) covering all 5 NPH city regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

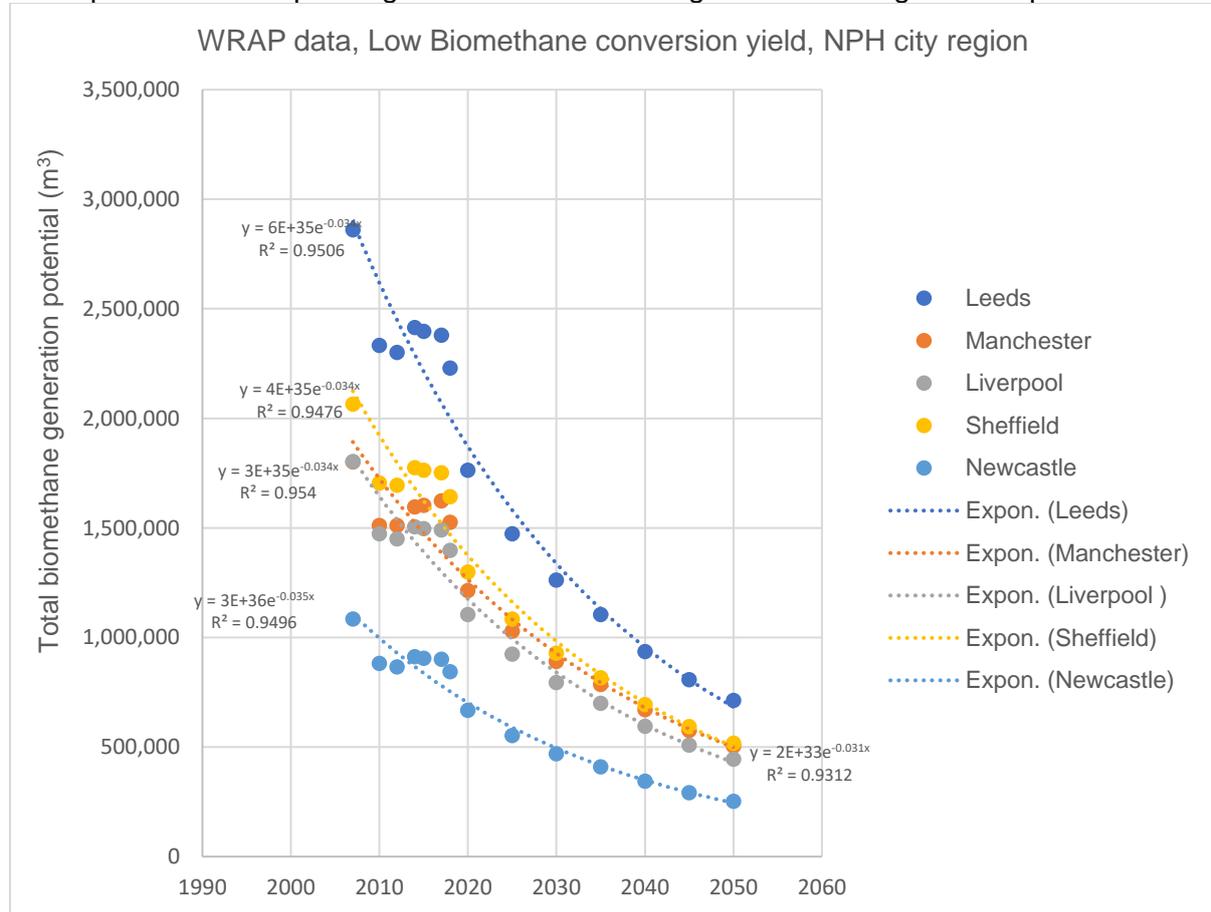


Figure 161. Total biomethane generation potential using (i) time-adjusted variable WRAP FW collection data with (ii) low FW to biomethane conversion yield data for all 5 NPH city regions for 2010-2050 (for data used, please see Appendix table 35). (dotted line represents collected data, whilst dashed line represents fitted data created using excels exponential best fit function, from which relevant equation is determined).

These findings demonstrate a large reduction in biomethane potential from 2,850,000m³ to 750,000m³ for Leeds, 2,100,000m³ to 500,000m³ for Sheffield, 1,900,000m³ to 500,000m³ for Manchester 1,800,000m³ to 495,000m³ for Liverpool and 1,100,000m³ to 250,000m³ for Newcastle NPH city regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 2,850,000m³ to 2,250,000m³ for Leeds, 2,100,000m³ to 1,600,000m³ for Sheffield, 1,800,000m³ to 1,500,000m³ for Manchester, 1,800,000m³ to 1,450,000m³ for Liverpool and 1,100,000m³ to 850,000m³ for Newcastle the period of 2007 to 2017.

These are accompanied by strong R² values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R² equals to 0.9506, 0.9476, 0.9312, 0.954, 0.9496 for Leeds, Sheffield, Manchester, Liverpool and Newcastle, respectively.

5.3.4.2b Time-adjusted variable WRAP FW collection data × Medium biomethane generation potential (67.50m³) scenario for NPH city regions

Figure 162 illustrates total biomethane generation potential (67.50m³) using time adjusted variable WRAP FW data collection in context of low FW to biomethane conversion yield (67.50m³/FW) covering all 5 NPH city regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

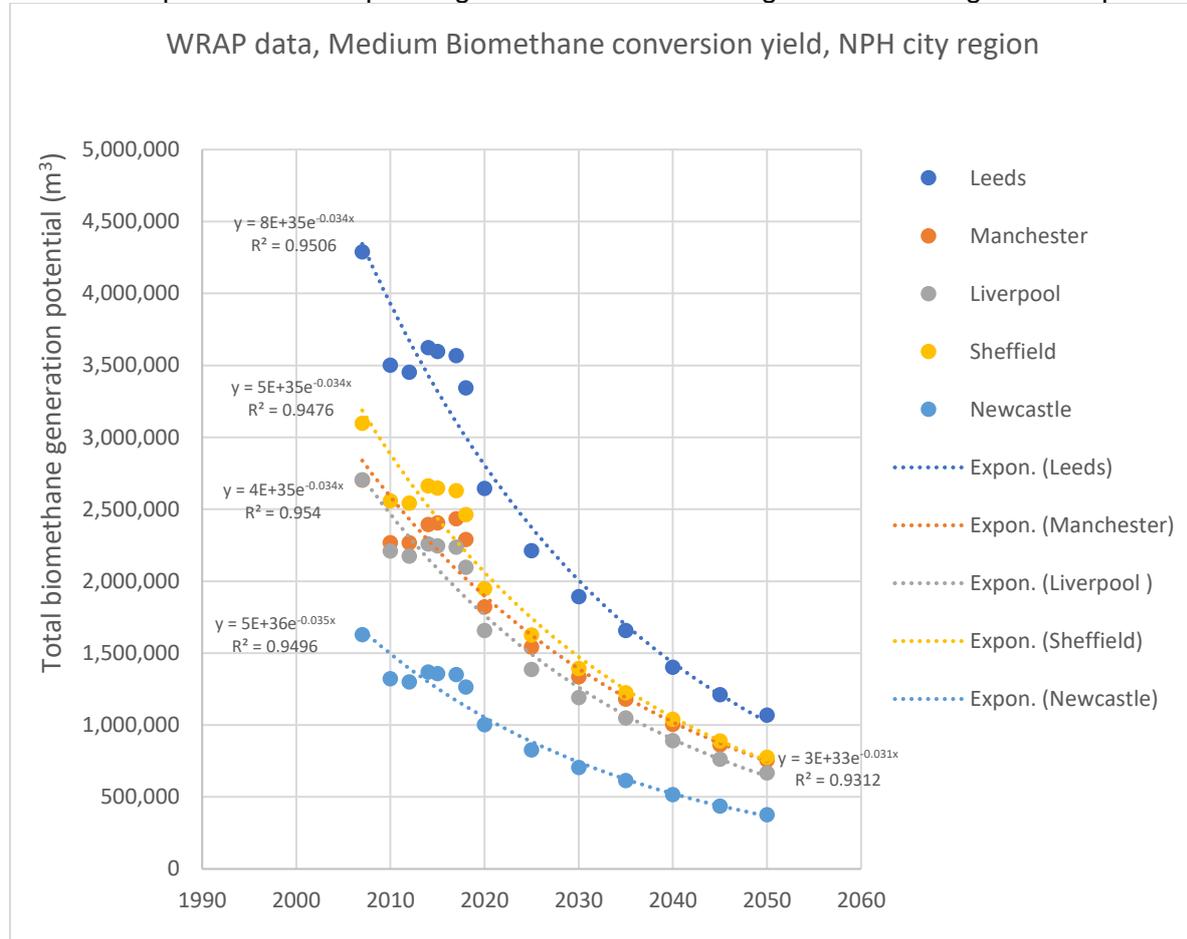


Figure 162. Total biomethane generation potential using (i) time-adjusted variable WRAP FW collection data with (ii) medium FW to biomethane conversion yield data for all 5 NPH city regions for 2010-2050 (for data used, please see Appendix table 36) (dotted line represents collected data, whilst dashed line represents fitted data created using excels exponential best fit function, from which relevant equation is determined).

These findings demonstrate a large reduction in biomethane potential from 4,275,000m³ to 1,125,000m³ for Leeds, 3,150,000m³ to 750,000m³ for Sheffield, 2,850,000m³ to 750,000m³ for Manchester 2,700,000m³ to 742,500m³ for Liverpool and 1,650,000m³ to 375,000m³ for Newcastle NPH city regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 4,275,000m³ to 3,375,000m³ for Leeds, 3,150,000m³ to 2,400,000m³ for Sheffield, 2,700,000m³ to 2,250,000m³ for Manchester, 2,700,000m³ to 2,175,000m³ for Liverpool and 1,650,000m³ to 1,275,000m³ for Newcastle the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.9506, 0.9476, 0.9312, 0.954, 0.9496 for Leeds, Sheffield, Manchester, Liverpool and Newcastle, respectively.

5.3.4.2c Time-adjusted variable WRAP FW collection data × High biomethane generation potential (90m³) scenario for NPH city regions

Figure 163 illustrates total biomethane generation potential (90m³) using time adjusted variable WRAP FW data collection in context of low FW to biomethane conversion yield (90m³/FW) covering all 5 NPH city regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

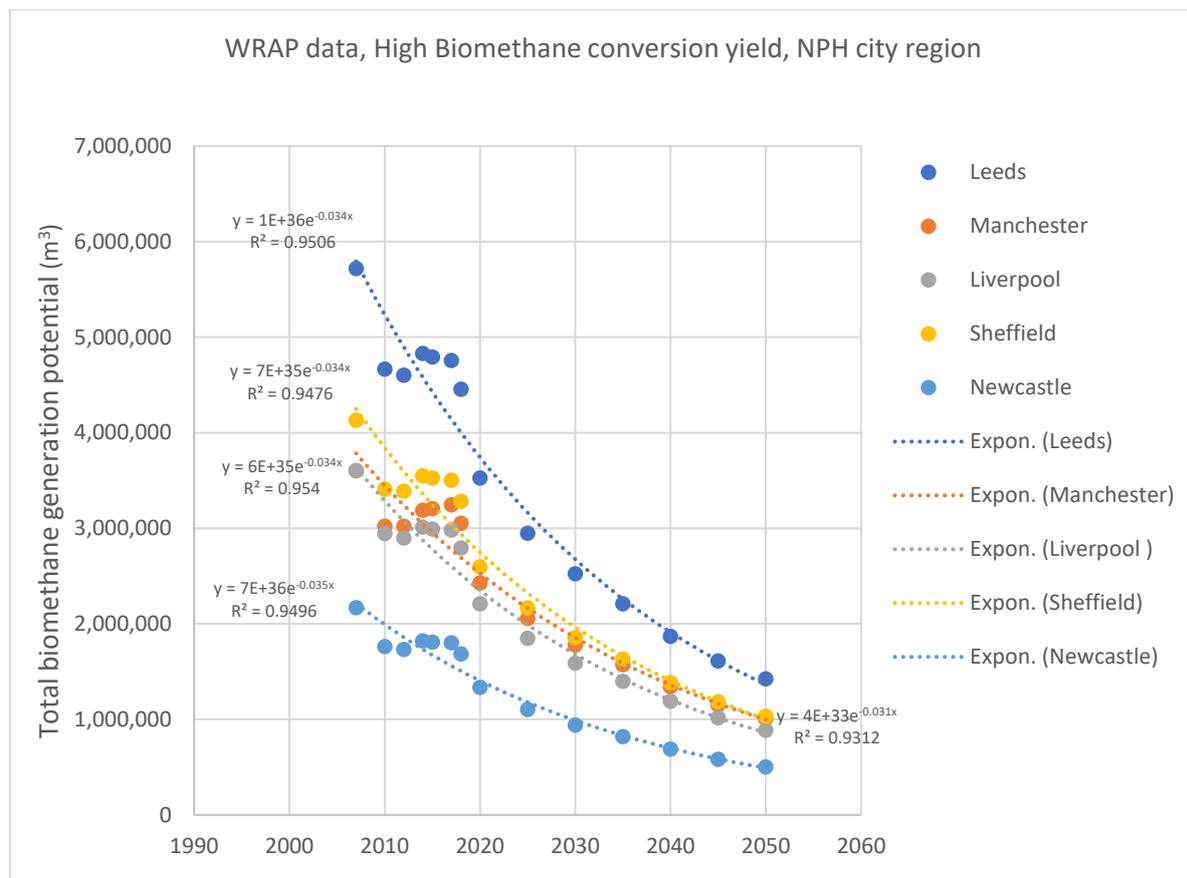


Figure 163. Total biomethane generation potential using (i) time-adjusted variable WRAP FW collection data with (ii) high FW to biomethane conversion yield data for all 5 NPH city regions for 2010-2050 (for data used, see Appendix table 37)

These findings demonstrate a large reduction in biomethane potential from 5,700,000m³ to 1,500,000m³ for Leeds, 4,200,000m³ to 1,000,000m³ for Sheffield, 3,800,000m³ to 1,000,000m³ for Manchester 3,600,000m³ to 990,000m³ for Liverpool and 2,200,000m³ to 500,000m³ for Newcastle NPH city regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 5,700,000m³ to 4,500,000m³ for Leeds, 4,200,000m³ to 3,200,000m³ for Sheffield, 3,600,000m³ to 3,000,000m³ for Manchester, 3,600,000m³ to 2,900,000m³ for Liverpool and 2,200,000m³ to 1,700,000m³ for Newcastle the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.9506, 0.9476, 0.9312, 0.954, 0.9496 for Leeds, Sheffield, Manchester, Liverpool and Newcastle, respectively.

5.3.4.2d Time-adjusted variable WRAP FW collection data × Low biomethane generation potential (45m³) scenario for NPH metropolitan county regions

Figure 164 illustrates total biomethane generation potential (45m³) using time adjusted variable WRAP FW data collection in context of low FW to biomethane conversion yield (45m³/FW) covering all 5 NPH metropolitan county regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

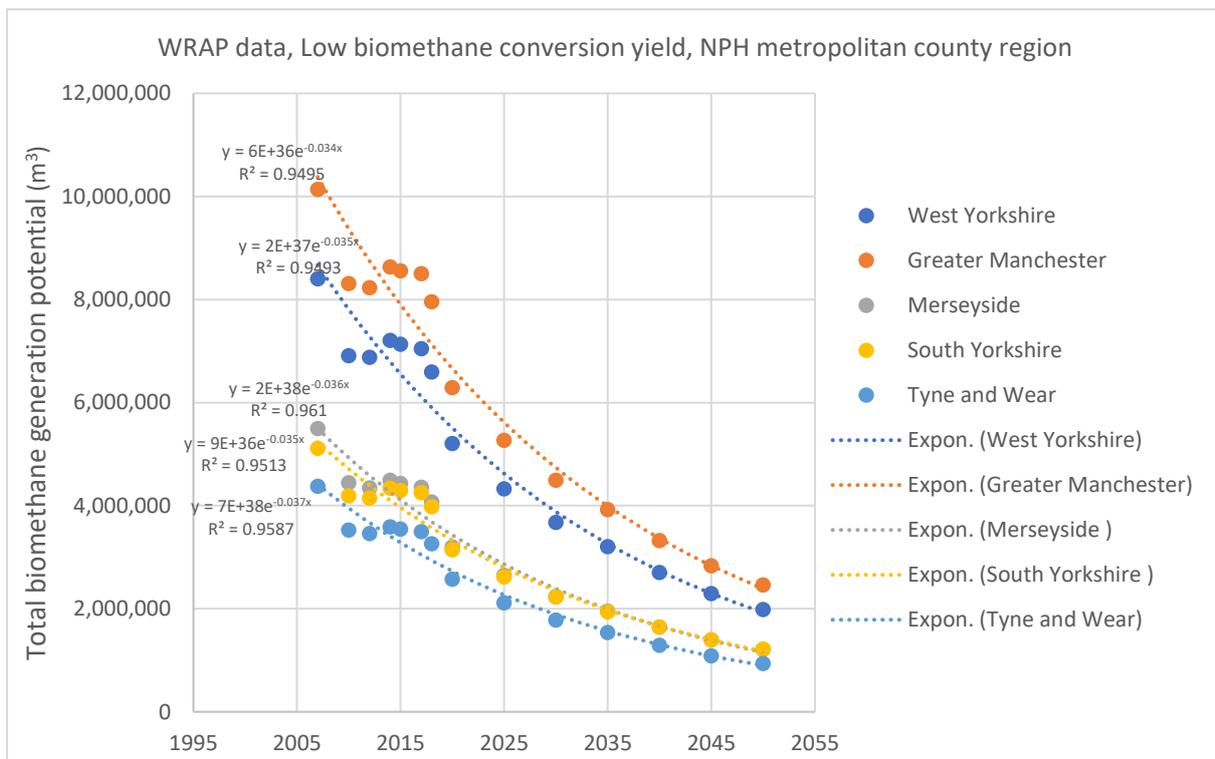


Figure 164. Total biomethane generation potential using (i) time-adjusted variable WRAP FW collection data with (ii) low FW to biomethane conversion yield data for all 5 NPH metropolitan county regions for 2010-2050 (for data used, see Appendix table 38)

These findings demonstrate a large reduction in biomethane potential from 10,100,000m³ to 2,400,000m³ for Greater Manchester, 8,400,000m³ to 2,000,000m³ for West Yorkshire, 5,800,000m³ to 1,000,000m³ for Merseyside 5,500,000m³ to 1,000,000m³ for South Yorkshire and 4,200,000m³ to 1,000,000m³ for Tyne and Wear NPH metropolitan county regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 10,100,000m³ to 7,950,000m³ for Greater Manchester, 8,400,000m³ to 6,300,000m³ for West Yorkshire, 5,800,000m³ to 4,050,000m³ for Merseyside, 5,500,000m³ to 3,950,000m³ for South Yorkshire and 4,200,000m³ to 3,250,000m³ for Tyne and Wear the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.9495, 0.9493, 0.961, 0.9513, 0.9587 for Greater Manchester, West Yorkshire, Merseyside, South Yorkshire and Tyne and Wear, respectively.

5.3.4.2e Time-adjusted variable WRAP FW collection data x medium biomethane generation potential (67.50m³) scenario for NPH metropolitan county regions

Figure 165 illustrates total biomethane generation potential (67.50m³) using time adjusted variable WRAP FW data collection in context of low FW to biomethane conversion yield (67.50m³/FW) covering all 5 NPH metropolitan county regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

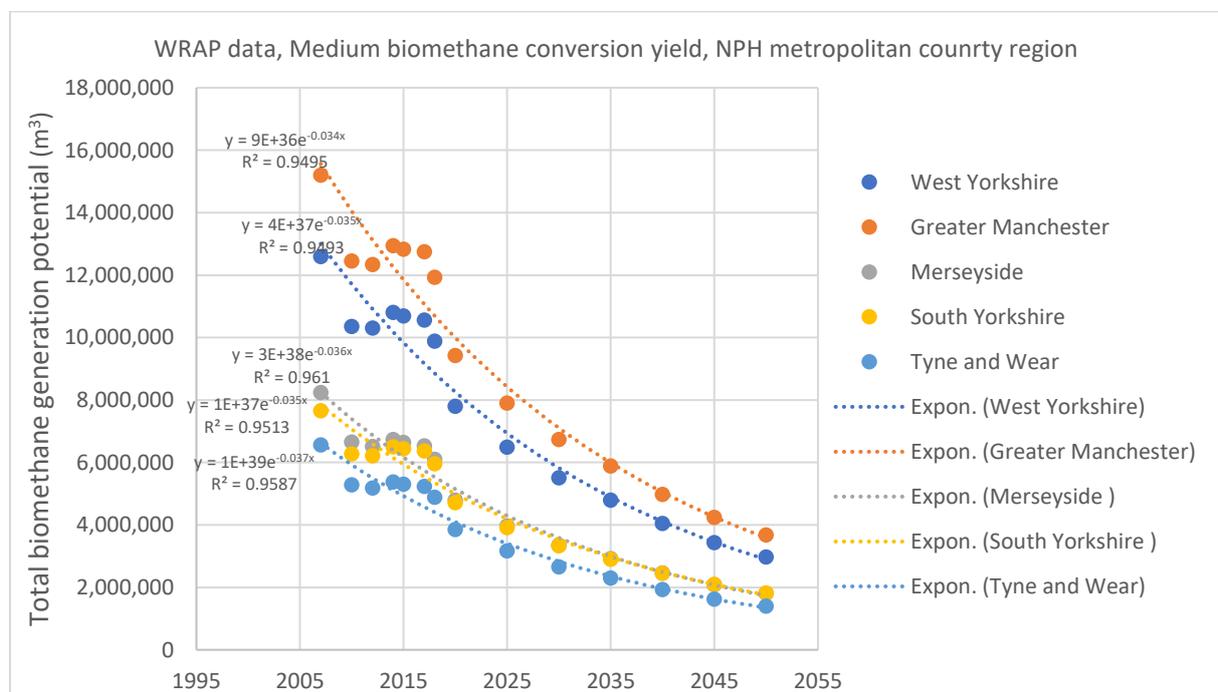


Figure 165. Total biomethane generation potential using (i) time-adjusted variable WRAP FW collection data with (ii) medium FW to biomethane conversion yield data for all 5 NPH metropolitan county regions for 2010-2050 (for data used, see Appendix table 39)

These findings demonstrate a large reduction in biomethane potential from 15,150,000m³ to 3,600,000m³ for Greater Manchester, 12,600,000m³ to 3,000,000m³ for West Yorkshire, 8,700,000m³ to 1,500,000m³ for Merseyside 8,250,000m³ to 1,500,000m³ for South Yorkshire and 6,300,000m³ to 1,500,000m³ for Tyne and Wear NPH metropolitan county regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 15,150,000m³ to 11,925,000m³ for Greater Manchester, 12,600,000m³ to 9,450,000m³ for West Yorkshire, 8,700,000m³ to 6,075,000m³ for Merseyside, 8,700,000m³ to 5,925,000m³ for South Yorkshire and 6,300,000m³ to 4,875,000m³ for Tyne and Wear the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.9495, 0.9493, 0.961, 0.9513, 0.9587 for Greater Manchester, West Yorkshire, Merseyside, South Yorkshire and Tyne and Wear, respectively.

5.3.4.2f Time-adjusted variable WRAP FW collection data × High biomethane generation potential (90m³) scenario for NPH metropolitan county regions

Figure 166 illustrates total biomethane generation potential (90m³) using time adjusted variable WRAP FW data collection in context of low FW to biomethane conversion yield (90m³/FW) covering all 5 NPH metropolitan county regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

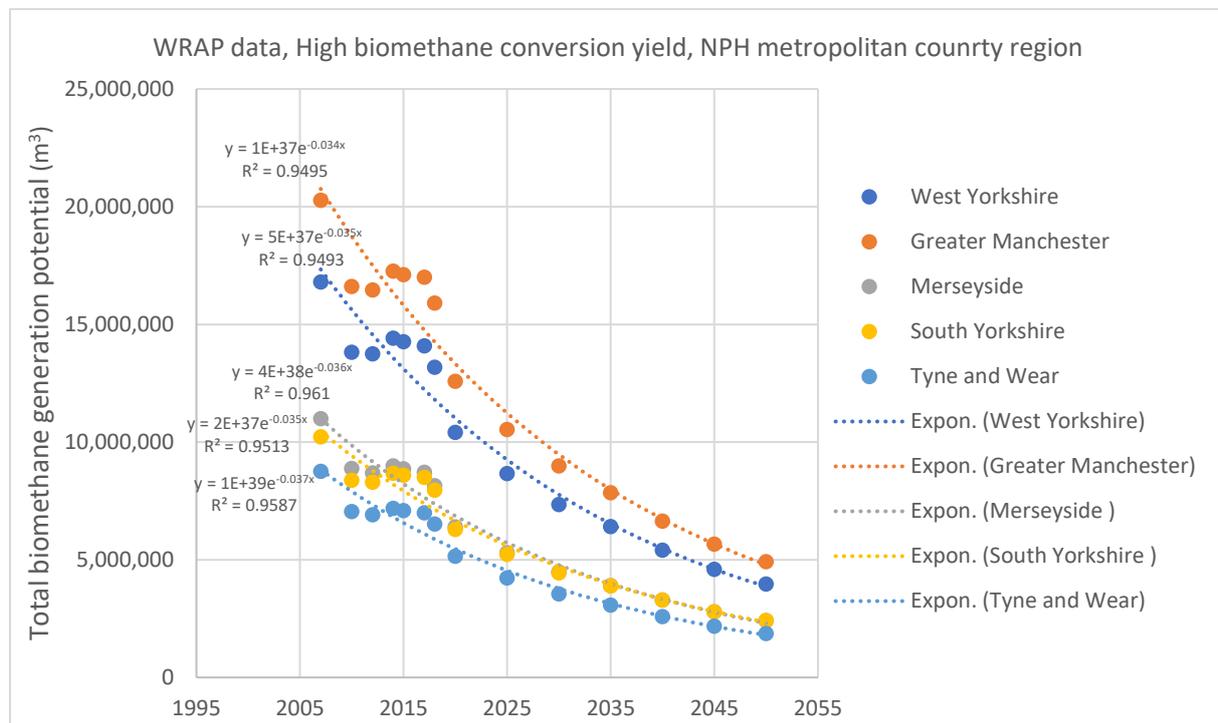


Figure 166. Total biomethane generation potential using (i) time-adjusted variable WRAP FW collection data with (ii) high FW to biomethane conversion yield data for all 5 NPH metropolitan county regions for 2010-2050 (for data used, see Appendix table 35)

These findings demonstrate a large reduction in biomethane potential from 20,200,000m³ to 4,800,000m³ for Greater Manchester, 16,800,000m³ to 4,000,000m³ for West Yorkshire, 11,600,000m³ to 2,000,000m³ for Merseyside 11,000,000m³ to 2,000,000m³ for South Yorkshire and 8,400,000m³ to 2,000,000m³ for Tyne and Wear NPH metropolitan county regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 20,200,000m³ to 15,900,000m³ for Greater Manchester, 16,800,000m³ to 12,600,000m³ for West Yorkshire, 11,600,000m³ to 8,100,000m³ for Merseyside, 11,000,000m³ to 7,900,000m³ for South Yorkshire and 8,400,000m³ to 6,500,000m³ for Tyne and Wear the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.9495, 0.9493, 0.961, 0.9513, 0.9587 for Greater Manchester, West Yorkshire, Merseyside, South Yorkshire and Tyne and Wear, respectively.

5.3.4.2g Time-adjusted variable Waste Data Flow (WDF) FW collection data × Low biomethane generation potential (45m³) scenario for NPH city regions

Figure 167 illustrates total biomethane generation potential (45m³) using time adjusted variable WDF FW data collection in context of low FW to biomethane conversion yield (45m³/FW) covering all 5 NPH city regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

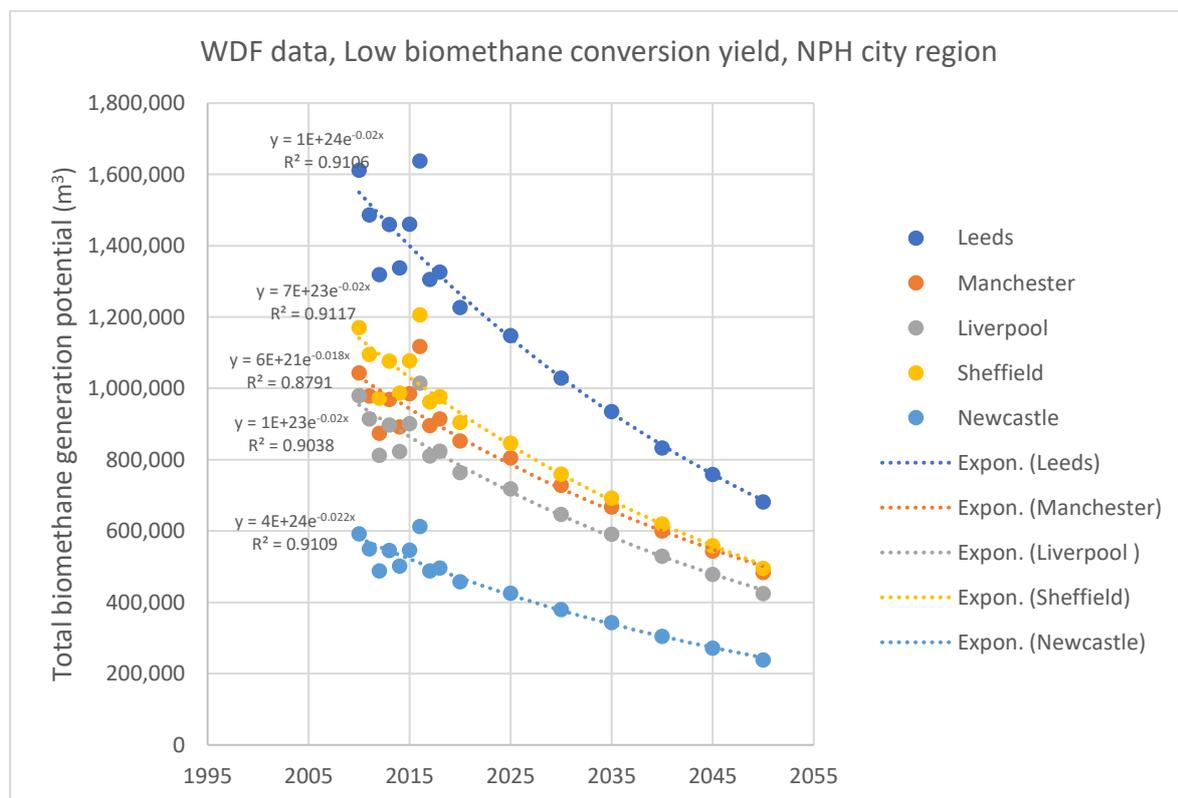


Figure 167. Total biomethane generation potential using (i) time-adjusted variable Waste Data Flow (WDF) FW collection data with (ii) low FW to biomethane conversion yield data for all 5 NPH city regions for 2010-2050 (for data used, see Appendix table 35)

These findings demonstrate a large reduction in biomethane potential from 1,610,000m³ to 700,000m³ for Leeds, 1,180,000m³ to 500,000m³ for Sheffield, 1,060,000m³ to 490,000m³ for Manchester 990,000m³ to 420,000m³ for Liverpool and 595,000m³ to 240,000m³ for Newcastle NPH city regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 1,610,000m³ to 1,250,000m³ for Leeds, 2,100,000m³ to 900,000m³ for Sheffield, 1,800,000m³ to 850,000m³ for Manchester, 1,800,000m³ to 785,000m³ for Liverpool and 1,100,000m³ to 470,000m³ for Newcastle the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.91, 0.9117,

0.8791, 0.9038, 0.9109 for Leeds, Sheffield, Manchester, Liverpool and Newcastle, respectively.

5.3.4.2h Time-adjusted variable Waste Data Flow (WDF) FW collection data × Medium biomethane generation potential (67.50m³) scenario for NPH city regions

Figure 168 illustrates total biomethane generation potential (67.50m³) using time adjusted variable WDF FW data collection in context of low FW to biomethane conversion yield (67.50m³/FW) covering all 5 NPH city regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

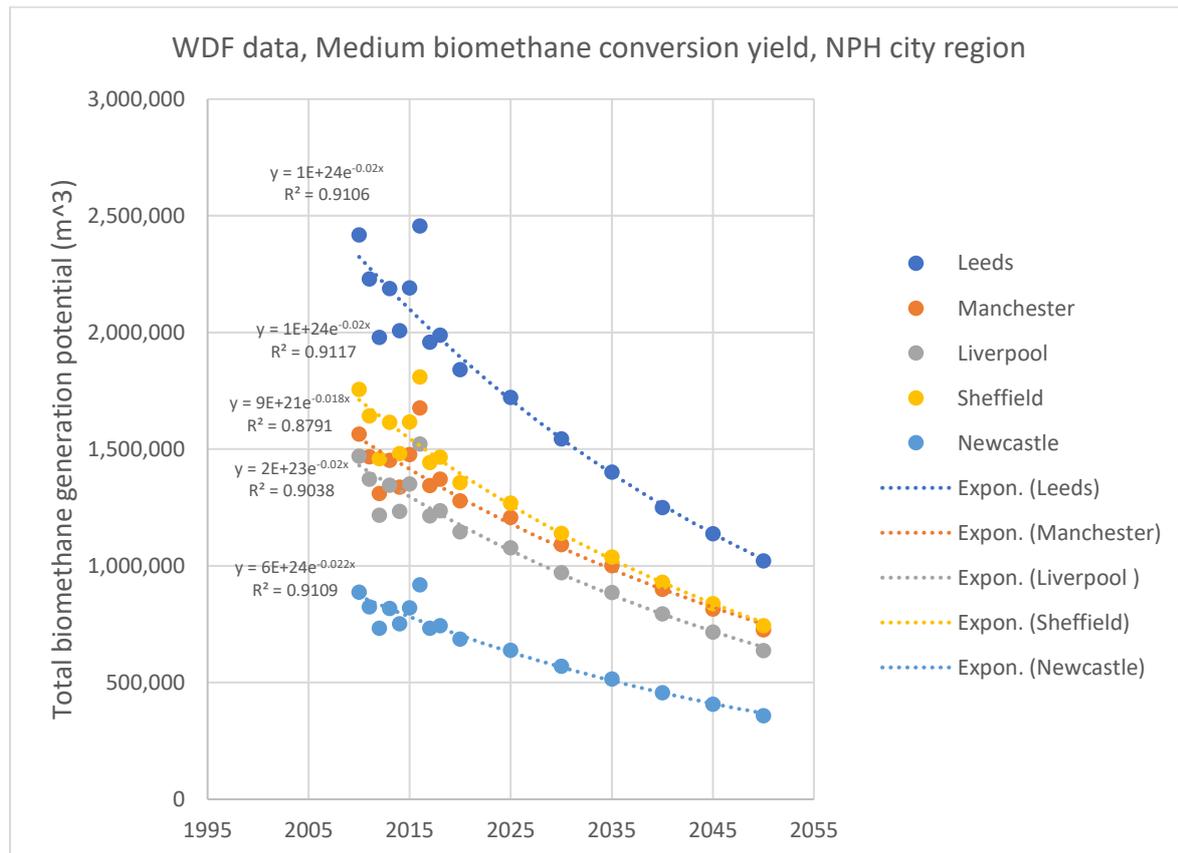


Figure 168. Total biomethane generation potential using (i) time-adjusted variable Waste Data Flow (WDF) FW collection data with (ii) medium FW to biomethane conversion yield data for all 5 NPH city regions for 2010-2050 (for data used, see Appendix table 35)

These findings demonstrate a large reduction in biomethane potential from 2,415,000m³ to 1,050,000m³ for Leeds, 1,770,000m³ to 750,000m³ for Sheffield, 1,590,000m³ to 735,000m³ for Manchester 1,485,000m³ to 630,000m³ for Liverpool and 892,500 to 360,000m³ for Newcastle NPH city regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 2,415,000m³ to 1,875,000m³ for Leeds, 3,150,000m³ to 1,350,000m³ for Sheffield, 2,700,000m³ to 1,275,000m³ for Manchester, 2,700,000m³ to 1,177,500m³ for Liverpool and 1,650,000m³ to 705,000m³ for Newcastle the period of 2007 to 2017.

These are accompanied by strong R² values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R² equals to 0.91, 0.9117,

0.8791, 0.9038, 0.9109 for Leeds, Sheffield, Manchester, Liverpool and Newcastle, respectively.

5.3.4.2i Time-adjusted variable Waste Data Flow (WDF) FW collection data × High biomethane generation potential (90m³) scenario for NPH city regions

Figure 169 illustrates total biomethane generation potential (90m³) using time adjusted variable WDF FW data collection in context of low FW to biomethane conversion yield (90m³/FW)s covering all 5 NPH city regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

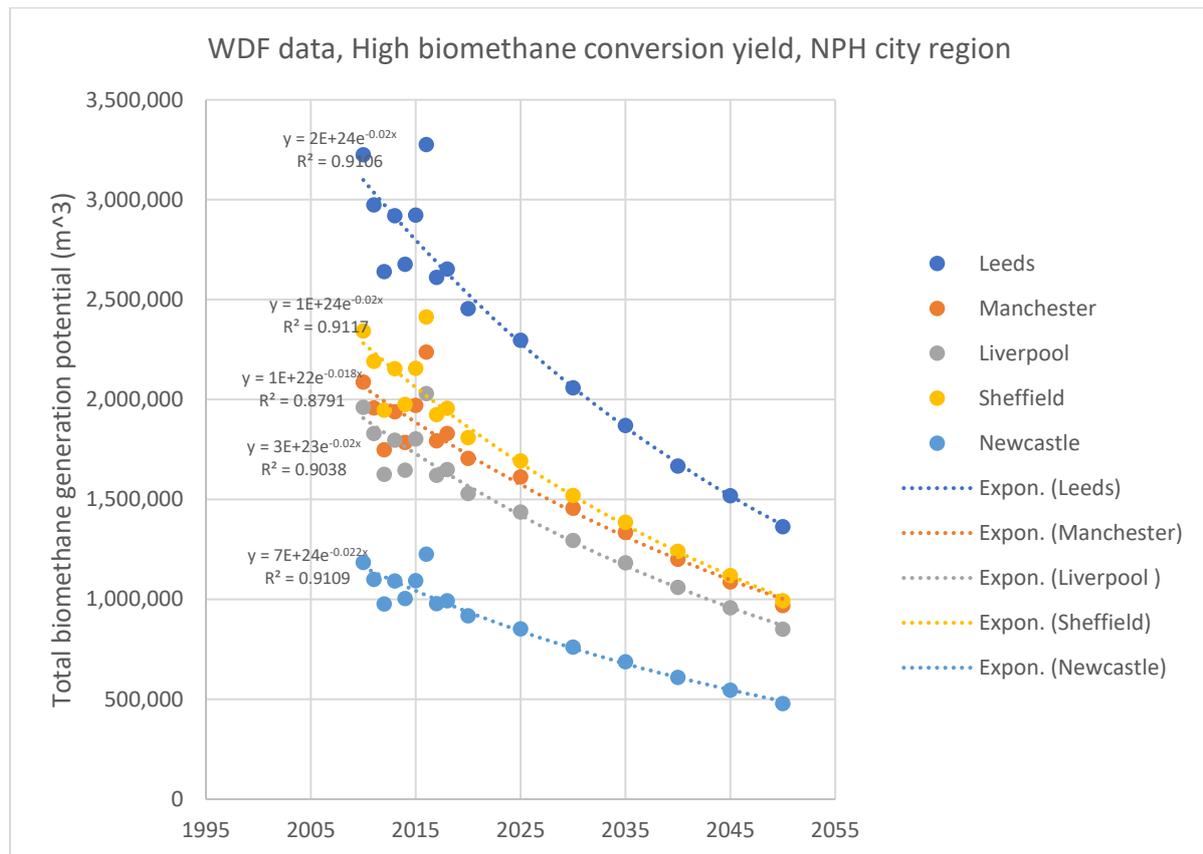


Figure 169. Total biomethane generation potential using (i) time-adjusted variable Waste Data Flow (WDF) FW collection data with (ii) high FW to biomethane conversion yield data for all 5 NPH city regions for 2010-2050 (for data used, see Appendix table 35)

These findings demonstrate a large reduction in biomethane potential from 3,220,000m³ to 1,400,000m³ for Leeds, 2,360,000m³ to 1,000,000m³ for Sheffield, 2,120,000m³ to 980,000m³ for Manchester 1,980,000m³ to 840,000m³ for Liverpool and 1,190,000m³ to 480,000m³ for Newcastle NPH city regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 3,220,000m³ to 2,500,000m³ for Leeds, 4,200,000m³ to 1,800,000m³ for Sheffield, 3,600,000m³ to 1,700,000m³ for Manchester, 3,600,000m³ to 1,570,000m³ for Liverpool and 2,200,000m³ to 940,000m³ for Newcastle the period of 2007 to 2017.

These are accompanied by strong R² values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R² equals to 0.91, 0.9117,

0.8791, 0.9038, 0.9109 for Leeds, Sheffield, Manchester, Liverpool and Newcastle, respectively.

5.3.4.2j Time-adjusted variable Waste Data Flow (WDF) FW collection data x Low biomethane generation potential (45m³) scenario for NPH metropolitan county regions

Figure 170 illustrates total biomethane generation potential (45m³) using time adjusted variable WDF FW data collection in context of low FW to biomethane conversion yield (45m³/FW) covering all 5 NPH metropolitan county regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

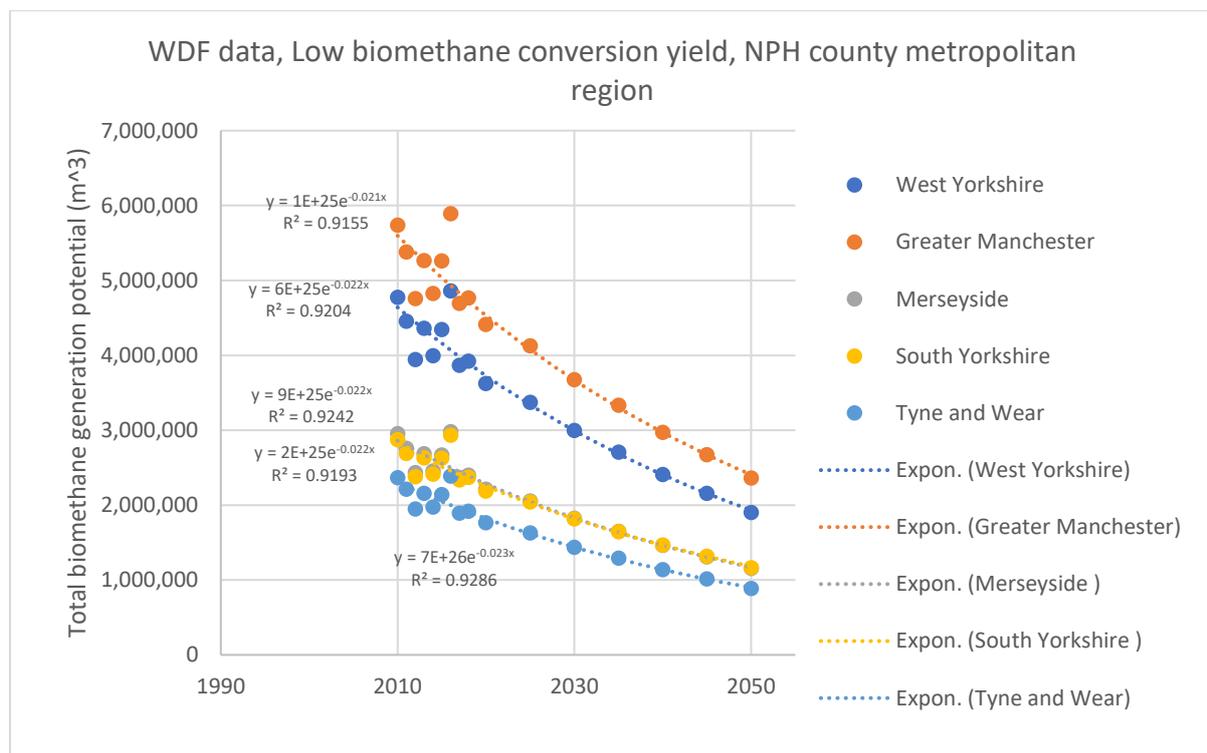


Figure 170. Total biomethane generation potential using (i) time-adjusted variable Waste Data Flow (WDF) FW collection data with (ii) low FW to biomethane conversion yield data for all 5 NPH metropolitan county regions for 2010-2050 (for data used, see Appendix table 35)

These findings demonstrate a large reduction in biomethane potential from 5,700,000m³ to 2,400,000m³ for Greater Manchester, 4,800,000m³ to 1,950,000m³ for West Yorkshire, 2,950,000m³ to 1,250,000m³ for Merseyside, 2,950,000m³ to 1,250,000m³ for South Yorkshire and 2,400,000m³ to 950,000m³ for Tyne and Wear NPH metropolitan county regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 5,700,000m³ to 4,450,000m³ for Greater Manchester, 4,800,000m³ to 3,600,000m³ for West Yorkshire, 2,950,000m³ to 2,150,000m³ for Merseyside, 2,950,000m³ to 2,150,000m³ for South Yorkshire and 2,400,000m³ to 1,000,000m³ for Tyne and Wear the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.9155, 0.9204, 0.9242, 0.9193, 0.9286 for Greater Manchester, West Yorkshire, Merseyside, South Yorkshire and Tyne and Wear, respectively.

5.3.4.2k Time-adjusted variable Waste Data Flow (WDF) FW collection data × Medium biomethane generation potential (67.50m³) scenario for NPH metropolitan county regions

Figure 171 illustrates total biomethane generation potential (67.50m³) using time adjusted variable WDF FW data collection in context of low FW to biomethane conversion yield (67.50m³/FW) covering all 5 NPH metropolitan county regions. The dots represent original data points and dash line represents corresponding data correlation arising from these original data points.

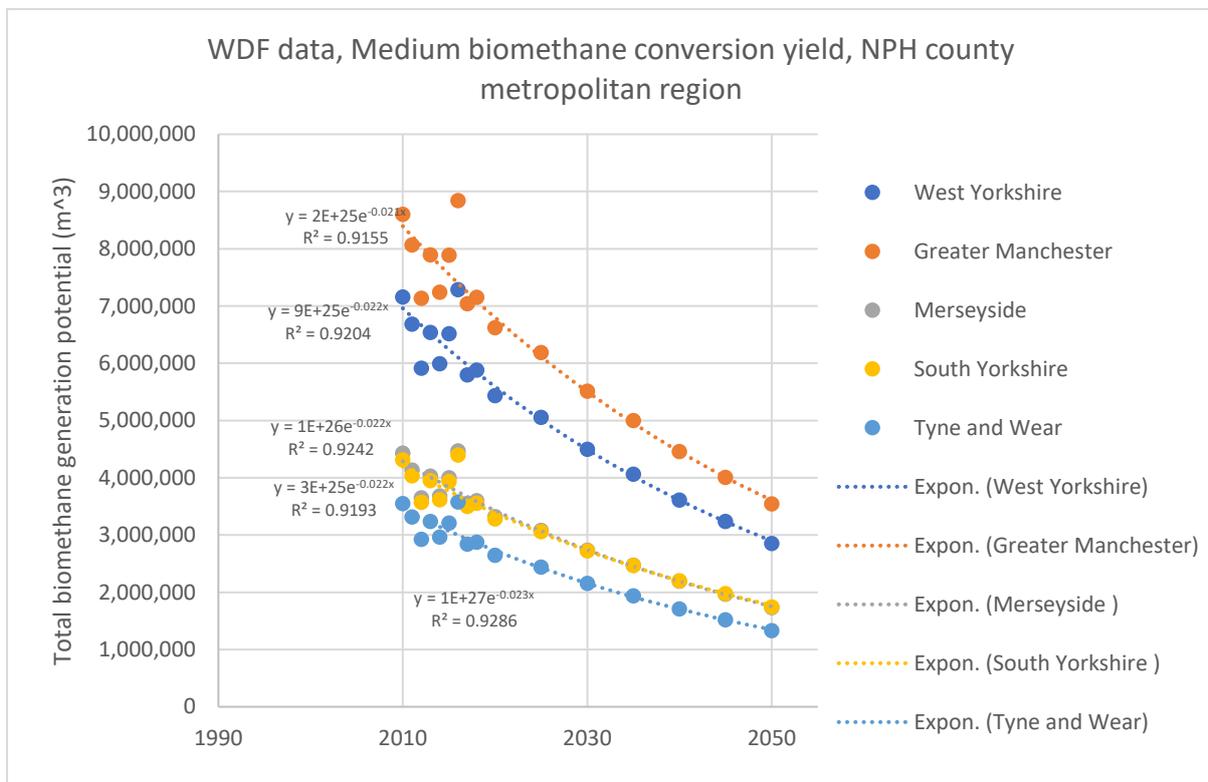


Figure 171. Total biomethane generation potential using (i) time-adjusted variable Waste Data Flow (WDF) FW collection data with (ii) medium FW to biomethane conversion yield data for all 5 NPH metropolitan county regions for 2010-2050 (for data used, see Appendix table 35)

These findings demonstrate a large reduction in biomethane potential from 7,550,000m³ to 3,600,000m³ for Greater Manchester, 7,200,000m³ to 2,900,000m³ for West Yorkshire, 4,425,000m³ to 1,875,000m³ for Merseyside 4,350,000m³ to 1,875,000m³ for South Yorkshire and 3,600,000m³ to 1,425,000m³ for Tyne and Wear NPH metropolitan county regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 7,550,000m³ to 6,675,000m³ for Greater Manchester, 7,200,000m³ to 5,400,000m³ for West Yorkshire, 4,525,000m³ to 3,225,000m³ for Merseyside, 4,350,000m³ to 3,225,000m³ for South Yorkshire and 3,600,000m³ to 1,500,000m³ for Tyne and Wear the period of 2007 to 2017.

These are accompanied by strong R^2 values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R^2 equals to 0.9155, 0.9204, 0.9242, 0.9193, 0.9286 for Greater Manchester, West Yorkshire, Merseyside, South Yorkshire and Tyne and Wear, respectively.

5.3.4.2I Time-adjusted variable Waste Data Flow (WDF) FW collection data × High biomethane generation potential (90m³) scenario for NPH metropolitan county regions

Figure 172 illustrates total biomethane generation potential (90m³) using time adjusted variable WDF FW data collection in context of low FW to biomethane conversion yield (90m³/FW) covering all 5 NPH metropolitan county regions. The dots represent original data points and dash line represents data correlation arising from these original data points.

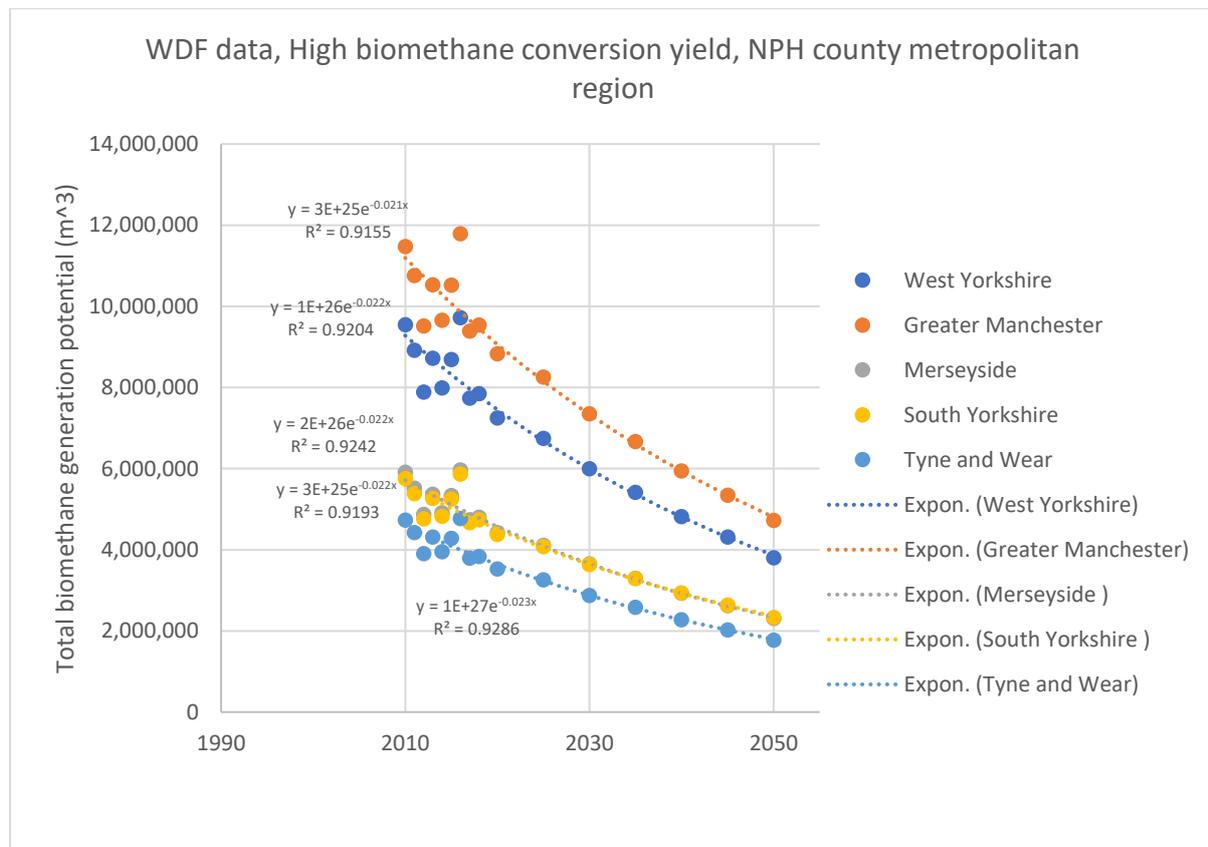


Figure 172. Total biomethane generation potential using (i) time-adjusted variable Waste Data Flow (WDF) FW collection data with (ii) high FW to biomethane conversion yield data for all 5 NPH metropolitan county regions for 2010-2050 (for data used, see Appendix table 35)

These findings demonstrate a large reduction in biomethane potential from 11,400,000m³ to 4,800,000m³ for Greater Manchester, 9,400,000m³ to 3,900,000m³ for West Yorkshire, 5,900,000m³ to 2,500,000m³ for Merseyside, 5,800,000m³ to 2,500,000m³ for South Yorkshire and 4,800,000m³ to 1,900,000m³ for Tyne and Wear NPH metropolitan county regions between the total projected period of 2007 and 2050.

When accounting for actual data inputs excluding extrapolated data these would include 11,400,000m³ to 9,900,000m³ for Greater Manchester, 9,400,000m³ to 7,200,000m³ for West Yorkshire, 5,900,000m³ to 4,300,000m³ for Merseyside, 5,800,000m³ to 4,300,000m³ for South

Yorkshire and 4,800,000m³ to 2,000,000m³ for Tyne and Wear NPH metropolitan county regions between the total projected period of 2007 to 2017.

These are accompanied by strong R² values to demonstrate overall strong consistency of results between 2007 and 2050 across all NPH city regions, where R² equals to 0.9506, 0.9476, 0.9312, 0.954, 0.9496 for Leeds, Sheffield, Manchester, Liverpool and Newcastle, respectively.

5.3.4.2m Variable total biomethane generation potential findings summary analysis – Observations, discussions and initial implications

The move findings respectively outline a few general trends of year-on-year decline in total biomethane generation potential for all NPH city and metropolitan city regions for all FW to biomethane conversion yield scenarios (low, medium and high).

The first observed trend would be the general doubling (or increase of 100%) of BMP for any year across all NPH city and metropolitan county regions (derived from both WDF and WRAP data) with high (90m³/t FW) against low (45m³/t FW) FW to Biomethane conversion BMC value.

Both WRAP and WDF BMP also exhibits an exponential decaying trend albeit with different starting points and at different rates of decay. Here interestingly, WRAP BMP data exhibiting a higher initial value compared to WDF data but also high rate of annual decay (or shorter half-life), which consequently leads to the convergence in the value of total BMP for both WRAP and WDF data at 2050 (see Figure 173 and Figure 174).

For WRAP data estimations, the NPH city region with greatest BMP potential between 2007 and 2050 is shown to be 5,700,000 to 1,500,000m³ for Leeds, whilst the WDF data shows this to be 3,220,000 to 1,400,000m³. Likewise, WRAP data estimations for highest NPH metropolitan county region with greatest BMP potential between these same period (2007 and 2050) would be 20,200,000 to 4,800,000 compared to the WDF values of 11,400,000 to 4,800,000m³.

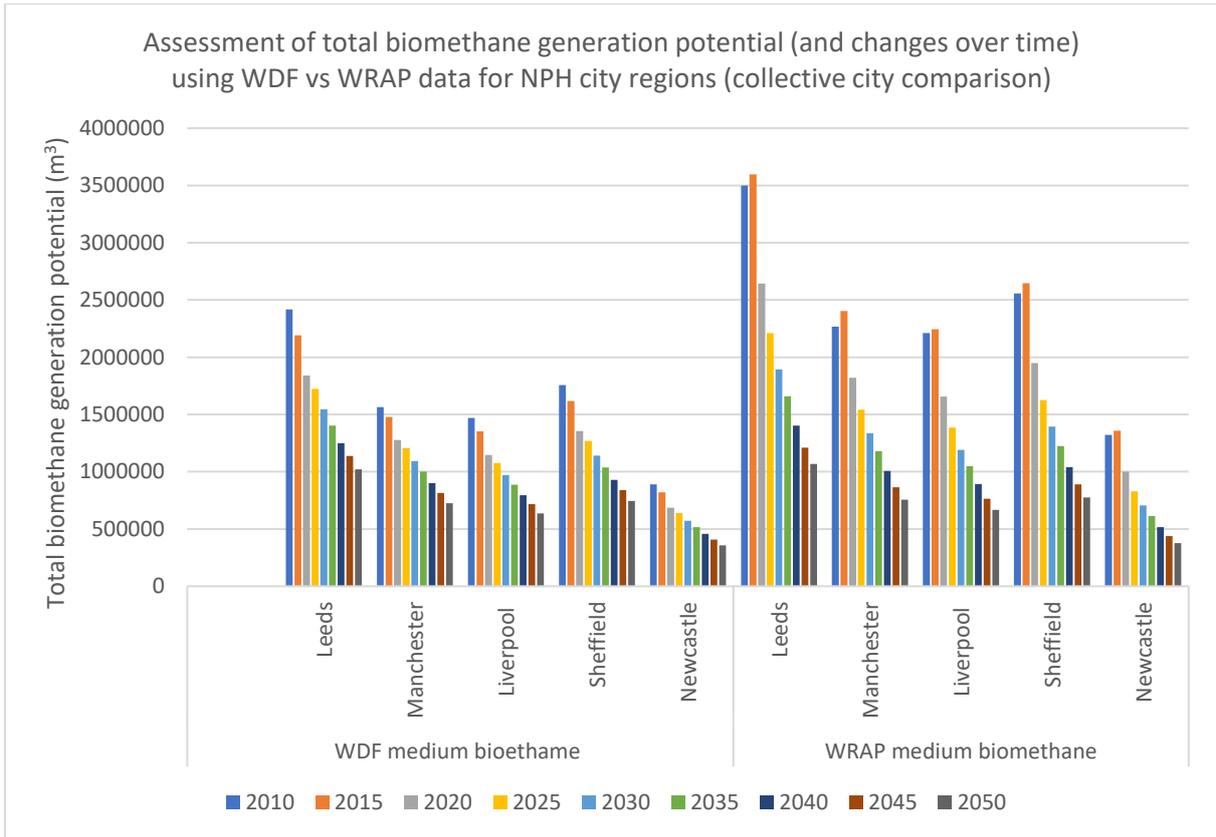


Figure 173. WRAP vs WDF data for medium scenario biomethane output (67.50m³) across all NPH city regions (comparison of collective cities for each category) (similar trends is shown for data on metropolitan county regions albeit at higher generation potential value).

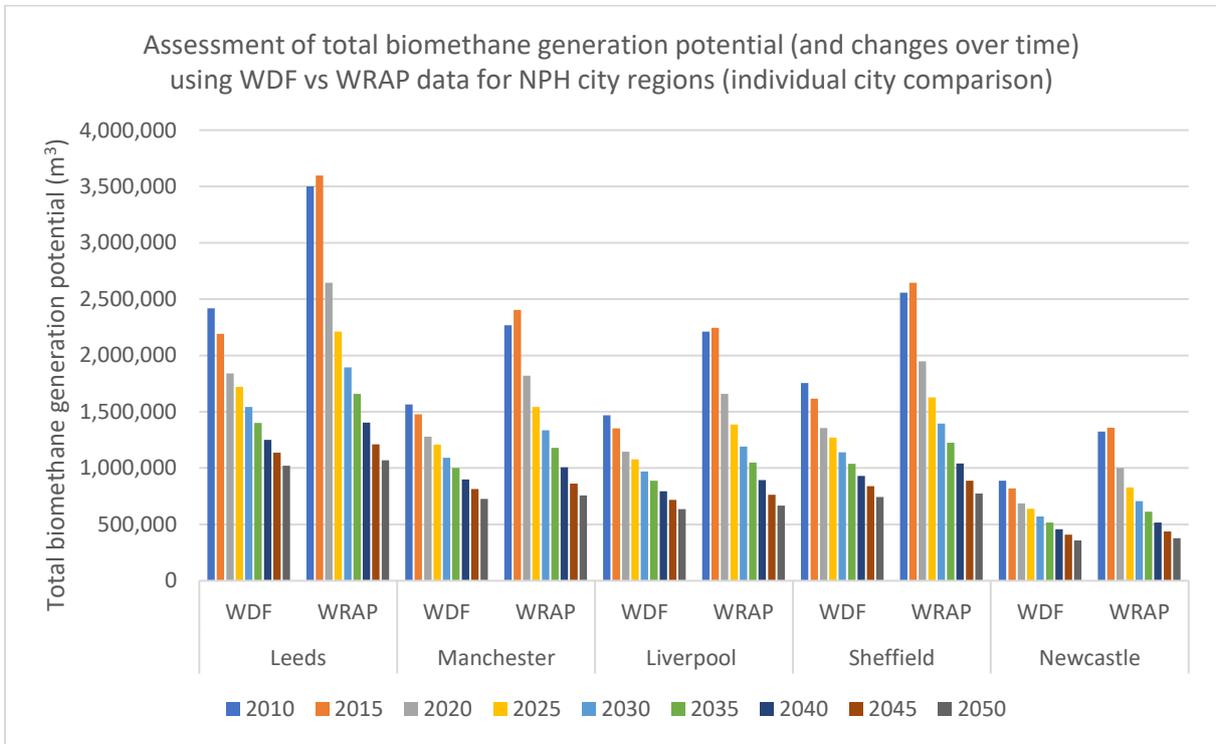


Figure 174. WRAP vs WDF data for medium scenario biomethane output (67.50m³) across all NPH city regions (comparison of individual cities for each category) (similar trends is shown for data on metropolitan county regions albeit at higher generation potential value).

Here it is important to re-iterate that the values post 2017 are project using Excel's inbuilt exponential regression trend curves. In consideration of this, alternative comparisons using non-projected data between WRAP and WDF data using the same measures above would yield, for the greatest NPH city BMP potential between 2007 and 2017 to be 5,700,000 to 4,500,000m³ for Leeds WRAP data, and 3,220,000 to 2,500,000m³ for Leeds WDF data. For the same comparison of NPH metropolitan county data, this would include 20,200,000m³ to 15,900,000m³ for Greater Manchester WRAP data, and 11,400,000 to 9,900,000m³ for Greater Manchester WDF data.

To conclude, the overall BMP ranging from highest to lowest in general (when standardizing for year and FW to biomethane conversion yield) would be Leeds > Sheffield > Manchester > Liverpool > Newcastle for NPH city region and Great Manchester > West Yorkshire > South Yorkshire = Merseyside > Tyne and Wear for NPH metropolitan county region.

5.3.4.2n Variable total biomethane generation potential findings – Limitations and proposal for future research

Limitations to the above findings on time-adjusted total methane generation potential for all NPH city and metropolitan county regions mainly arises from the limited dataset used, which although is deemed sufficient for reasonable forward projection estimation to 2050 for purpose of this research, could be further optimized to help establish greater dynamic variations in changes to total biomethane generation projection during all time periods assessed.

By adopting the same or improved approach and using limited datasets found in this research (attributed to time and resource limitations outlined in Methodology 3 – see Chapter 4.4), future studies should establish a more comprehensive comparative assessment of more datasets when they are found to be or are made available.

These results in comparison to fixed and time-adjusted total biomethane generation values indicates anticipated lower future outputs in the real world scenario of there being consistent decay in FW collection (and FW to biomethane conversion rate) output attributed to the abovementioned reasons.

This is mainly attributed to year-on-year declines in household FW collection as specified by both datasets due potentially to a combination of factors mentioned in relevant earlier research sections. Namely, they include but are limited to reduction in (i) household FW production and collection due to combination of economic and behavioural changes, (ii) capture rate by the waste contractors across all households due to reduced LA funding or (iii) household participation (whilst total data still assumes full participation of all households). Although the impact of these specific factors on the total decline FW collection overtime is beyond the scope of the present research, they would constitute an important area of further research with strong implications on policy and investment recommendations.

The research should further extend to policy recommendations that would help local authorities within and beyond NPH city and metropolitan county regions where FW collection and recycling is feasible and beneficial (i.e. due to high FW production or landfill) to promote deployment of FWtTBC pathway. Here critically, the nuance would be in how the design of

such policy could affect the relative rate of anticipated decline in FW collection over time until the 2050 period, i.e. whether at the rate set by WRAP or WDF data, or combination thereof (a variation in the rate of decline) across specific regions based on their local conditions.

A summary of possible relevant general policies as alluded to in the fixed FW collection section above is outlined in Table 135 below, and is conditional based on the local regions. Again, the aim of such policies should be to maximise FW capture rate whilst simultaneously minimize their production and landfill for meeting UK government’s elimination of FW to landfill by 2030.

Table 135. General policy recommendations based on WRAP and WDF FW data projections between 2017 and 2050

	Policy recommendations	Policy focus
1	Offer conditional loans and investments and non-financial support schemes to help FW trials and studies by local authorities and universities across NPH and other prospective regions to reassess annual projected local FW output available for collection up to 2050 using WRAP and WDF data as reference.	Gather more data and insight on local FW available for collection from past to present and future, using WDF and WRAP data trend as reference
2	Offer conditional loans and investments to LA for implementation of FW collection trials and schemes based on the results attained by the first policy support (i.e. insights on estimated FW available for collection in each relevant region), and apply further conditional support (financial or other) to meet key objectives of reduction in household FW production and increase in FW capture rate.	Help enable local authorities to operate more efficiently and alignment of specific objectives to support the government’s own waste reduction pledges
3	Extend policy 1 and 2 for collection and recycling of commercial and industrial FW alongside household FW where there are sufficient availability of supply and recycling infrastructure, based on findings of greater BMP to arise from mixed household and commercial or industrial FW in section 5.3.2 (Finding 1 - Technical FW to biogas and biomethane conversion yield method overview)	Help enable FW collection to become financially more self-sufficient by promoting collection strategies that involve potentially more players and to include FW varieties that will likely yield greater potential BMP and revenues (i.e. from Biomethane sales).

Another key factor affecting the real-world deployment of the FWtTBC pathway would be infrastructure availability of AD plants across relevant NPH city and metropolitan county regions that would ultimately determine capacity to recycle and convert collected FW to useable biogas or biomethane. This is assessed in the next section (5.3.5 - Finding 4) alongside corresponding key financial metrics, i.e. breakdown of revenues, costs and returns on financial investments, that would enable real-world FWtTBC pathway deployment.

5.3.5 Finding 4 – Total local AD capacity for each NPH region on FW collection and corresponding biomethane generation potential

This section outlines total realistic biomethane generation potential in context of infrastructure availability within NPH city and metropolitan county regions of Leeds/West Yorkshire and Manchester/Greater Manchester for each fixed and variable FW collection scenarios which correlates with specific biomethane generation scenarios.

An analysis is carried out by combining NFCCC’s AD plant data with total FW collection and biomethane generation potential data (see finding 2 and 3 results) to estimate (i) total capacity for FW intake (tonnes/year) with corresponding total number of individual (person) that can be accommodated (based on specified FW production data), and (ii) FW production from % population which total AD waste capacity can accommodate (hereafter known as ‘% population saturation’) for each of the 2 selected NPH region.

Results can then be used to inform degree of need for establishing new AD plant of desired capacity at suitable locations to further enable deployment of FWtTBC pathway within these NPH region, i.e. in NPH regions where FW collection scheme deployment is underway but are found to possess insufficient AD capacity relative to total household FW collection potential.

5.3.5.1 NPH Leeds city and West Yorkshire Metropolitan county region findings

Leeds has 4 eligible large sized AD plants that are situated within a moderate distance to the city centre, scattered to the east, north and south of the city. An analysis of nearby populated regions has revealed a number of densely populated towns that are within close proximity to Leeds, as outlined in Table 136 below.

Table 136. Summary of general AD plant data for Leeds NPH region including location, developer, general distance from relevant NPH city centre and nearby towns and cities with estimated population within close proximity

NPH region	Plant name	Developer	County	Postcode	Distance (miles) from city centre (miles)*	Example towns OR cities with significant population**	Estimated population (2021 data)
Leeds	South Kirby Business Park	Shanks Waste Management	West Yorkshire	WF9 4DG	22.5	Wakefield, Pontefract, Castleford, Knottingley, Featherstone, Normanton	336,000
Leeds	Maltings Organic Treatment Facility	AB Agri	North Yorkshire	LS25 5DN	17.3	Leeds	793,000
Leeds	Greencore Grocery	Greencore Grocery Limited	North Yorkshire	YO8 5BJ	27.5	York, Selby, Howden, Hull	561,000
Leeds	Allerton Waste Recovery Park	AmeyCespa	North Yorkshire	HG5 0SD	28.6	Harrogate, Ripon, Wetherby, Easingworld	190,000
						Total	1,880,000

*Driving distance according to google maps, using shortest distance (not the fastest route), **Discretionary, within close to reasonable distance that is equal to or less than distance from Leeds city centre

The number of individuals in which all AD plants combined can collectively accommodate depends largely on the anticipated FW output per individual within each household. When accounting for FW only AD plant capacity (60% of total AD waste capacity), these ranges from 1.2 million individuals in the case with extreme high per capita FW output of 100 kg/person/year, to 6.1 individuals in the case with extreme high per capita FW output of 20

kg/person/year. However, when all (FW and non-FW) AD waste capacity is used, the combined population that can be accommodated ranges from 1.97 million to 9.83 million people case with extreme high and low per capita FW output of 100 and 20 kg/person/year, respectively. These results are collectively outlined in the last row of the last 3 columns of Table 137, Table 138 and Table 139 (under total population covered).

Here Table 137 demonstrates that under the low per capita FW output scenario of 20 kg/person/year, 3 out of the 4 AD plants (SKBP, MOTF and AWRP) is capable of accommodating for all annual household FW produced from the entire population of Leeds, by using their FW only capacity. This however is reduced to only 2 AD plants (SKBP and MOTF, for either FW only or combined total capacity) when considering the medium per capita FW output scenario of 40 kg/person/year (see Table 138).

Table 137. Waste capacity data for individual AD plants for Leeds NPH region – for low FW collection scenario, using medium food waste collection scenario (20kg/person/year)

NPH region	AD plant name	Waste type description	Total feedstock	FW feedstock	Other feedstock	Total population covered (FW capacity used only)	Total population covered (Non-FW capacity used only)	Total population covered (All capacity used only)
Leeds	South Kirby Business Park (SKBP)	Organic fraction of MSW	65,000	39,000	26,000	1,950,000	1,300,000	3,250,000
	Maltings Organic Treatment Facility (MOTF)	Food waste & green waste	82,500	50,000	32,500	2,500,000	1,625,000	4,124,500
	Greencore Grocery (GG)	Food waste	9,125	9125	0	456,250	0	456,250
	Allerton Waste Recovery Park (AWRP)	Organic fraction of MSW	40,000	24,000	16,000	1,200,000	800,000	2,000,000
	Total		196,625	122,125	74,500	6,106,250	3,725,000	9,831,250

Table 138. Waste capacity data for individual AD plants for Leeds NPH region – for low FW collection scenario, using medium food waste collection scenario (40kg/person/year)

NPH region	AD plant name	Waste type description	Total feedstock	FW feedstock	Other feedstock	Total population covered (FW capacity used only)	Total population covered (Non-FW capacity used only)	Total population covered (All capacity used only)
Leeds	South Kirby Business Park (SKBP)	Organic fraction of MSW	65,000	39,000	26,000	975,000	650,000	1,625,000
	Maltings Organic Treatment Facility (MOTF)	Food waste & green waste	82,500	50,000	32,500	1,250,000	812,500	2,062,500
	Greencore Grocery (GG)	Food waste	9,125	9125	0	228,125	0	228,125
	Allerton Waste Recovery Park (AWRP)	Organic fraction of MSW	40,000	24,000	16,000	600,000	400,000	1,000,000
	Total		196,625	122,125	74,500	3,053,125	1,862,500	4,915,625

When factor in relevant 2021 population, only Maltings Organic Treatment Facility (MOTF) is shown to be able to accommodate all annual household FW produced by all population of Leeds (793,000) should all of their waste (FW and non-FW) capacity is used under the highest (100 kg/person/year) FW output per capita scenario (see Table 139). Under this scenario, all remaining AD plants can only accommodate for 650,000 (SKBP), 91,250 (GG) and 400,000 (AWRP), which falls short of total population of Leeds. Similarly, when accounting for use of

FW only capacity, MOTF would only accommodate for total FW produced by the estimated population of 500,000 which falls significant shorter of the Leeds population of 793,000 (Table 139).

Table 139. Waste capacity data for individual AD plants for Leeds NPH region – for low FW collection scenario, using medium food waste collection scenario (100kg/person/year)

NPH region	AD plant name	Waste type description	Total feedstock	FW feedstock	Other feedstock	Total population covered (FW capacity used only)	Total population covered (Non-FW capacity used only)	Total population covered (All capacity used only)
Leeds	South Kirby Business Park (SKBP)	Organic fraction of MSW	65,000	39,000	26,000	390,000	260,000	650,000
	Maltings Organic Treatment Facility (MOTF)	Food waste & green waste	82,500	50,000	32,500	500,000	325,000	825,000
	Greencore Grocery (GG)	Food waste	9,125	9125	0	91,250	0	91,250
	Allerton Waste Recovery Park (AWRP)	Organic fraction of MSW	40,000	24,000	16,000	240,000	160,000	400,000
	Total		196,625	122,125	74,500	1,221,250	745,000	1,966,250

Also it is important to note that the AD operator with greatest capacity, MOTF can accommodate approximately 9 times more total waste and 5 times more FW than the smallest AD operator (GG) and is located geographically closer to Leeds, with the latter positioned close to York, Selby, Howden and Hull (Table 136). A summary of all AD plants with respect to the number of household individuals which they can accommodate based on per capita FW output rates of 20, 40 and 100 kg/pp/year is shown in Table 140, Figure 175 and Figure 176 below.

Table 140. AD plant total number of people (or population) that can be accommodated based on waste capacity used and scenarios on low, medium and high FW collection per person

Number of Individuals that can be accommodated by respective AD plants based on FW collection scenario and specific waste capacity utilized (no unit)							
			South Kirby Business Park	Maltings Organic Treatment Facility	Greencore Grocery	Allerton Waste Recovery Park	Total from all AD plants
FW collection scenario	Low (20kg/pp/year)	Food waste	1,950,000	2,500,000	456,250	1,200,000	6,106,250
		Other waste	1,300,000	1,625,000	0	800,000	3,725,000
		Total feedstock	3,250,000	4,125,000	456,250	2,000,000	9,831,250
	Medium (40kg/pp/year)	Food waste	975,000	1,250,000	228,125	600,000	3,053,125
		Other waste	650,000	812,500	0	400,000	1,862,500
		Total feedstock	1,625,000	2,062,500	228,125	1,000,000	4,915,625
	High (100kg/pp/year)	Food waste	390,000	500,000	91,250	240,000	1,221,250
		Other waste	260,000	325,000	0	160,000	745,000
		Total feedstock	650,000	825,000	91,250	400,000	1,966,250

*Lowest and highest number of individuals that can be accommodated by the combined plants is outlined in red and green fonts respectively.

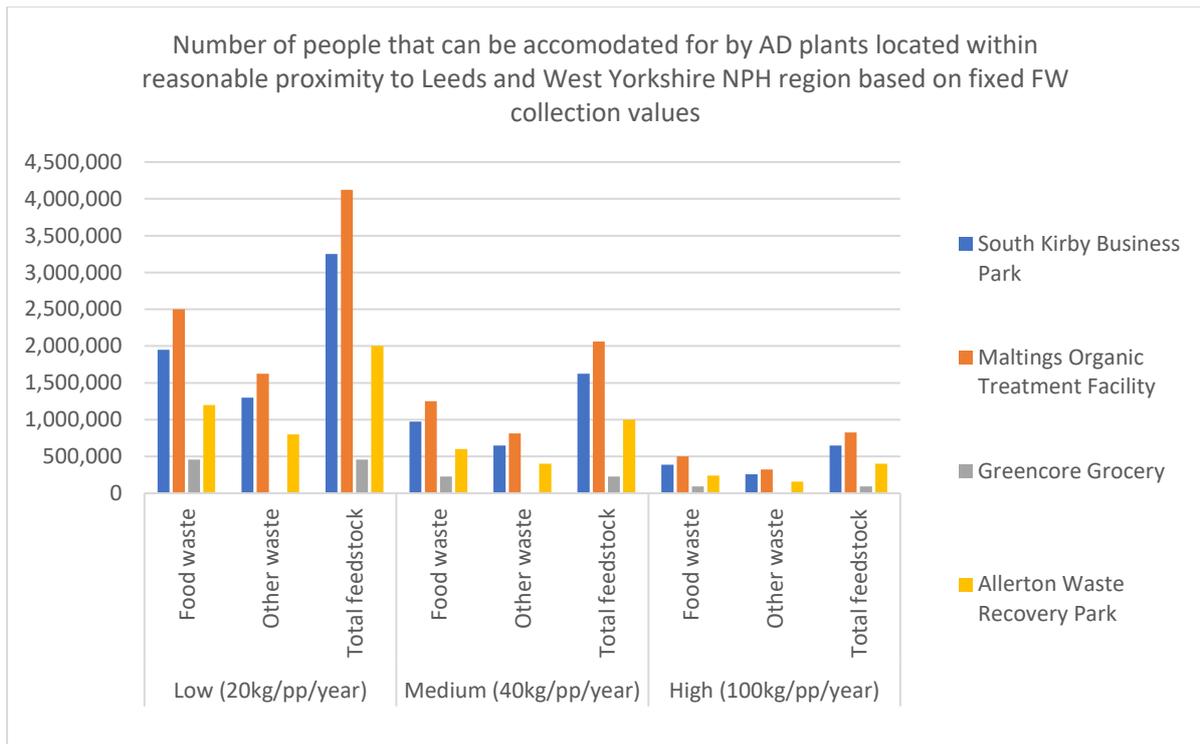


Figure 175. Total number of people (or population) that can be accommodated by individual AD plants located within reasonable proximity to Leeds and West Yorkshire NPH region based on their relative waste capacity and fixed FW collection scenario of low, medium and high (20, 40, 100 kg/pp/year) FW collection per person.

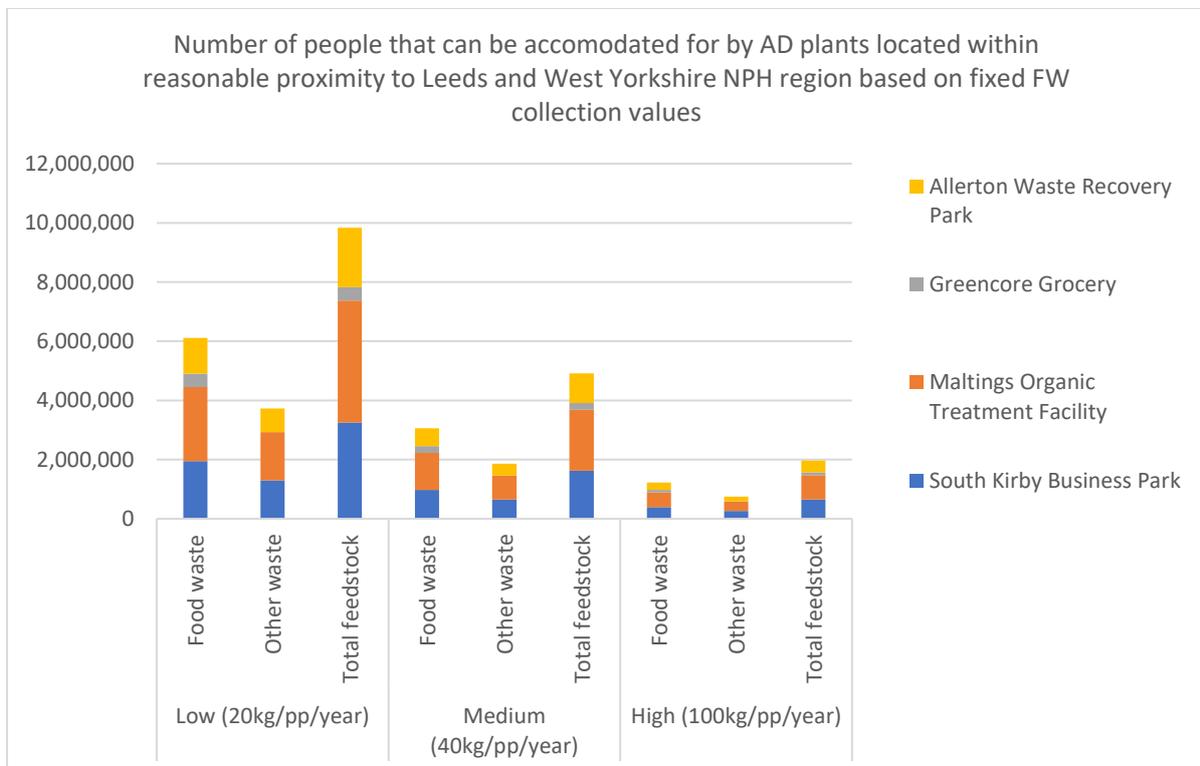


Figure 176. Total number of people (or population) that can be accommodated by all AD plants combined (aggregate total) located within reasonable proximity to Leeds and West Yorkshire NPH region based on their relative waste capacity and fixed FW collection scenario of low, medium and high (20, 40, 100 kg/pp/year) FW collection per person

Interestingly, the total combined capacity from all 4 AD plants (SKBP, MOTF, GG and AWRP) would accommodate for total populations that reside within all surrounding town and city regions. As outlined in Table 136, this includes in addition to Leeds city, York, Selby, Howden, Hull, Wakefield, Pontefract, Castleford, Knottingley, Featherstone, Normanton, Harrogate, Ripon, Wetherby and Easingworld which holds a combined population of 1.88 million. In this context however, it is critical to note that real world AD operators will likely involve a mixture of different waste source input, which would inevitably translate to apportioning a specific capacity of each AD towards digestion of other FW categories (i.e. commercial or industrial), as rarely would one type of FW, such as household FW, constitute the entire and sole feedstock of any single AD plant. There will also be the likelihood of such AD accommodating populations from additional regions should sufficient capacity for FW intake remain available and that costs of FW logistics and transport is not deemed to be excessive.

The next section on population saturation analysis, where analysis of how much additional population measured as a % of the NPH Leeds population, is consequently used to determine the magnitude of additional population that can be accommodated using remaining FW capacity left for each corresponding AD plant.

5.3.5.1a Fixed food waste collection data scenario – AD Food Waste ‘% population saturation’ analysis

The population saturation analysis (PSA) represents an analytical approach used to determine the % of population within a given region whose total annual household FW output can be accommodated by the given capacity of specific AD plants in question, in context of low, medium or high (20, 40 or 100 kg/pp/year) per capita household FW production rate. Here a population saturation value (PSV) of 100% refers to the annual FW produced by a given population of a given region can be accommodated by the precise full capacity of the select AD plants. Likewise, a PSV of 1000% refers to AD plant capacity that can accommodate for 10 times the FW produced by a given population of a given region.

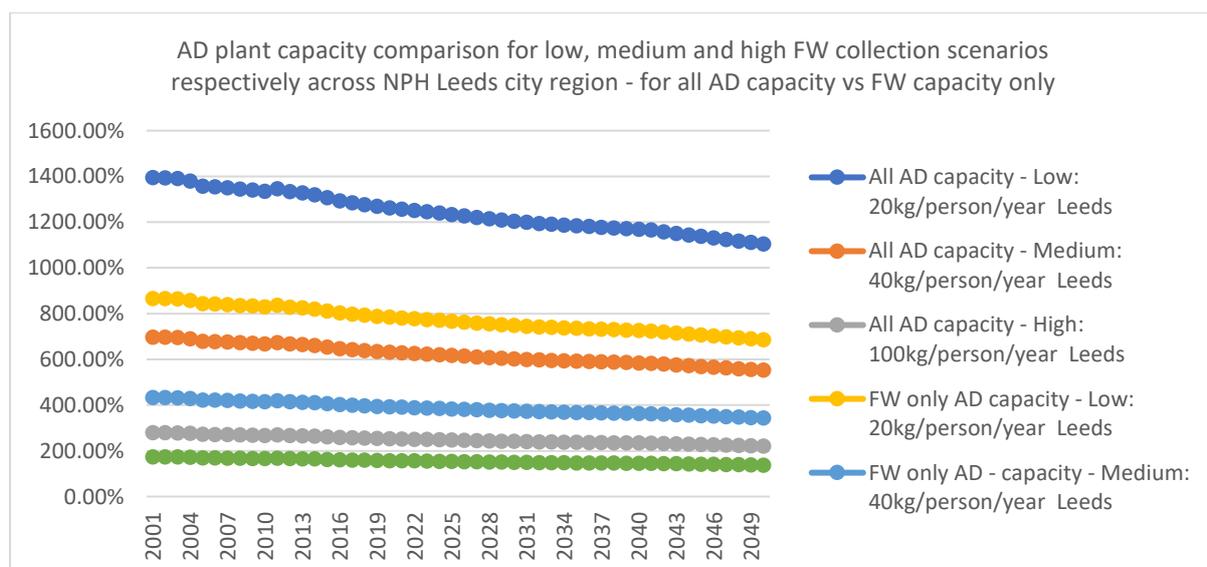


Figure 177. Percentage population 'saturation' for Leeds NPH Leeds city region with regard to FW collected vs. AD plant waste capacity for 2010-2050 using fixed FW collection scenario value of 20, 40 and 100 kg/person/year (for data used, please see Appendix table 47)

The above results for NPH Leeds city region suggest a PSA of over 100% across all scenarios suggesting combined AD plant capacity is more than sufficient to accommodate for FW production from the entire NPH Leeds based population. Here the PSV range is of 137.12% to 1393.84% for the lowest (2010, 20kg/person/year, FW + Other waste AD capacity) and highest (2050, 100 kg/person/year, FW waste only AD capacity) scenarios (see Figure 177), respectively.

This indicates that local AD infrastructure is extremely future proof in accommodating FW from all populations in Leeds city region (up to at least 2050 under all scenarios) for biogas or biomethane conversion. Here however additionally assumes that all AD capacity is used for household FW input, and with the same AD operator's non-FW capacity used for the intake of other wastes for co-digestion.

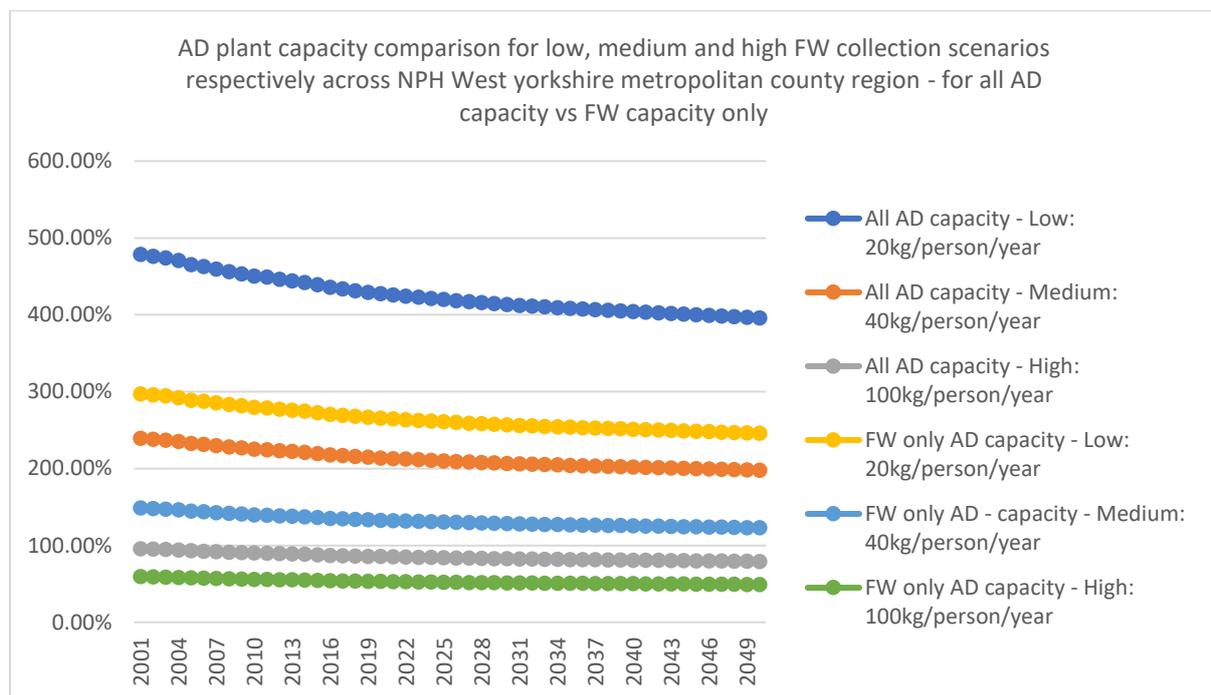


Figure 178. Percentage population 'saturation' for Leeds NPH West Yorkshire metropolitan county region with regard to FW collected vs. AD plant waste capacity for 2010-2050 using fixed FW collection scenario value of 20, 40 and 100 kg/person/year (for data used, please see Appendix table 48)

In contrast, the results for NPH Leeds metropolitan county region suggest a % population saturation of over 100% for 4 out of 6 scenarios, with the 2 remaining scenarios (both related to FW collection rate of 100kg/person/year) hovering at around 80-96% and 50-60% respectively. This suggesting that there is sufficient scope for combined AD plant capacity to accommodate for FW production from all populations of NPH West Yorkshire County region, which pertains to all scenarios in relation to collection rate of 20 and 40 kg/person/year (Figure 178).

This indicates that, under assumptions of all AD capacity is used for household FW input, local AD infrastructure is future-proof towards accommodating FW from all populations in both Leeds city region and West Yorkshire metropolitan county region (up to at least 2050 under all scenarios) with for biomethane conversion should the FW collection rate remain to be at either 20 or 40 kg/person/year. Under high fixed collection rate of 100 kg/person/kg however, the combined AD plant waste capacity will be able to accommodate for all household FW produced

across all NPH city regions but not metropolitan county regions owing to the much larger resulting FW output of the latter.

If the aim is to enable 100% household FW recycling, then these findings do outline the need for any policy or strategy to address the extreme eventuality of lack of AD capacity for intaking all household FW produced if such FW per capita output value becomes sufficiently high. Although under real world scenarios, it can be safely assumed that the total combined capacity should be able to accommodate for both NPH city and metropolitan county regions given several indications of typical FW output per person to rarely consistently exceed 40 kg/person/year (i.e. from WRAP and WDF datasets).

5.3.5.1b Time-adjusted variable food waste collection data scenario – AD Food Waste ‘% population saturation’ analysis

Applying the same method of analysis (as used above for fixed FW collection data) using variable time-adjusted variable WDF and WRAP FW collection data to NPH city populations demonstrates a population saturation range of 200% to 1300% between the lowest and highest data points, as can be seen by assessing the lowest (2010, WRAP data, AD FW capacity only) and highest data points (2050, WDF data, AD all waste capacity) in Figure 179.

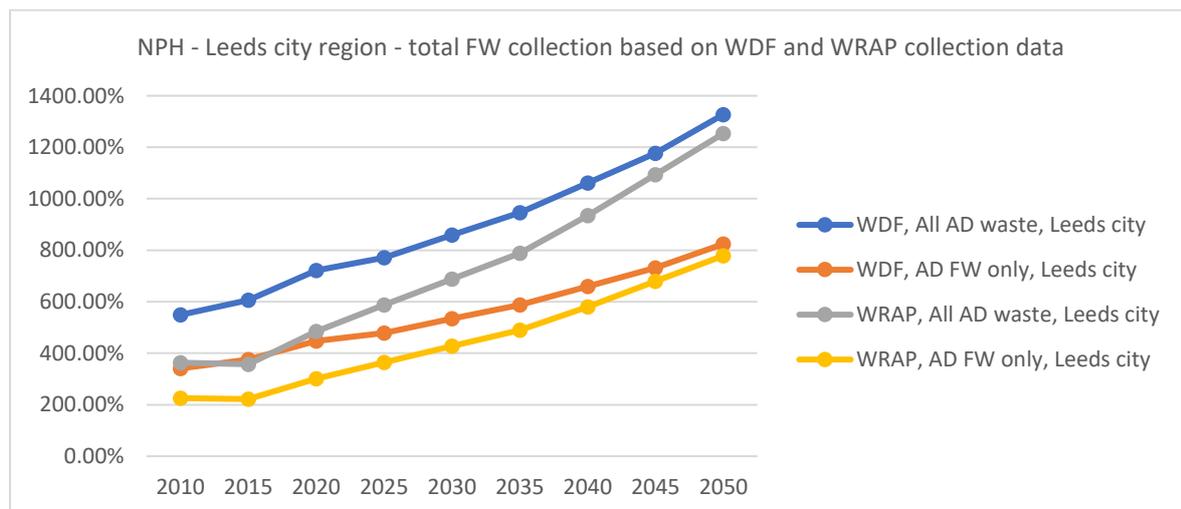


Figure 179. Percentage population ‘saturation’ for Leeds NPH Leeds city region with regard to FW collected vs. AD plant waste capacity for 2010-2050 using variable WDF and WRAP scenarios (for data used, please see Appendix table 49)

Interestingly, the same method of application using NPH metropolitan county population data (in place of NPH Leeds city population data) demonstrates a population saturation range of 60% to 475% between the lowest and highest data points, and with 3 out of 4 scenarios achieving at least full population saturation (see Figure 180).

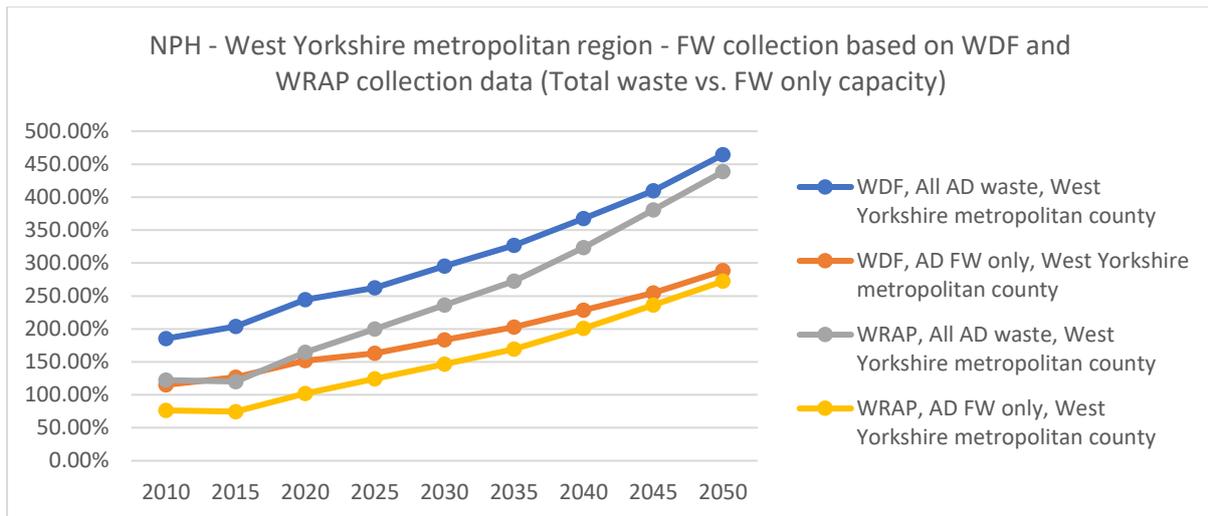


Figure 180. Percentage population 'saturation' for Leeds NPH Leeds city region with regard to FW collected vs. AD plant waste capacity for 2010-2050 using variable WDF and WRAP scenarios (for data used, please see Appendix table 50)

Both results indicates that total AD capacity across Leeds and West Yorkshire region is not only extremely future-proof against changes to household FW collection, but rather may face significant lack of feedstock FW supply issues arising from projected sharp future reductions in household FW supply availability (as reflected by data in Figure 179 and Figure 180).

Given the above findings, the upside potential of lack of household FW (HHFW) feedstock relative to total AD capacity appears to be much more likely, which demands specific government policies to promote either continued supply of sufficient HHFW or bridging of suitable alternative FW feedstock to replace diminishing quantities of HHFW to ensure participating AD operators will have sufficient business confidence in partaking in the FWtBC pathway deployment. To this end, such policies, which is summarized in Table 141, should also possess sufficient flexibility to accommodate for the unlikely but possible reverse eventuality of FW oversupply (i.e. with high HHFW production per capita scenario of 100 kg/person/year) and lack of AD infrastructure capacity. Here resulting biomethane production produced from success of such policies will constitute a key energy and revenue output, which is estimated and quantified in the next section (see Section 5.3.5.1c).

Table 141. Summary of policies designed to accommodate for future anticipated eventuality of mainly lack of HHFW feedstock supply relative to AD capacity, but also the less likely reverse scenario of HHFW oversupply. Here all AD operators is assumed to be the 4 operators mentioned covering Leeds and West Yorkshire

	General policy recommendation	Specific policy objectives
1	Implement financial incentive in form of pledges to all AD operators that would appropriately mitigate their future risk of reduced HHFW intake should they undertake long term commitment (i.e dedicated contract) for recycling HHFW	Mitigate long term risk in HHFW intake by AD plants, and to promote HHFW intake in general, likely to be more important for larger operators
2	Develop financial incentives and non-financial supporting networks to enable different AD operators to work together in case of HHFW overcapacity, e.g. by redirecting FW to closest AD with sufficient capacity leftover	Mitigate unlikely risk of HHFW oversupply relative to capacity of any specific AD plant, likely to be more important for smaller operators
3	To support 1 and 2, implement more bridging schemes between AD operators and LA to ensure good collaboration towards strategizing the HHFW collection logistics process	Ensure more efficient logistics of FW collection from source (households) to destination (AD plant)

5.3.5.1c Biomethane generation potential in context of total AD plant waste intake capacity

This section summaries findings with regard to biomethane generation potential in context of total waste capacity of AD plants based across NPH Leeds city and West Yorkshire metropolitan county region.

Assuming for full utilization of AD waste capacity for household FW collection after 2020, all scenarios are shown to have full (100%) population saturation capacity and would therefore enable full biomethane generation potential outlined in relevant sections in finding 3 (see finding 3.1 and 3.2), with the only limiting factor being total household FW collected for input.

Here the only exception includes the WRAP data scenario for 2010 to 2015 where AD capacity could only accommodate for around 75% of the total West Yorkshire metropolitan county region owing to high FW output per person for collection and high total regional population.

Although beyond the scope of this research, it is worth noting that the biomethane generation potential during these periods if not limited by total AD FW intake capacity constraints should be much greater given that the total estimated household FW available for collection is much greater than the total AD intake capacity (according to WDF and WRAP data) as outlined in Chapter 5 above (see Chapter 5.2.2, 5.2.3 and 5.2.4).

Table 142Table 146 below shows relevant data for total biomethane potential for each AD plant under low, medium and high household FW to Biomethane conversion (BMC) levels (of 45m³/t, 67.50m³/t and 90m³/t FW, respectively) for all Leeds and Yorkshire based AD plants. These are accompanied by separate graphs for each BMC level for illustrating general trends that maybe notable for establishing suitable government policy recommendations for supporting FWtTBC pathway deployment.

Table 142. Data summary for total FW biomethane potential assuming for 100% AD plant capacity operation

		AD plant				
		South Kirby Business Park (SKBP)	Maltings Organic Treatment Facility (MOTF)	Greencore Grocery (GG)	Allerton Waste Recovery Park (AWRP)	Total
Low FW to Biomethane conversion rate (45m³/t)	Total feedstock	2,925,000	3,712,500	410,625	1,800,000	8,848,125
	FW feedstock	1,755,000	2,250,000	410,625	1,080,000	5,495,625
	Other feedstock	1,170,000	1,462,500	0	720,000	3,352,500
Medium FW to Biomethane conversion rate (67.50m³/t)	Total feedstock	4,387,500	5,568,750	615,938	2,700,000	13,272,188
	FW feedstock	2,632,500	3,375,000	615,938	1,620,000	8,243,438
	Other feedstock	1,755,000	2,193,750	0	1,080,000	5,028,750
High FW to Biomethane conversion rate (90m³/t)	Total feedstock	5,850,000	7,425,000	821,250	3,600,000	17,696,250
	FW feedstock	3,510,000	4,500,000	821,250	2,160,000	10,991,250
	Other feedstock	2,340,000	2,925,000	0	1,440,000	6,705,000

For the low FW to biomethane methane conversion (BMC) scenario of 45m³/t FW, the highest BMP is found to be 3,712,500m³ from MOTF for digestion of FW and other (non-FW) feedstock, and the lowest BMP is found to be 410,625m³ arising from GG for digestion of FW only. When accounting for FW only, the lowest BMP remains unchanged with the highest BMP being reduced to 2,250,000m³ for MOTF. Likewise, BMP arising from highest and lowest other (non-FW) feedstock is found to be from 1,462,000m³ from MOTF and 720,000m³ from AWRP respectively, which is still significant relative to BMP derived from FW. Here the interesting observation is the approximate mixing ratio of FW to non-FW to be approximately 3 to 1 across 3 out of 4 biomethane AD plants (SKBP, MOTF and AWRP) (see Figure 181).

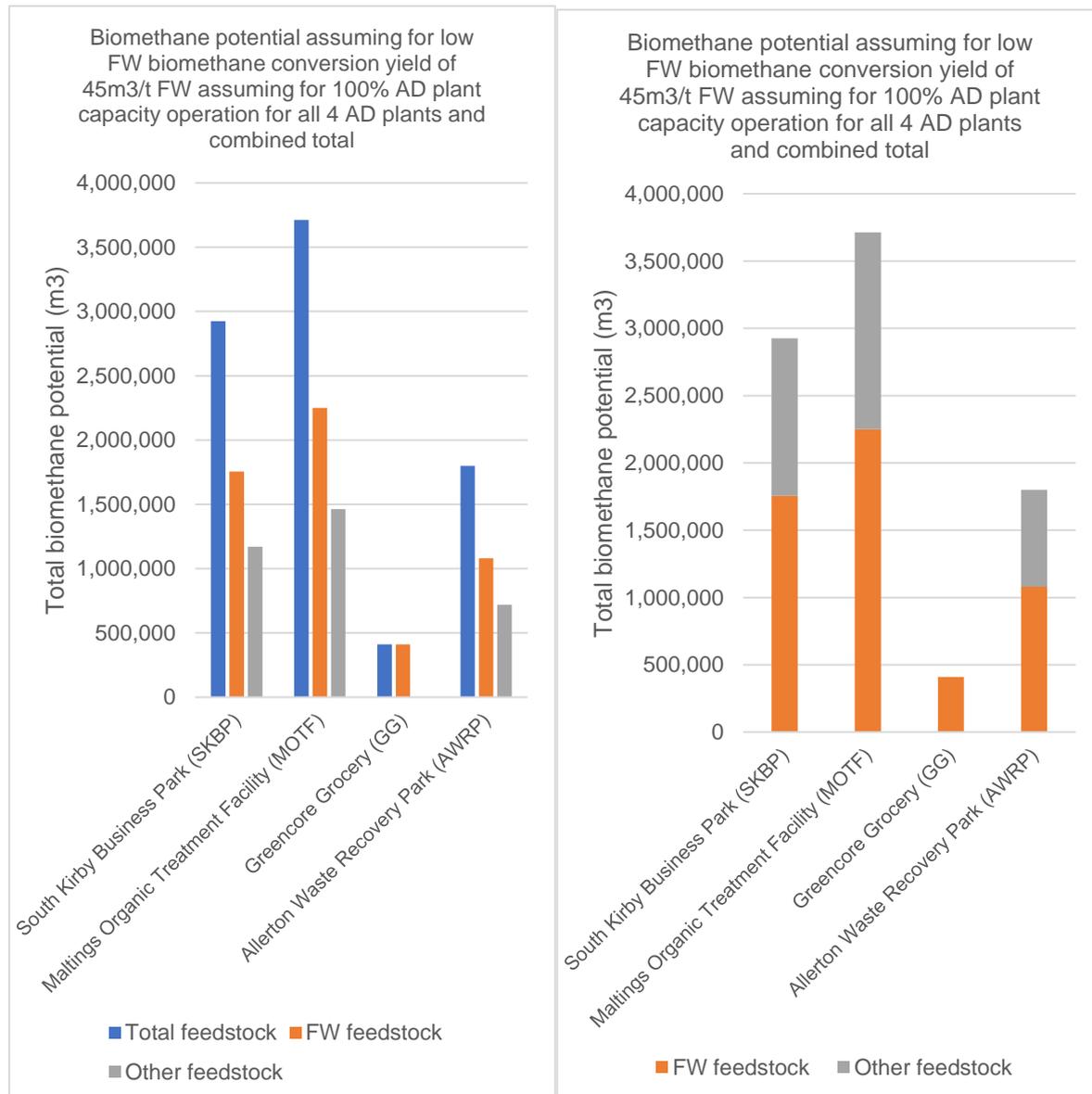


Figure 181. Biomethane production potential for all Leeds and West Yorkshire based AD plants based on waste feedstock - using Low FW to biomethane yield of 45m³/t (with all AD plant values shown individually) (for data, see Appendix table 51)

For the medium FW to biomethane methane conversion (BMC) scenario of 67.50m³/t FW, the highest BMP is found to be 5,568,750m³ from MOTF AD plant for digestion of FW and non-FW feedstock, and the lowest BMP is found to be 615,938m³ arising from GG AD plant for digestion of FW only. When accounting for FW only, the lowest BMP remains unchanged with the highest BMP being reduced to 3,375,000m³ for MOTF AD plant. Likewise, BMP arising from highest and lowest other (non-FW) feedstock is found to be from 2,193,000m³ from MOTF and 1,080,000m³ from AWRP respectively, which is still significant relative to BMP derived from FW. Similar to low and high BMC scenario, it is worth noting the observation of approximate mixing ratio of FW to non-FW to be approximately 3 to 1 across 3 out of 4 biomethane AD plants (SKBP, MOTF and AWRP) (see Figure 182).

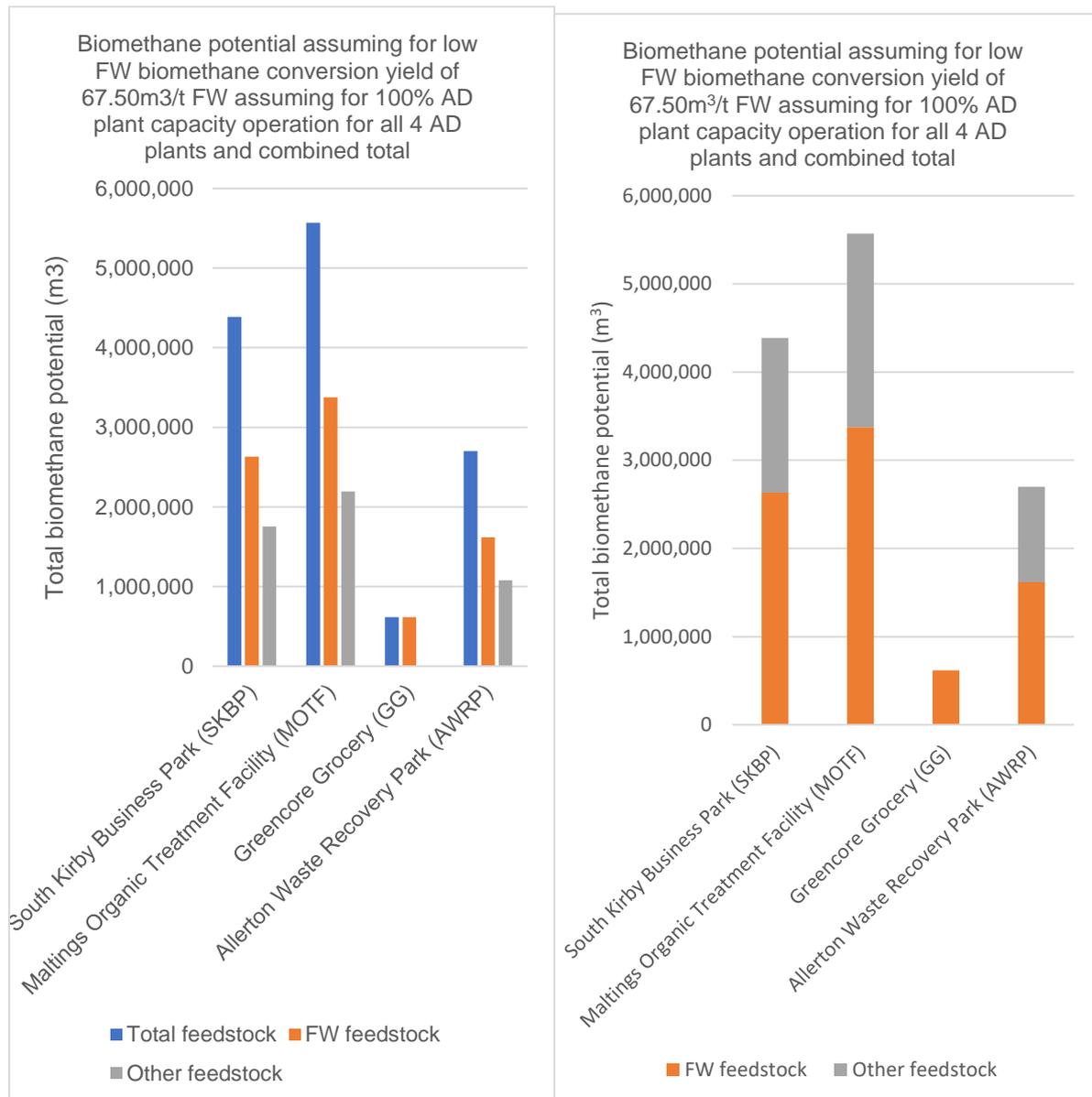


Figure 182. Biomethane production potential for all Leeds and West Yorkshire based AD plants based on waste feedstock - using Medium FW to biomethane yield of 67.50m³/t (with all AD plant values shown individually) (for data, see- Appendix table 52)

For the high FW to biomethane methane conversion (BMC) scenario of 90m³/t FW, the highest BMP is found to be 7,425,000m³ from MOTF AD plant for digestion of FW and non-FW feedstock, and the lowest BMP is found to be 821,250m³ arising from GG AD plant for digestion of FW only. When accounting for FW only, the lowest BMP remains unchanged with the highest BMP being reduced to 4,500,000m³ for MOTF AD plant. Likewise, BMP arising from highest and lowest other (non-FW) feedstock is found to be from 2,925,000m³ from MOTF and 1,440,000m³ from AWRP respectively, which is still significant relative to BMP derived from FW. Similar to low and medium BMC scenario, it is worth noting the observation of approximate mixing ratio of FW to non-FW to be approximately 3 to 1 across 3 out of 4 biomethane AD plants (SKBP, MOTF and AWRP) (see **Error! Reference source not found.**).

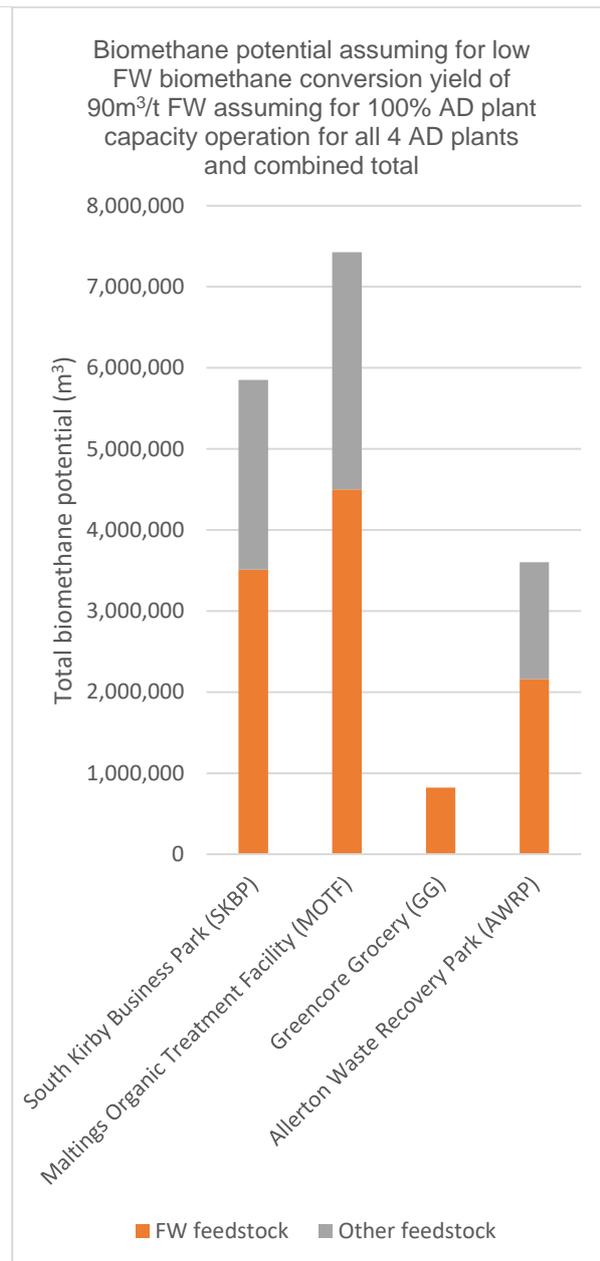


Figure 183. Biomethane production potential for all Leeds and West Yorkshire based AD plants based on waste feedstock - using High FW to biomethane yield of 90m³/t (with all AD plant values shown individually) (for data, see Appendix table 52)

To summarize all 3 figures of low, medium and high BMC above, the trend is identical for all 3 (low, medium and high) BMC scenarios, with exception to the total BMP value for each scenario given that they are derived from the same AD plants with same FW and other (non-FW) waste production capacities. Also to conclude, the order of AD plant with the highest to lowest BMP potential for any BMC used, would be MOTF, SKBP, AWRP and GG. A like by like comparison shows that MOTF and SKBP to hold approximately twice the BMP (and total waste feedstock) capacity than AWRP, which extends further to 7 to 9 times BMP capacity compared to that of GG.

In consideration of determining suitable AD plant infrastructure for accommodating local household FW collection for biomethane production, MOTF and SKBP AD plant would evidently constitute the primary players owing to their large waste capacity and BMP potential. These would respectively cover major NPH city regions of Leeds (MOTF), and its surrounding regions of Wakefield, Pontefract, Castleford, Knottingley, Featherstone and Normanton (with a combined estimated 2021 population of 336,000) to the South East of Leeds. The role of AWRP is none the less important for feasible deployment of the FWtTBC pathway for the north and northeast of Leeds region, covering Harrogate, Ripon, Wetherby and Easingworld with a combined estimated 2021 population of 190,000. Here the weakest region of AD infrastructure availability for FWtTBC pathway deployment would be to the North and Northeast OF Leeds, i.e. York, Selby, Howden and Hull, which is within closest proximity to GG AD plant, where there exist a combined estimated 2021 population of approximately 561,000. It is not known however whether if there exist alternative infrastructure within the surrounding vicinity that could accommodate for alternative routes of FW recycling, i.e. more local AD plants or large commercial scale AD plants currently under construction that is not documented in the NCPPP database, local incineration plants that would give rise to a less sustainable method of FW disposal, i.e. via incineration of mixed wastes in areas with no dedicated FW collection schemes. Though it is beyond the scope of this research project. future relevant research should also take account of these real world variables and factors in consideration of competing disposal routes for collected household FW.

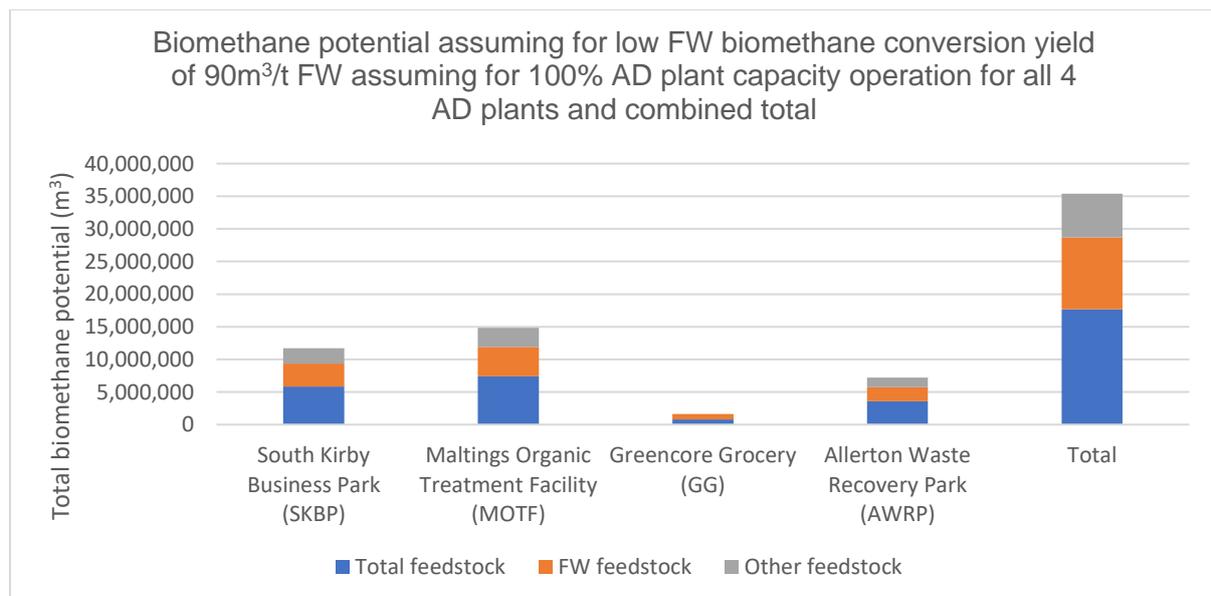


Figure 184. Biomethane production potential for all Leeds and West Yorkshire based AD plants based on waste feedstock - using High FW to biomethane yield of 90m³/t (with all AD plant values stacked) (for data, see Appendix table 52)

In considering all 4 AD plants (MOTF, SKBP, AWRP and GG), the total combined annual waste derived BMP is shown to be between 17,696,250m³, 26,544,376m³ and 35,392,500m³ respectively, which does demonstrate a significant quantity of waste derived energy potential.

In the pure context of FWtTBC pathway deployment, the necessity of looking into establishing a local network of alternative AD infrastructure surrounding areas to North and Northeast of Leeds covered by GG AD plant is evident. This is to help mainly mitigate the risk of waste capacity oversaturation should there be accelerated support and consequently, increased deployment and collection of household FW destined for AD digestion that constitute part of the FWtTBC pathway deployment. Other accompanying strategies would involve increased simultaneous investments into food bank trials especially in regions of experiencing poverty or declining social-economic welfare, to help contribute towards lowering total household FW output, with aim of these food banks trials to expand into other regions as means of an even more effective method of FW recycling.

In light of additional findings above, a series of additional policy recommendations accompanied by the intended outcome in support for effective FWtTBC pathway deployment across relevant regions in consideration of limitations to local AD plant infrastructure is outlined in Table 143 below.

Table 143. General policy recommendations on promoting FWtTBC pathway deployment by supporting more flexible and effective use of available AD plant infrastructure

Policy recommendation		Specific policy objectives
1	Offer funded initiatives to conduct research targeting especially the North to Northeast of Leeds on local FW production from household and other, i.e. commercial and industrial outlets. Done ideally in collaboration with local authority, residents, businesses and university to in regions with interest or commitment to implement or extend FW collection trials or schemes to gather further data and insight on deployment of these trials or schemes	Establish more data and insight on critical regions where there maybe plans to implement or upscale FW collection trials or schemes, where AD infrastructure maybe weak or insufficient to accommodate for extra FW collected as a result
2	Establish greater investment, loans or other financial incentives to help establish new AD or expand existing AD infrastructure in regions across North to Northeast of Leeds city should there be likely indicator of increased household FW recycling trials in the future	Prepare for infrastructure to accommodate future household FW recycling trials and scheme implementation
3	Establish loan and investment schemes for Food banks in regions across North to Northeast of Leeds city where there is low or declining socio-economic welfare regions with risk for high FW output but low AD plant capacity	Mitigate risk of FW to landfill in regions where AD infrastructure isn't readily available to accommodate for reduced FW
4	Adopt selective financial support approach in form of investment or loan to ensure AD plants will achieve minimum FW to biomethane conversion (BMC) yield, i.e. rewards for achieving set BMC or help support underperforming operators to achieve set BMC, These must however be condition to equitable distribution of additional revenues to other participating stakeholders.	To ensure maximization of FW derived biomethane that could maximum revenue, and equitable distribution of revenue to key stakeholders

These policy recommendations are designed specifically to address the two most important risk factors that could substantially affect cost and revenue returns from the regional deployment of the FWtTBC pathway. To this end, the intended effect of the policy recommendations would be (i) minimize region specific infrastructure capacity risk, i.e. with lack of FW intake capacity, as well as to (ii) maximize biomethane potential (BMP) attainable

by each AD plant, i.e. which amounts to doubling of BMP given low ($45\text{m}^3/\text{t}$) to high ($90\text{m}^3/\text{t}$) FW to biomethane conversion (BMC) rates found in this study.

The translation of these BMC findings to actual revenue will be explored in the next chapter (Chapter 6), which is especially important by relevant stakeholders (i.e. Leeds City Council, Anaerobic digestion operators, local residents) for examining maximum renewable energy outputs achievable on a regional basis concerning Leeds NPH city or the entire West Yorkshire NPH metropolitan country region or beyond (i.e., surrounding regions as mentioned above). This is to ensure full capacity utilization can be effectively achieved and benefits effectively recouped through careful and well-informed strategizing, planning and deployment of FWtTBC pathway backed by strong government policy support.

Chapter 6: Process operations financial data results and findings

6.1 Introduction and summary

This section outlines both costs and revenues associated with FW to Transport Biomethane Conversion (FWtTBC) pathway deployment in context of key stakeholders across each pathway component. Namely, they include waste contractors, AD operations and refuel station operators. Here it is reasonable to assume the deployment of the entire pathway can be reasonably achieved either by a single company operating across all 3 components or as individual companies specializing in operations of each separate component. The latter is commonly more realistic and representative as this often involves collaboration between different stakeholder at the data gathering, strategic, planning and operational level across each individual component of the FWtTBC pathway.

To this end, revenue, cost of deployment and return on investments are individually assessed for determining the overall financial feasibility of the FWtTBC pathway deployment. These are collectively summarized in Table 144 below to outline the respective contents of the next sections of this chapter, with more specific breakdown of details and discussions to follow.

Table 144. Summary and overview of financial metrics of revenue, cost and return on investment relating to FWtTBC pathway deployment

Metric	Sub-metric	Revenue breakdown	
Revenue	1.1	Energy sales	1.1a Biomethane sales (transport fuel)
			1.1b Biomethane sales (CHP)
	1.2	Policy incentives	1.2a RTFC (correspond to biomethane sales for transport use)
			1.2b RHI (correspond to biomethane use for CHP)
	1.3	Other	1.3a Digestate sales
			1.3b Landfill diversion costs
		AD cost	Description
Cost	2.1	AD plant related cost (main)	2.1a Capital cost of AD plant establishment (CAPEX - total or annualized)
			2.1b Operational cost (calculated as % of capital cost –OPEX)
	2.2	FW collection cost + Refuel station cost	2.2a Capital cost – Initial depot infrastructure and transport vehicle cost (very rough ground up estimation due to very limited data reference)
			2.2b Total labour and maintenance cost (for equipment and infrastructure), calculated as % of capital cost (same as AD method)
	3.1	ROI type 1	3.1a. Total AD cost against (i) all revenues, (ii) energy sales only revenue, (iii) energy sales with policy incentive revenue
			3.1b. Total AD, FW collection and Refuel station costs against (i) all revenues, (ii) energy sales only revenue, (iii) energy sales with policy incentive revenue
3.2	ROI type 2	3.2. Total AD, FW collection and Refuel station costs against (i) all revenues, (ii) energy sales only revenue, (iii) energy sales with policy incentive revenue	

For revenue, the analysis mainly focuses on three key revenue sources attainable from FWtTBC pathway deployment based on available data attained from Boolean search method.

These include revenues arising from (i) direct energy sales, (ii) government policy incentives, and (iii) other sources (see Table 145). To elaborate, energy sales revenue would include total revenue arising from sales of biomethane primarily as transport fuel or alternatively as CHP (heat and electricity), whilst those arising government incentives such as RTFC or RHI revenues would accompany such sales of biomethane that are used either as transport fuel or for CHP, respectively. The final source of revenue generation would involve sales of digestates and cost prevented from landfilling of FW which will become increasingly important in context of UK's tightening environmental and landfill regulations affect food and other wastes.

Table 145. Summary of revenue calculation method for FWtTBC pathway deployment, in context of relevant Process Operations (as outlined in Chapter 4.3 - Methodology 2, refer to calculation section)

	Revenue	Revenue breakdown
1.1	Energy sales	1.1a Biomethane sales (transport fuel)
		1.1b Biomethane sales (CHP)
1.2	Policy incentives	1.2a RTFC (correspond to biomethane sales for transport use)
		1.2b RHI (correspond to biomethane use for CHP)
1.3	Other	1.3a Digestate sales
		1.3b Landfill diversion costs

For total costs, total capital and operational cost at the AD plant, FW collection, and refuel station levels are considered. Where relevant, these include both CAPEX and OPEX, where OPEX is estimated to be a % of CAPEX as means of a general estimation based on acceptable existing estimation values due to lack of specific operational data. This may present to be an area of future study in collaboration with relevant stakeholders and operators for elucidating such results with greater accuracy.

Here the AD related costs are estimated based on their respective size, i.e. by considering cost per unit energy produced for small, medium and large AD plants, while FW collection and transport refuelling costs is calculated as a % of total AD operational costs given lack of specific data found for separate FW collection and transport refuelling trials and schemes. This method however more likely assumes either that all components and operational processes of the FWtTBC pathway are being deployed largely if not solely by the AD operator, or relevant third party collaborators that are in close collaboration with the AD plant operator, to the extent where in which conversion of such cost related data (i.e. FW and transport refuelling being specific % of total AD costs) is known (see Table 146). Given lack of data found for this area of the present study, any such value estimations for FW collection (FWC) and transport refuel station (TRS) operation is largely based on the best estimate real-world (AD to FWC and TRS) cost conversion data.

Table 146. Summary of cost calculation method for FWtTBC pathway deployment, in context of relevant Process Operations (as outlined in Chapter 4.3 - Methodology 2, refer to calculation section)

	Total cost	Description
2.1	AD plant related cost (main)	Capital cost of AD plant establishment (CAPEX - total or annualized)
		Operational cost (calculated as % of capital cost – OPEX)
2.2	Total FW collection cost (Capital and Operational)	Estimated to be a reasonable % of total AD capital and operational cost
2.3	Total Refuel station (Capital and Operational)	Estimated to be a reasonable % of total AD capital and operational cost

For return on investment (ROI) several calculation possibilities exist. Here the general calculation is to divide total combined cost of AD plant procurement and operations against combined revenues, which is assumed to be the greatest financial barrier and driver of FWtTBC pathway deployment. This is found to be the case at Leeds based on interview data with Leeds LA, which indicated that the successful procurement of initial AD plant infrastructure at Leeds would have enabled them to more confidently adopt larger scale city wide household FW collection schemes for biomethane conversion for use either as transport fuel or CHP. The reality of this procurement effort (via bidding) being unsuccessful however has in turn likely prevented the upscale of existing household FW collection efforts at Rothwell. It is also possible estimate ROI using different operational assumptions, as outlined in Table 147 below.

Table 147. Summary of Return on Investment (ROI) calculation method for FWtTBC pathway deployment, in context of relevant Process Operations (as outlined in Chapter 4.3 - Methodology 2, refer to calculation section)

ROI focus	Description	Assumption	
3.1	Entire FWtTBC pathway deployment	Total cost of FWtTBC pathway deployment (across FW collection, AD operation and Refuel station operation – capital and operational) against total main revenues streams (biomethane sales, tariff incentives, digestate sales, landfill tax avoided).	AD plant in charge of FW collection, AD operations and biomethane refuel operations
3.2	AD plant operations only	Total cost of AD plant (capital and operational) against total main revenues streams (biomethane sales, tariff incentives, digestate sales, landfill tax avoided).	AD plant in charge of AD digestion of FW only
3.3	AD plant and refuel station operations	Total cost of AD plant and refuel station (capital and operational) against total main revenues streams (biomethane sales, tariff incentives, digestate sales, landfill tax avoided)	AD plant hosts an on-site refuel station operated by the same AD operator

Below outlines specific assumptions and rationales associated with financial calculations of revenue and costs of AD plant operation using Malting Organics Treatment Facility (MOTF) AD plant as an example to demonstrate possible Return on investment (ROI) achievable by accounting for extreme (upper and lower) variations in combined revenues against costs (see Table 148).

Table 148. Assumptions for financial revenue, cost and Return on Investment (ROI) calculations

No.	Assumption type	Assumption
1	AD plant capacity relative to quantity of collected household FW	MOTF AD plant alone is able to accommodate for FW output arising from 500,000 to 2,500,000 people assuming for highest and lowest FW output per individual of 100 and 20 kg/person/year, with Rothwell FW collection data of 40 kg/person/year suggest more realistically 1,000,000 people can be accommodated. There all combined FW intake capacity from AD plants being sufficient to accommodate for the entire population of Leeds or West Yorkshire under all reasonable scenarios of FWtTBC pathway deployment.
2	Cost calculation reference metrics	Original data source for all capital cost data, which mainly include either official operator websites or specialist online news reports, are assumed to be accurate in their reporting of estimated capital cost associated with the construction of each AD. Consequently, any resulting operational costs which is calculated as % of capital costs (for which there is reasonable data available for this estimation) is also deemed to be within acceptable limits. This method will also extends to estimation costs of FW collection and transport refuelling (as % of capital cost of relevant AD in question). Where direct capital costs data is unavailable, cost estimations of Maltings organics and other relevant AD plants is estimated using cost data from other AD plants of similar type and size

These assumptions are established to reinforce existing findings of this research, namely those in Chapter 5.3.5 which demonstrates more than sufficient AD infrastructure to

accommodate for all household FW collected at NPH Leeds city and West Yorkshire region as well as surrounding towns and cities (i.e. to South and Southeast of Leeds), and to also overcome the present research's limitation on there being lack of financial data for FW collection and transport refuelling. For the latter, it is important to note that the total cost of FW collection and transport refuel station operation will be estimated to be a reasonable % of capital costs of relevant AD in question (AD CAPEX), given there to be some literature data available for this method of estimation.

By applying these assumptions and methods of revenue, cost and ROI calculation, it is hoped for any region specific findings that indicates a strong financial ROI to pave way for deployment of new FWtTBC pathway across specific regions of interest, such as both Leeds city and nearby regions close to Leeds that fall within close proximity to the 4 aforementioned AD plants (see Table 136). The next section will outline how specifically each metric is calculated using key scenario examples to demonstrate suitable avenues of FWtTBC pathway development.

6.2 Revenue Findings overview

This section outlines aggregate revenue from biomethane sale and policy incentives for hypothetical FWtTBC pathway deployment in NPH city regions. This is achieved by integrating existing FW collection (FWC) and FW to biomethane conversion (BMC) yield results from above findings with relevant revenue data presented in this section.

Below outlines data calculation for each specific revenue streams as outlined in Table 145 above by combining known revenue data on specific FWtTBC pathway components. These include (i) unit energy sales value of biomethane and electricity, (ii) redeemable financial revenue from each RTFC or RHI unit, and (iii) unit non-energy redeemable financial value of digestate sales or kg FW diverted from landfill, and these will be explored in more depth in the order stated above.

6.2.1 Transport biomethane (TBM) sales revenues

6.2.1a Transport biomethane (TBM) sales revenue base data - used for transport biomethane revenue calculations

This section outlines first existing revenue sales data for TBM in either Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) form, which hereafter will be alternatively known as Compressed Biomethane (CBM) or Liquefied Biomethane (LBM), followed by calculation of total potential CBM or LBM revenues associated with the Biomethane Potential (BMP) associated with each relevant region or AD plant.

With regard to revenue unit conversions, CBM and LBM is assumed to be priced similarly to that of CNG and LNG, from which data is readily available from the Low CVP Biomethane Report (LowCVP, 2011). The calculations also integrates a number of technical assumptions and measurements for the suitable conversion of Compressed (CMB) and Liquid (LBM) biomethane to actual revenues. These include assuming that the density of biomethane is 0.7 kg/m^3 which is equivalent to that of natural gas under standard temperature and pressure to

enable revenue calculations to be measured in both m³ and kg terms (i.e. p/m³ and p/kg) for all biomethane forms (LBM, CBM and LCBM). It is also assumed that CBM and LBM are being stored at conditions of 200/250 bar and -162 degrees Celsius, respectively, to enable safe storage and refuelling operations.

Table 149 and Table 150 below outlines the unit pricings of both CBM and LBM which is supplied by CNG and LNG stations respectively. The table outlines key trend results of both fuel being cheaper with increased scale of the refuel station, likely due to reduced combined (capital and operational) costs of station infrastructure and daily operations.

Table 149. CNG and LNG costs according to Low Carbon CVP data (excluding VAT), which respectively supplied CBM and LBM though for purpose of keeping originality of data the original wordings of CNG and LNG station is used.

LowCVP+Biomethane+Report_Part+1+Final (1)						
Table 2.3 Gas refuelling CNG and LNG station costs and fuel price (before VAT)						
Station Size (kg/day)	CNG Station Fuel Price (p/kg)	LNG Station Fuel Price (p/kg)	LCNG Station Fuel Price (p/kg)	CNG Station Fuel Price (p/m³)	LNG Station Fuel Price (p/m³)	LCNG Station Fuel Price (p/m³)
500	117.15	122.15	143.15	82.01	85.51	100.21
1,000	95.15	107.15	120.15	66.61	75.01	84.11
2,000	84.15	100.15	113.15	58.91	70.11	79.21
5,000	77.15	93.15	106.15	54.01	65.21	74.31
10,000	75.15	92.15	101.15	52.61	64.51	70.81

*p/m³ assumes standard conversion rate of 0.7kg/m³ for biomethane

Below outlines sales prices for all CNG and LNG for all station sizes with inclusion of additional 17.5% VAT as reported using original data (please note at time of writing the VAT has increased to 20%).

Table 150. CNG and LNG costs according to Low Carbon CVP data (including VAT – of 17.5% at time of report)

Gas refuelling CNG station costs and fuel price (after VAT - assumed at 17.5%)						
Station Size (kg/day)	CNG Station Fuel Price (p/kg)	LNG Station Fuel Price (p/kg)	LCNG Station Fuel Price (p/kg)	CNG Station Fuel Price (p/m³)	LNG Station Fuel Price (p/m³)	LCNG Station Fuel Price (p/m³)
500	140.58	146.58	171.78	98.41	102.61	120.25
1,000	114.18	128.58	144.18	79.93	90.01	100.93
2,000	100.98	120.18	135.78	70.69	84.13	95.05
5,000	92.58	111.78	127.38	64.81	78.25	89.17
10,000	90.18	110.58	121.38	63.13	77.41	84.97

Here it is worth noting that above 2011 fuel price data are used as they represent the best official data on CBM and LBM pricing, despite the researchers efforts to gather more recent representative data. This dataset consequently likely portrays a gross underestimation of fuel sales prices to-date (2021, at time of writing the thesis), and is rectified by using reasonable assumptions 10% to 25% fuel price increase to reflect on equivalent discrepancies between 2011 and 2022 petrol prices (of approximately 128-132p/L in 2011 (Guardian, 2011) and a 140-167p/L at 2022 (HeyCar, 2022) for unleaded fuel, at time of writing). This however is

anticipated to show further possible sharp increases for the foreseeable future, which will likely make CBM and LBM production to be more profitable with time, assuming that their prices would increase at the same level as that of general transport fuel prices. Below shows the adjusted fuel pricing data by converting biomethane sales from p/kg to p/m³ using the assumption that the density of biomethane is 0.7 kg/m³ using the reason given above (see Table 151).

Table 151. Adjusted CNG and LNG prices, which sales of compressed and liquified biomethane prices assumed to be at equivalent value.

Station Size (kg/day)	2011 price scenario (same as above)			10% increase			25% increase		
	CNG Station Fuel Price (p/m ³)	LNG Station Fuel Price (p/m ³)	LCNG Station Fuel Price (p/m ³)	CNG Station Fuel Price (p/m ³)	LNG Station Fuel Price (p/m ³)	LCNG Station Fuel Price (p/m ³)	CNG Station Fuel Price (p/m ³)	LNG Station Fuel Price (p/m ³)	LCNG Station Fuel Price (p/m ³)
500	98.41	102.61	120.25	108.25	112.87	132.27	123.01	128.26	150.31
1,000	79.93	90.01	100.93	87.92	99.01	111.02	99.91	112.51	126.16
2,000	70.69	84.13	95.05	77.75	92.54	104.55	88.36	105.16	118.81
5,000	64.81	78.25	89.17	71.29	86.07	98.08	81.01	97.81	111.46
10,000	63.13	77.41	84.97	69.44	85.15	93.46	78.91	96.76	106.21

These give rises a table of biomethane sales revenue attainable per tonne of household FW in consideration of low (45m³), medium (67.50m³) and high (90m³) FW to biomethane conversion (BMC) rates, as outlined respectively in Table 152, Table 153 and Table 154 below.

The calculations uses the following equation of (assuming biomethane can refer to CNG, LNG or LCNG or CBM, LBM or LCBM, both which represent interchangeable terms):

CBM revenue per tonne FW (t/FW) = Biomethane yield per tonne of FW × Biomethane fuel price relative to CNG station size and biomethane type

Table 152. Assumed revenues of Compressed Biomethane (CBM) and Liquified Biomethane (LBM) per tonne of FW assuming for low FW to biomethane conversion yield of 45m³/t and price parity with CNG and LNG prices

Station Size (kg/day)	Low BMC (45m ³)			10% increase			25% increase		
	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)
500	£44.28	£46.17	£54.11	£48.71	£50.79	£59.52	£55.35	£57.72	£67.64
1,000	£35.97	£40.50	£45.42	£39.56	£44.55	£49.96	£44.96	£50.63	£56.77
2,000	£31.81	£37.86	£42.77	£34.99	£41.64	£47.05	£39.76	£47.32	£53.46
5,000	£29.16	£35.21	£40.13	£32.08	£38.73	£44.14	£36.45	£44.01	£50.16
10,000	£28.41	£34.83	£38.24	£31.25	£38.32	£42.06	£35.51	£43.54	£47.79

For the low FW to BMC scenario of 45m³/t FW, CBM revenue attainable from sale of energy equivalent from each tonne of FW ranges from £28.41 to £44.28 using the standard 2011 pricing rates. This would increase further to £31.25 to £48.71 and £35.51 to £55.35 under 10%

and 25% increased rate assumption, that is more applicable to 2022 energy pricing. The same revenue attainable for LBM would amount to £34.83 to £46.17, £38.32 to £50.79 and £43.54 to £57.72 for the 2011 pricing, 10% increase and 25% increase pricing scenario respectively. Likely, revenue attainable for LCBM would amount to £38.24 to £54.11, £42.06 to £59.52 and £47.79 to £67.64 for the 2011 pricing, 10% increase and 25% increase pricing scenario respectively.

Table 153. Assumed revenues of Compressed Biomethane (CBM) and Liquified Biomethane (LBM) per tonne of FW assuming for medium FW to biomethane conversion yield of 67.50m³/t and price parity with CNG and LNG prices

Station Size (kg/day)	Medium BMC (67.50m ³)			10% increase			25% increase		
	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)
500	£66.43	£69.26	£81.17	£73.07	£76.19	£89.28	£83.03	£86.58	£101.46
1,000	£53.95	£60.76	£68.13	£59.35	£66.83	£74.94	£67.44	£75.94	£85.16
2,000	£47.72	£56.79	£64.16	£52.48	£62.46	£70.57	£59.64	£70.98	£80.20
5,000	£43.75	£52.82	£60.19	£48.12	£58.10	£66.20	£54.68	£66.02	£75.24
10,000	£42.61	£52.25	£57.35	£46.87	£57.48	£63.09	£53.26	£65.31	£71.69

For the medium FW to BMC scenario of 67.50m³/t FW, CBM revenue attainable from sale of energy equivalent from each tonne of FW ranges from £42.61 to £66.43 using the standard 2011 pricing rates. This would increase further to £46.87 to £73.07 and £53.26 to £83.03 under 10% and 25% increased rate assumption, that is more applicable to 2022 energy pricing. The same revenue attainable for LBM would amount to £52.25 to £69.26, £57.48 to £76.19 and £65.31 to £86.58 for the 2011 pricing, 10% increase and 25% increase pricing scenario respectively. Likely, revenue attainable for LCBM would amount to £57.35 to £81.17, £63.09 to £89.28 and £71.69 to £101.46 for the 2011 pricing, 10% increase and 25% increase pricing scenario respectively.

Table 154. Assumed revenues of Compressed Biomethane (CBM) and Liquified Biomethane (LBM) per tonne of FW assuming for high FW to biomethane conversion yield of 90m³/t and price parity with CNG and LNG prices

Station Size (kg/day)	High BMC (90m ³)			10% increase			25% increase		
	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)	CBM revenue (p/t FW)	LBM revenue (p/t FW)	LCBM revenue (p/t FW)
500	£88.57	£92.35	£108.23	£97.43	£101.58	£119.04	£110.71	£115.43	£135.28
1,000	£71.94	£81.01	£90.84	£79.13	£89.11	£99.92	£89.92	£101.26	£113.54
2,000	£63.62	£75.72	£85.55	£69.98	£83.29	£94.10	£79.52	£94.64	£106.93
5,000	£58.33	£70.43	£80.25	£64.16	£77.46	£88.27	£72.91	£88.03	£100.31
10,000	£56.82	£69.67	£76.47	£62.50	£76.64	£84.11	£71.02	£87.08	£95.59

For the high FW to BMC scenario of 90m³/t FW, CBM revenue attainable from sale of energy equivalent from each tonne of FW ranges from £56.82 to £88.57 using the standard 2011 pricing rates. This would increase further to £62.50 to £97.43 and £71.02 to £110.71 under

10% and 25% increased rate assumption, that is more applicable to 2022 energy pricing. The same revenue attainable for LBM would amount to £69.67 to £92.35, £76.64 to £101.58 and £87.08 to £115.43 for the 2011 pricing, 10% increase and 25% increase pricing scenario respectively. Likely, revenue attainable for LCBM would amount to £76.47 to £108.23, £84.11 to £119.04 and £95.59 to £135.28 for the 2011 pricing, 10% increase and 25% increase pricing scenario respectively.

Given there to be 75 combinations of possible total revenue scenarios calculations applicable to all NPH city and metropolitan county regions attributed to the above-mentioned variables of (i) 5 FW collection scenarios, (ii) 3 FW to biomethane conversion yield scenarios, and (iii) 5 fuel sales price ranges (for each of CBM, LBM or LCBM) dependent on refuel station size, a reductive approach is used to determine maximum and minimum value to establish lowest and highest CBM sales revenue for both fixed and variable FW collection scenario. In determining this approach, each individual metric elements are further assessed below.

These metric elements include 4 factors that critically underpin the total revenue attainable from CBM and LBM sales values derived from all NPH city and metropolitan regions. Namely they include FW collection (FWC), Biomethane conversion (BMC), population pertain to each relevant region and unit sales price for each biomethane type (LBM, CBM and LCBM). These factors consequently come into play for estimating the difference between highest and lowest revenue potential across different regions, which is determined by the below equation (where biomethane can be used interchangeably with CBM, LBM and LCBM):

Total biomethane sales revenue equation 1:

$$\text{Total annual biomethane sales revenue for any given region (£/year)} = \text{FWC (tFW/person/year)} \times \text{total region population (person)} \times \text{BMC (m}^3\text{/tFW)} \times \text{per tonne FW revenue yield (£/m}^3\text{)}$$

When estimating for total revenue across the same NPH region, then the population element is removed to give rise to the following equation:

Total biomethane sales revenue equation 2:

$$\text{Total annual biomethane sales revenue in given region (£/year)} = \text{total FWC in known region (tFW/ year)} \times \text{BMC (m}^3\text{/tFW)} \times \text{per tonne FW revenue yield (£/m}^3\text{)}$$

Using all available data from existing findings for FWC (FW collection rate), BMC (biomethane conversion rate) and transport biomethane sales, the former 2 factors and their effects on total biomethane sales revenue generation is summarized in Table 155 below.

Table 155. Factors with quantification data showing magnitude of biomethane sales revenue affected by each factor

	Low BMC	Medium BMC	High BMC
	45	67.50	90
Low FWC - 20	1	1.5	2
Medium FWC – 40	2	3	4
High FWC – 100	5	7.5	10

These factors are further combined with factors affecting biomethane sales pricing using CBM as the primary example, for which 4 different levels of revenue sales value estimations are found with respect to different estimation assumptions outlined in Table 156 below.

Table 156. Difference in revenue prices for CBM calculation only

	Difference multiplier	Assumption
1	1	No inherent difference
2	1.25	Difference between 2011 and 2022 revenue of 25% for same plant size
3	1.56	Difference between different plant sizes in 2011 (for CBM)
4	1.948	Highest CBM sales value (smallest plant, +25% value) divided by lowest CBM sales value (largest plant, 2011 figures) (for CBM)

When accounting for greatest differences in potential revenue generation outlined in both Table 155 (×10 multiplier) and Table 156 (×1.948 multiplier), this amounts of a total combined revenue difference potential of 19.48 as outlined in Table 157 below.

Table 157. Table of revenue potential difference underpinned by biomethane conversion yield (BMC) from FW, FW collection (FWC) and biomethane sales revenue scenarios

			Low BMC	Medium	High
			45m ³	67.50m ³	90m ³
No change in biomethane revenue	Low FWC	20 kg/pp/yr	1	1.5	2
	Medium FWC	40 kg/pp/yr	2	3	4
	High FWC	100 kg/pp/yr	5	7.5	10
25% increase in biomethane revenue	Low FWC - 20	20 kg/pp/yr	1.25	1.875	2.5
	Medium FWC	40 kg/pp/yr	2.5	3.75	5
	High FWC	100 kg/pp/yr	6.25	9.375	12.5
No change in biomethane revenue	Low FWC	20 kg/pp/yr	1.56	2.34	3.12
	Medium FWC	40 kg/pp/yr	3.12	4.68	6.24
	High FWC	100 kg/pp/yr	7.8	11.7	15.6
25% increase in biomethane revenue	Low FWC	20 kg/pp/yr	1.948	2.922	3.896
	Medium FWC	40 kg/pp/yr	3.896	5.844	7.792
	High FWC	100 kg/pp/yr	9.74	14.61	19.48

When discounting for discrepancy in per person FW collection (FWC), as eliminated by the WRAP and WDF FW collection scenario data, these differences are still relatively high as is underpinned by the dual factors of difference in BMC and refuel prices would amount to approximately 3.9 times difference which is still extremely significant in revenue terms (see Table 158).

Table 158. Biomethane revenue difference potential when discounting for FW collection rate of each household individual per year (FWC)

			Low BMC	Medium BMC	High BMC
			45m ³	67.50m ³	90m ³
1	No revenue difference	1	1	1.5	2
2	2022 vs 2011 - 25% like for like increase	1.25	1.25	1.875	2.5
3	Highest / lowest station fuel price difference	1.56	1.56	2.34	3.12
4	2022 Highest vs 2011 lowest fuel price different	1.948	1.948	2.922	3.896

Likewise, when eliminating discrepancy in biomethane potential of FW as seen under scenarios of single AD plant operations (where biomethane yield of FW is assumed to be a

constant average during a specific period of operation) the discrepancies between the highest and the lowest would be approximately 6.25 difference which is higher than the above scenario which eliminates discrepancies in FWC but not BMC (see Table 159).

Table 159. Biomethane revenue difference potential when discounting for biomethane conversion yield of collected household FW(BMC)

			Low FWC	Medium FWC	High FWC
			20 kg/pp/yr	40 kg/pp/yr	100 kg/pp/yr
1	No revenue difference	1	1	2	5
2	2022 vs 2011 - 25% like for like increase	1.25	1.25	2.5	6.25
3	Highest / lowest station fuel price difference	1.56	1.56	3.12	7.8
4	2022 Highest vs 2011 lowest fuel price different	1.948	1.948	2.922	3.896

These upper end results demonstrate the overall importance of effective planning and strategizing of FWtTBC pathway deployment that could materially affect the revenues attainable from biomethane sales alone. The next section will outline respective revenue potential between the highest and lowest revenue generation scenarios for each FW collection scenario (fixed, variation) across NPH city and metropolitan county region, with or without context of AD infrastructure capacity availability (latter focusing on Leeds and Maltings organics infrastructure).

Below outlines a series of possible revenue graph comparisons between different scenarios of compressed biomethane (CBM) across all NPH city and metropolitan county regions between 2000 and 2050 for determining overall magnitude of energy sales revenue potential available. These comparisons can be between the highest and lowest CBM sales potential accounting for either 3, 2 or 1 metrics combined to illustrate the impact of each combination of factors on total CBM sales revenue potential as outlined in Table 160 below.

Table 160. Summary of CBM revenue potential calculations, taking account of either 3, 2 or 1 factor, all of which involves difference in CBM (compressed biomethane) unit sales prices

No. metrics involved	Metric equation	Description
3	FWC x BMC x CBM unit sales price	Combined effect of of FW collection per person, and FW Biomethane conversion yield and CBM sales price on total CBM sales revenue
2	FWC x CBM unit sales price	Combined effect of FW collection per person and CBM sales price on total CBM sales revenue
	BMC x CBM unit sales price	Combined effect of CBM sales price and FW Biomethane conversion yield on total CBM sales revenue
1	CBM Unit sales price	Effect of CBM sales price only on total CBM sales revenue

The next section will compare only the highest and the lowest findings arising from (i) 3 metric factors (of FWC, BMC and CBM unit sales price) and (ii) 2 two metric factor (for WRAP and WDF variable FW scenarios, varying BMC x CBM unit sales price) for both NPH city and metropolitan county regions to illustrate the difference in magnitude of CBM sales revenue

attainable. Though it is worth noting the above possible discrepancy in such results when accounting for only 2 metric factors as outlined in Table 158, Table 159 and Table 160 above.

6.2.1b CBM sales revenues - all NPH city regions, 3 metric factor comparison of highest against lowest Compressed Biomethane (CBM) sales revenue potential using (i) FW collection (FWC), (ii) Biomethane Conversion yield from FW (BMC) and (ii) CBM sales revenue price metrics

A 3 metric factor comparison using the lowest and the highest values of (i) FWC, (ii) BMC and (iii) CBM unit sales price outlines a lowest CBM revenue scenario potential for Leeds to be between £400,000 (2000 figures) and £510,000 (2050 figures) (Figure 185). This for the highest CBM revenue scenario potential is very substantially increased to £7,800,000 (2000 figures) and £9,900,000 (2050 figures) respectively. This for Newcastle, which have the lowest CBM sales revenue potential amongst all NPH city regions, demonstrates a lowest to highest 2000-2050 CBM revenue scenario potential of £148,000 to £178,000 and £2,880,000 and £3,460,000 respectively.

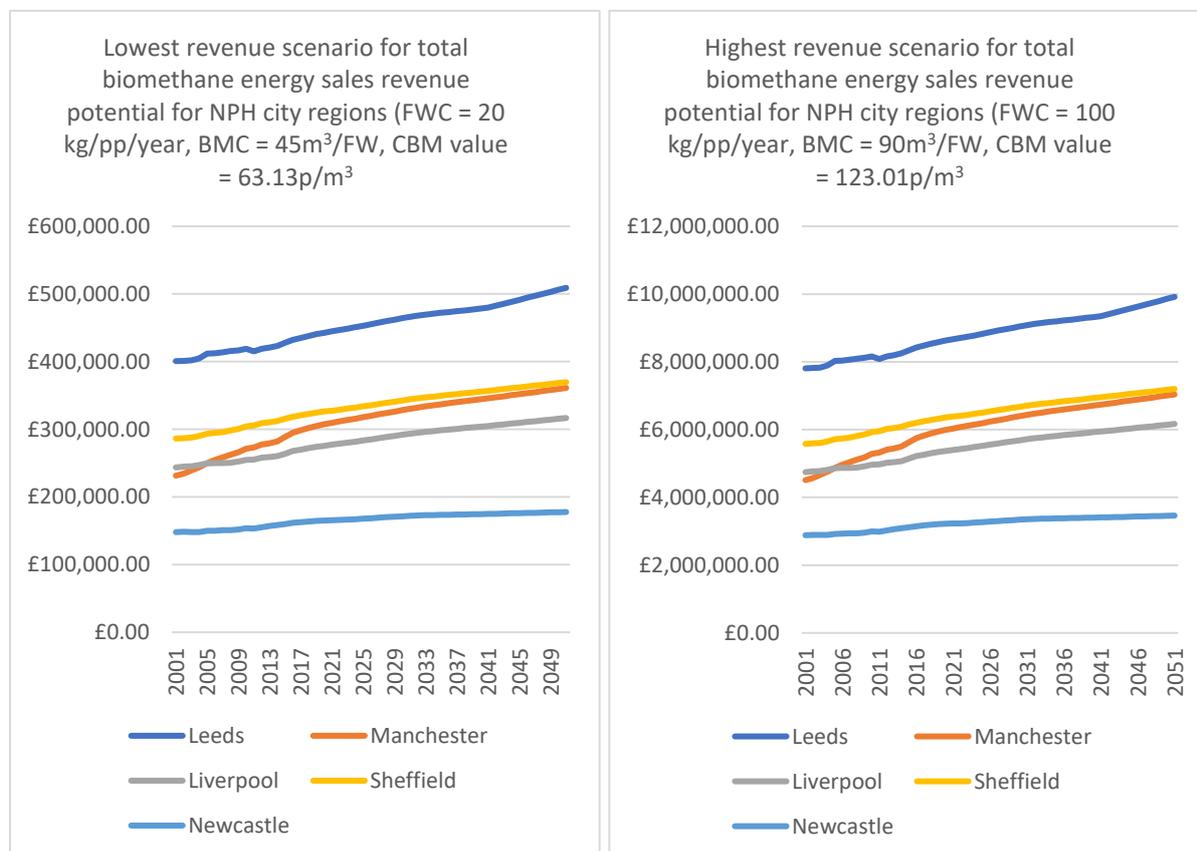


Figure 185. Comparison of lowest and highest compressed biomethane (CBM) sales revenues for all NPH city regions in the period 2001-2050 with a value difference of 19.48 times between the two, (lowest and highest scenario data represented by left and right graphs respectively), based input data outlined in Table 157 above

These findings demonstrate the discrepancies in revenue to fall within the ranges of £2.5 million to £3.3 million (Newcastle 2020 to 2050 figure comparison) and £7.3 million to £9.4 million (Leeds 2020 to 2050 figure), and is significant for the establishment of micro to small sized commercial AD plants which could accommodate for deployment micro to small scale local FW collection trials or schemes and small sized refuel stations.

It will be interesting to compare these results to findings for NPH city regions derived from that of variable WRAP and WDF data, which removes the variation in annual quantity of FW collected from each household individual (see 6.2.1d).

6.2.1c CBM sales revenues - all NPH metropolitan county regions, 3 metric factor comparison of highest against lowest Compressed Biomethane (CBM) sales revenue potential using (i) FW collection (FWC), (ii) Biomethane Conversion yield from FW (BMC) and (iii) CBM sales revenue price metrics

A 3 metric factor comparison using the lowest and the highest values of (i) FWC, (ii) BMC and (iii) CBM unit sales price outlines a lowest CBM revenue scenario potential for West Yorkshire to be between £1,170,000 (2000 figures) and £1,410,000 (2050 figures) (see Figure 186). This for the highest CBM revenue scenario potential is very substantially increased to £22,740,000 (2000 figures) and £27,540,000 (2050 figures) respectively. This for Tyne and Wear, which have the lowest CBM sales revenue potential amongst all NPH metropolitan county regions, demonstrates a lowest to highest 2000-2050 CBM revenue scenario potential of £608,000 to £653,000 and £11,840,000 and £12,730,000 respectively.

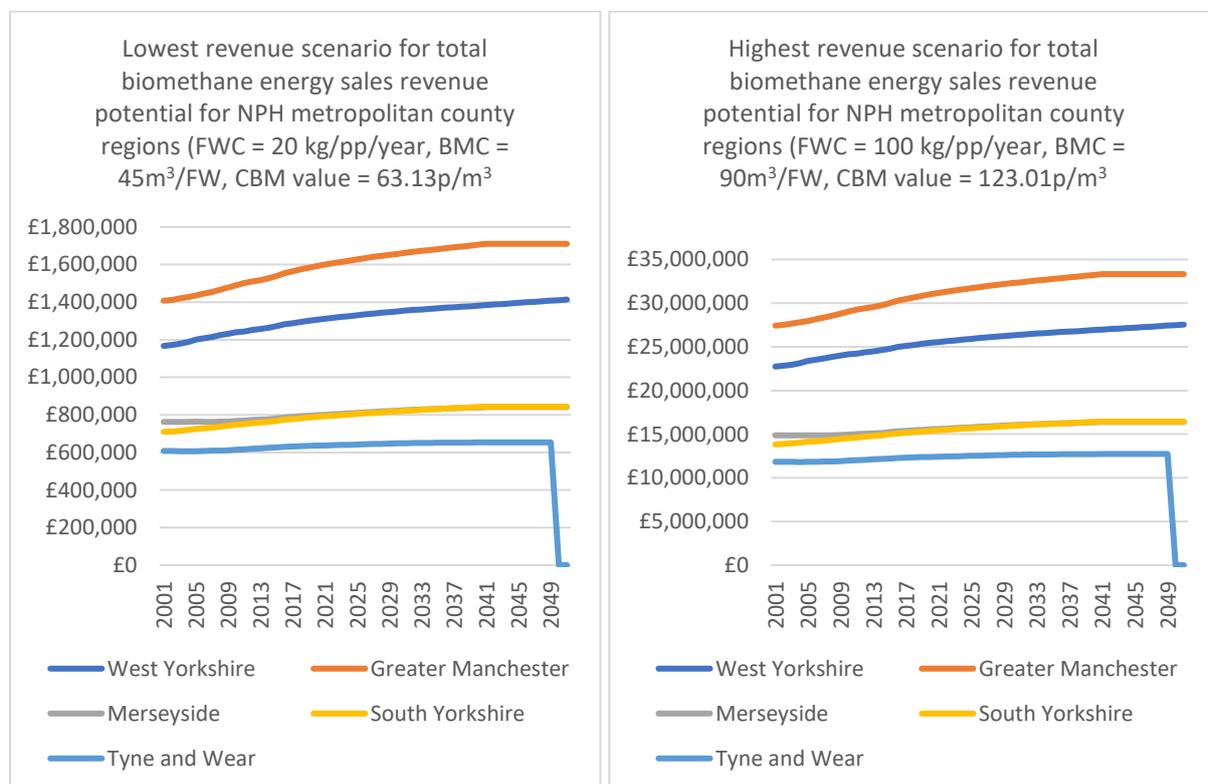


Figure 186. Comparison of lowest and highest compressed biomethane (CBM) sales revenues for all NPH metropolitan county regions in the period 2001-2050 with a value difference of 19.48 times between the two (lowest and highest scenario data represented by left and right graphs respectively), based input data outlined in Table 157 above

The findings demonstrate the discrepancies in revenue to fall within the ranges of £11.2 million to £12.1 million (Tyne & Wear 2020 to 2050 figure comparison) and £21.5 million to £26 million (West Yorkshire 2020 to 2050 figure), and is extremely significant for the establishment of moderate to large sized commercial AD plants which could accommodate for deployment medium to large scale city or county wide FW collection trials or schemes and large sized refuel stations.

It will be interesting to compare these results to findings for NPH metropolitan county regions derived from that of variable WRAP and WDF data, which removes the variation in annual quantity of FW collected from each household individual (see 6.2.1e).

6.2.1d CBM sales revenues - all NPH city regions, variable (WDF data) FW collection data scenario

A 2 metric factor comparison of lowest and highest values of (i) BMC and (ii) CBM unit sales price using the WDF variable FW collection dataset demonstrates several notable findings applicable to all NPH city regions (see Figure 187). For Leeds city which holds the greatest revenue generation potential amongst all NPH cities, its lowest CBM revenue scenario potential stands at £1,020,000 in 2010 declining to £430,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £3,970,000 in 2010 which again declines significantly to £1,680,000 by 2050.

For Newcastle city which holds the lowest revenue generation potential amongst all NPH cities, its lowest CBM revenue scenario potential stands at £374,000 in 2010 declining to £151,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £1,460,000 in 2010 which again declines significantly to £588,000 by 2050.

It is interesting to note the sharp rebound in CBM revenue in 2015 and 2016 for all NPH city regions, owing mainly to the sharp increased FW collected during these 2 years, before further sharp decline in the ensuing years. The consistent annual decline in CBM revenue potential owes largely to the estimated decline in FW collection for all NPH city regions beyond 2021. This decline does show to have a large cumulative effect on total revenue potential overtime, which as above finding demonstrates more than halves between the estimated period of 2010 and 2050.

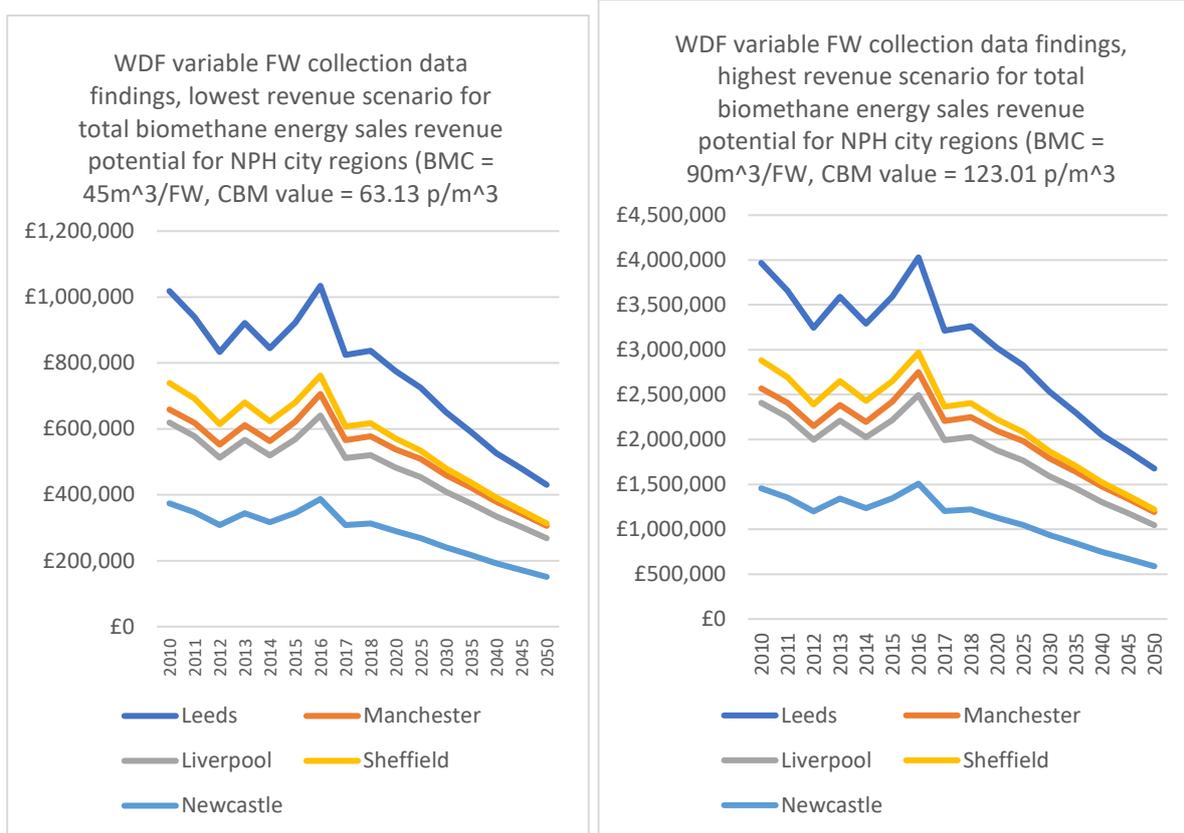


Figure 187. Compressed Biomethane (CBM) sales revenue potential scenario – Using WDF variable FW collection data for all NPH city regions, illustrating lowest (left) and highest (right) total revenue generation potential scenarios as determined by biomethane conversion yield and unit sales value of CBM (see figure heading for details) (see Appendix table 59 and Appendix table 60)

6.2.1e CBM sales revenues - all NPH city regions, variable (WRAP data) FW collection data scenario

A 2 metric factor comparison of lowest and highest values of (i) BMC and (ii) CBM unit sales price using the WRAP variable FW collection dataset demonstrates several notable findings applicable to all NPH city regions (Figure 188). For Leeds city which holds the greatest revenue generation potential amongst all NPH cities, its lowest CBM revenue scenario potential stands at £1,800,000 in 2010 declining to £450,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £7,040,000 in 2010 which again declines significantly to £1,750,000 by 2050.

For Newcastle city which holds the lowest revenue generation potential amongst all NPH cities, its lowest CBM revenue scenario potential stands at £685,000 in 2010 declining to £159,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £2,670,000 in 2010 which again declines significantly to £620,000 by 2050.

It is interesting to note the slight rebound in CBM revenue in the period of 2014 to 2018 for all NPH city regions, owing mainly to the slightly increased FW collected during these 5 years, before further decline in the ensuing years. The consistent annual decline in CBM revenue potential owes largely to the estimated decline in FW collection for all NPH city regions beyond 2021. Similar to WDF data trend observed above, this decline does show to have a large

cumulative effect on total revenue potential overtime, which as above finding demonstrates more than halves between the estimated period of 2010 and 2050.

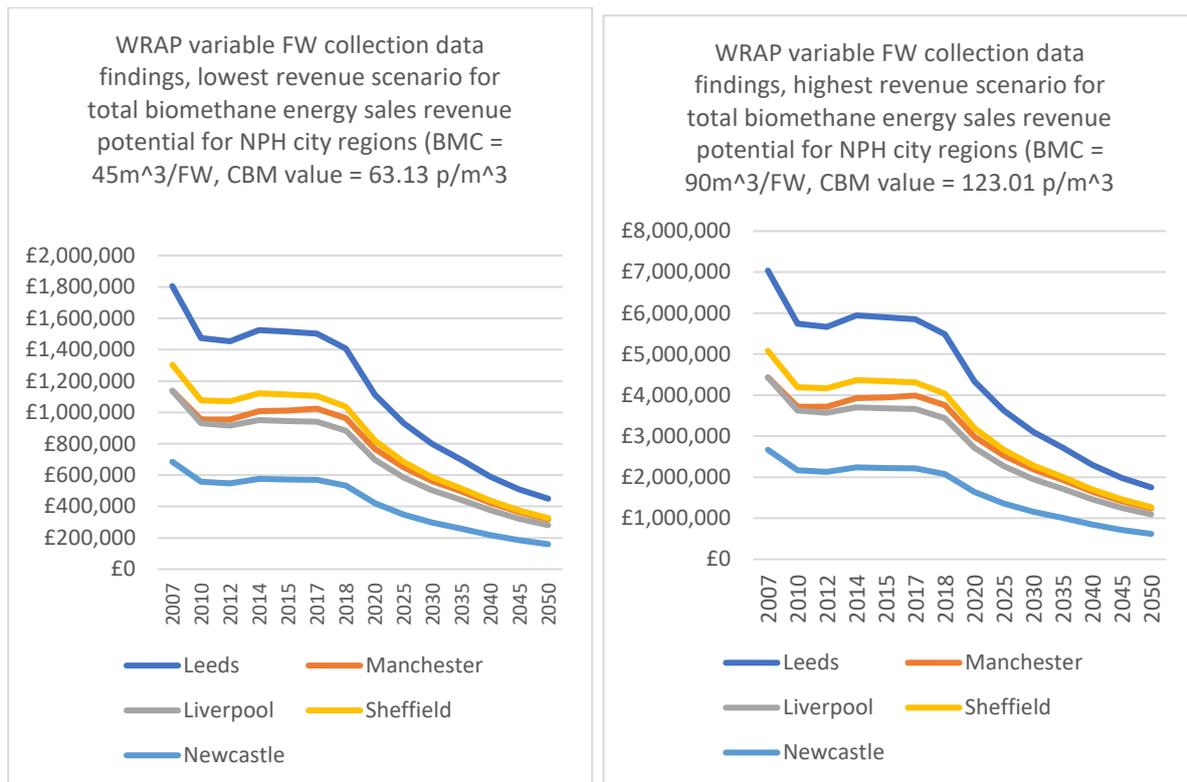


Figure 188. Compressed Biomethane (CBM) sales revenue potential scenario – Using WRAP variable FW collection data for all NPH city regions, illustrating lowest (left) and highest (right) total revenue generation potential scenarios as determined by biomethane conversion yield and unit sales value of CBM (see figure heading for details)

6.2.1f CBM sales revenues - all NPH metropolitan county regions, variable (WDF data) FW collection data scenario

A 2 metric factor comparison of lowest and highest values of (i) BMC and (ii) CBM unit sales price using the WDF variable FW collection dataset demonstrates several notable findings applicable to all NPH metropolitan county regions. For Greater Manchester city which holds the greatest revenue generation potential amongst all NPH metropolitan counties, its lowest CBM revenue scenario potential stands at £3,620,000 in 2010 declining to £1,490,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £14,111,000 in 2010 which again declines significantly to £5,808,000 by 2050.

For Tyne and Wear city which holds the lowest revenue generation potential amongst all NPH metropolitan counties, its lowest CBM revenue scenario potential stands at £1,494,000 in 2010 declining to £559,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £5,821,000 in 2010 which again declines significantly to £2,178,000 by 2050.

It is interesting to note the sharp rebound in CBM revenue in 2015 and 2016 for all NPH metropolitan county regions, owing mainly to the sharp increased FW collected during these 2 years, before further sharp decline in the ensuing years (same trend as seen with NPH city region data). The consistent annual decline in CBM revenue potential owes largely to the estimated decline in FW collection for all NPH metropolitan county regions beyond 2021. Again, this decline does show to have a large cumulative effect on total revenue potential overtime,

which as above finding demonstrates more than halves between the estimated period of 2010 and 2050.

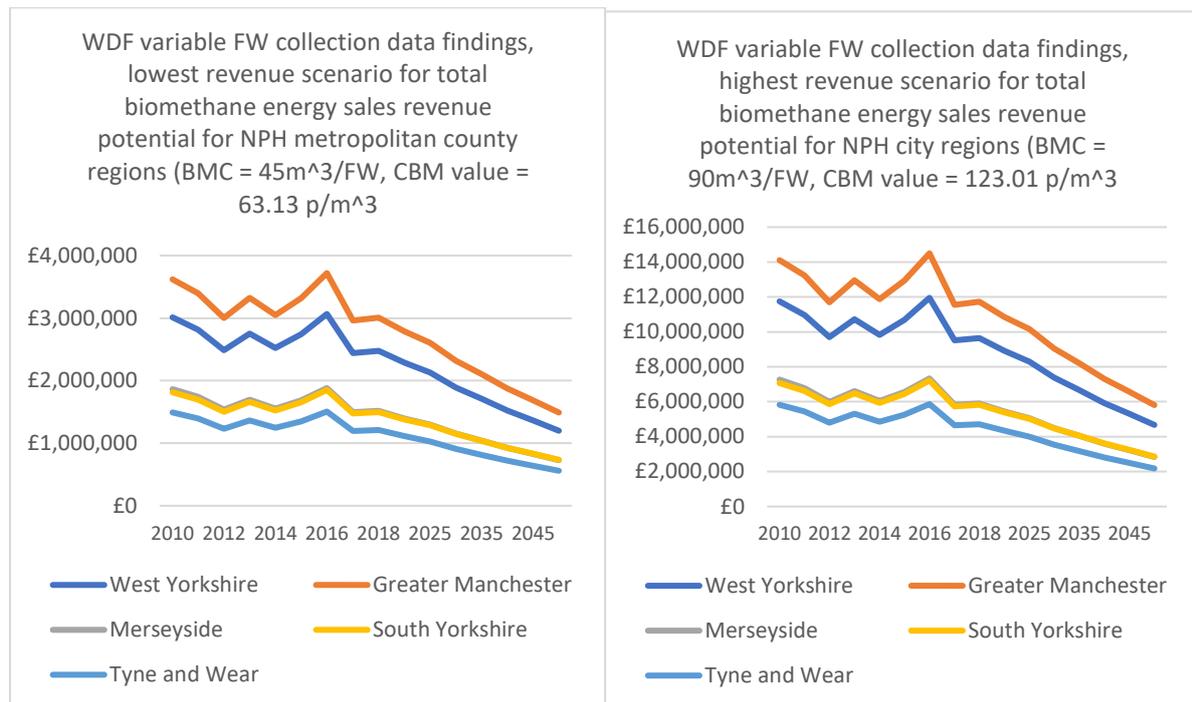


Figure 189. Compressed Biomethane (CBM) sales revenue potential scenario – Using WDF variable FW collection data for all NPH metropolitan county regions, illustrating lowest (left) and highest (right) total revenue generation potential scenarios as determined by biomethane conversion yield and unit sales value of CBM (see figure heading for details)

6.2.1g CBM sales revenues - all NPH metropolitan county regions, variable (WRAP data) FW collection data scenario

A 2 metric factor comparison of lowest and highest values of (i) BMC and (ii) CBM unit sales price using the WRAP variable FW collection dataset demonstrates several notable findings applicable to all NPH metropolitan county regions. For Greater Manchester city which holds the greatest revenue generation potential amongst all NPH metropolitan counties, its lowest CBM revenue scenario potential stands at £6,399,000 in 2010 declining to £1,552,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £24,938,000 in 2010 which again declines significantly to £6,048,000 by 2050.

For Tyne and Wear city which holds the lowest revenue generation potential amongst all NPH metropolitan counties, its lowest CBM revenue scenario potential stands at £2,763,000 in 2010 declining to £589,000 by 2050. By contrast, its highest CBM revenue scenario potential is very substantially increased to £10,766,000 in 2010 which again declines significantly to £2,297,000 by 2050.

It's interesting to note the slight rebound in CBM revenue in the period of 2014 to 2018 for all NPH metropolitan county regions, owing mainly to the slightly increased FW collected during these 5 years, before further decline in the ensuing years. The consistent annual decline in CBM revenue potential owes largely to the estimated decline in FW collection for all NPH metropolitan county regions beyond 2021. Again this decline does show to have a large

cumulative effect on total revenue potential overtime, which as above finding demonstrates more than halves between the estimated period of 2010 and 2050.

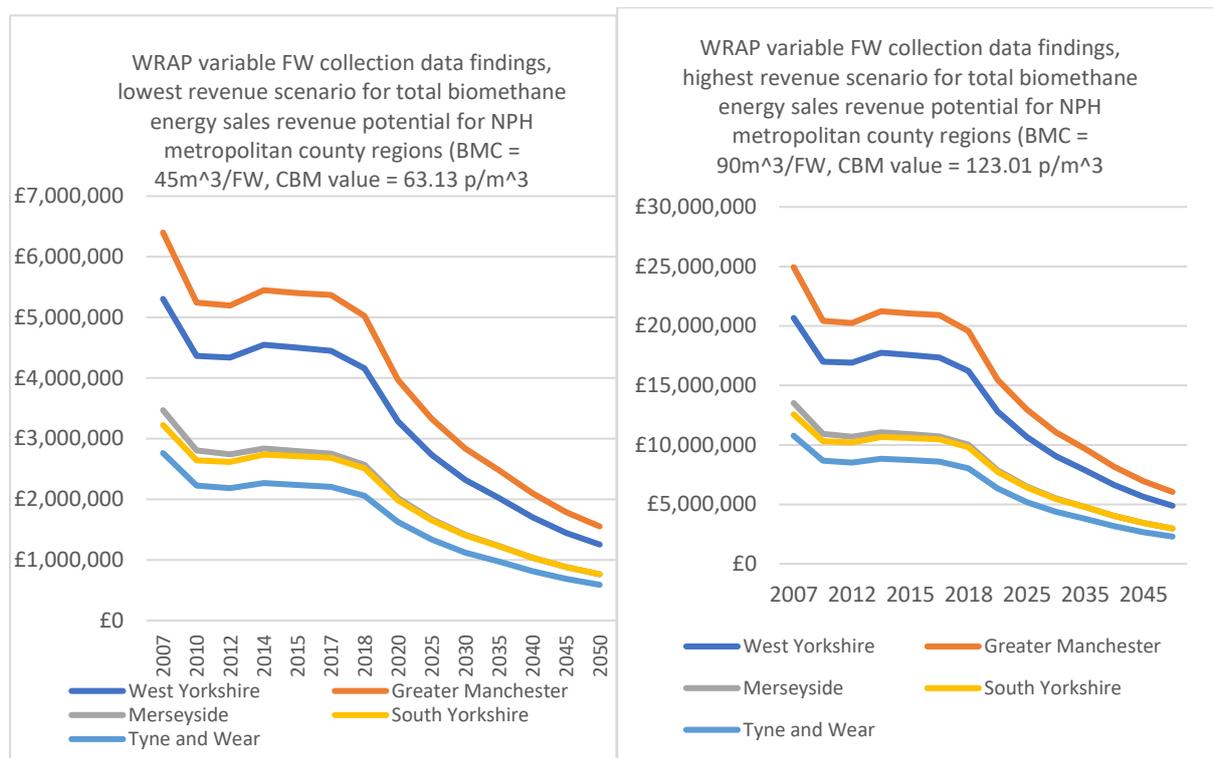


Figure 190. Compressed Biomethane (CBM) sales revenue potential scenario – Using WRAP variable FW collection data for all NPH metropolitan county regions, illustrating lowest (left) and highest (right) total revenue generation potential scenarios as determined by biomethane conversion yield and unit sales value of CBM (see figure heading for details) (see Appendix table 59 and Appendix table 60)

6.2.1h CBM sales revenues - WRAP and WDF variable NPH city region and metropolitan county region FW collection data comparisons and trends

Here a comparison between total CBM sales revenue between WDF and WRAP data for NPH city and metropolitan county regions demonstrates a greater initial CBM sales revenue potential for WRAP in 2010, which declines at an exponentially greater rate to achieve approximate similar values to that of WDF revenue potential value in 2050. This again to reiterate, is due to the CBM sales revenue potentially being proportional to total FW collected for digestion under the WRAP and WDF variable FW collection scenario, in which both FW collection per individual and CBM unit sales pricing is fixed. An example of this includes comparison of WDF and WRAP lowest and highest CBM revenue potential scenarios for both the NPH city and metropolitan county regions, (see Figure 187, Figure 188, Figure 189 and Figure 190 above), which is summarized in Table 161 below.

Table 161. Comparison of highest and lowest CBM sales revenue potential data between WDF and WRAP scenarios for 2010 and 2050.

		Lowest 2010	Highest 2010	Lowest 2050	Highest 2050
NPH city	WDF (Leeds)	£1,020,000	3,970,000	£430,000	£1,680,000
	WRAP (Leeds)	£1,800,000	£7,040,000	£450,000	£1,750,000
	WDF (Newcastle)	£374,000	£1,460,000	£151,000	£588,000
	WRAP (Newcastle)	£685,000	£2,670,000	£159,000	£620,000
	WDF (Greater Manchester)	£3,620,000	£14,111,000	£1,490,000	£5,808,000

NPH metropolitan county	<i>WRAP (Greater Manchester)</i>	<i>£6,399,000</i>	<i>£24,938,000</i>	<i>£1,552,000</i>	<i>£6,048,000</i>
	<i>WDF (Tyne and Wear)</i>	<i>£1,494,000</i>	<i>£5,821,000</i>	<i>£559,000</i>	<i>£2,178,000</i>
	<i>WRAP (Tyne and Wear)</i>	<i>£2,763,000</i>	<i>£10,766,000</i>	<i>£589,000</i>	<i>£2,297,000</i>

These demonstrate for NPH Leeds city region, the lowest 2010 CBM sales revenue potential scenario value for WRAP is estimated to be £1,800,000, which is significantly greater than the estimated WDF value of £1,020,000. Both values respectively declines to £450,000 and £430,000 respectively, reaching almost parity in their values. Likewise, the highest 2010 CBM sales revenue potential scenario value for WRAP is estimated to be £7,040,000, which is significantly greater than the estimated WDF value of £3,970,000. Here again both values respectively declines to £1,750,000 and £1,680,000 respectively, reaching almost parity in their values. The same applies for all other WDF and WRAP NPH city and metropolitan county regions under both high and low CBM sales revenue potential scenarios.

To this end, it is worth noting that under all WDF and WRAP NPH city and metropolitan county scenarios, this trend of exponential decay overtime from 2010 to 2050 in total CBM revenue, there exist significantly strong revenue potential in the highest revenue potential scenario. By contrast, the lowest revenue potential scenario indicates the need for additional FW supply for the generation of extra CBM to ensure they are sufficiently robust to justify continued deployment of the FWtTBC pathway to achieve adequate return on investment values.

This is especially evident in regions where existing infrastructure, i.e. FW collection, AD plant station and transport refuelling stations, are in place for the full deployment of FWtTBC pathway, where the remaining critical barriers of deployment would be certainty of FW supply and financial returns on investment. As with the analysis conducted within the scope of this study, it would involve the NPH Leeds city or West Yorkshire metropolitan county region for which known AD infrastructure and FW feedstock intake capacity is available.

Consequently, the next section further outlines CBM sales revenue findings arising from a single large AD plant (Maltings Organics Treatment Facility or MOTF) with sufficient capacity to accommodate for all annual FW derived from the NPH Leeds city region. The results will be used to inform suitable government supporting policies for mitigating any potential feedstock uncertainty and financial revenue risks of FWtTBC pathway deployment (applicable to Leeds and other NPH city and metropolitan county regions) as elucidated in this section.

6.2.1i CBM sales revenues – for Maltings Organics Treatment Facility (MOTF)

Below outlines CBM generation potential from all highest and lowest fixed and variable FW collection scenarios (accounting for biomethane conversion yields and CBM sales prices from refuel station) to Maltings Organics Treatment Facility (MOTF) AD plant only assuming for full annual capacity utilization. This is due to that MOTF AD plants satisfies all conditions for accommodate locally collected FW from Leeds city region (across different districts and towns) and constitutes a perfect example AD plant from which all cost and financial values can be based on to estimate useful financials for strategizing potential deployment of additional AD plants or expansion of current ones.

Here key assumptions includes that MOTF plant is operating at maximum dedicated FW intake capacity of 50,000 tonnes, and combined capacity of 82,500 tonnes (including additional

32,500 tonnes capacity reserved for other wastes). This in context of above fixed and variable FW collection scenarios, estimate that by using its dedicated FW capacity alone, MOTF can accommodate for total FW collected from between:

1. Population of 500,000, 1,000,000 or 2,500,000 (using assumed fixed FW collection scenarios of 20, 40 or 100 kg/person/year, respectively)
2. Population of 680,000 to 2,900,000 (using time-adjusted variable WRAP and WDF FW collection scenarios of 2010 and 2050, respectively).

This consequentially outlines how real-world household FW production and collection would have significantly impact the total population which MOTF could accommodate by using its dedicated FW intake capacity, which ranges between 500,000 to 2,900,000 across all scenarios. What is clear however is that MOTF at full or near full dedicated FW intake capacity utilization would be able to accommodate for at least a majority of household FW (approx. 56%-90%) produced by the entire Leeds population (700,000 to 890,000 in 2010-2050) even at the lower end of the estimation, At higher end of this estimation , the dedicated FW intake capacity can potentially accommodate for the entire population of NPH West Yorkshire region which has an estimated population of 2-2.5 million in 2010-2050. It is also important to note that should MOTF choose to utilize its remaining 32,500 tonnes capacity that are typically reserved for non-FW intakes for FW intake, then it will have an further 65% increase FW intake capacity to accommodate for FW collected across Leeds and West Yorkshire regions.

Here the calculation for estimating Maltings Organics total household FW derived (Compressed Biomethane) CBM revenue generation potential applies the below basic equation for each waste stream on a total AD plant capacity basis and in consideration of potential fixed fuel price adjustments from the base price (for reasons outlined in section 5.4.2.1a):

Total CBM revenue sales = Total FW Quantity (Tonnes) x FW to biomethane Yield (where BMC = 90m³ or 45m³) x CBM unit sales value (63.13p/m³ or £98.41p/m³)

To breakdown this calculation first the existing sales revenue values from CBM derived per tonne of FW is established by the equation (with results outlined in Table 162, Table 163 and Table 164):

CBM revenue per tonne of FW (£) = FW to biomethane conversion Yield (where BMC = 90m³, 67.50m³ or 45m³) x CBM unit sales value (63.13p/m³ or £98.41p/m³) / 100

Table 162. CBM sales revenue values per tonne of FW as calculated by multiplying FW to biomethane conversion yield by CBM unit sales value (low FW to biomethane conversion scenario of BMC = 45m³/t)

Station Size	2011 baseline values			10% increase			25% increase		
	CBM	LBM	LCBM revenue (p/t FW)	CBM	LBM	LCBM revenue (p/t FW)	CBM	LBM	LCBM revenue (p/t FW)
(kg/day)	revenue (p/t FW)	revenue (p/t FW)		revenue (p/t FW)	revenue (p/t FW)		revenue (p/t FW)	revenue (p/t FW)	
500	£44.28	£46.17	£54.11	£48.71	£50.79	£59.52	£55.35	£57.72	£67.64
1,000	£35.97	£40.50	£45.42	£39.56	£44.55	£49.96	£44.96	£50.63	£56.77
2,000	£31.81	£37.86	£42.77	£34.99	£41.64	£47.05	£39.76	£47.32	£53.46
5,000	£29.16	£35.21	£40.13	£32.08	£38.73	£44.14	£36.45	£44.01	£50.16
10,000	£28.41	£34.83	£38.24	£31.25	£38.32	£42.06	£35.51	£43.54	£47.79

Table 163. CBM sales revenue values per tonne of FW as calculated by multiplying FW to biomethane conversion yield by CBM unit sales value (medium FW to biomethane conversion scenario of BMC = 67.50m³/t)

Station Size	2011 baseline values			10% increase			25% increase		
	CBM	LBM	LCBM revenue (p/t FW)	CBM	LBM	LCBM revenue (p/t FW)	CBM	LBM	LCBM revenue (p/t FW)
(kg/day)	revenue (p/t FW)	revenue (p/t FW)		revenue (p/t FW)	revenue (p/t FW)		revenue (p/t FW)	revenue (p/t FW)	
500	£66.43	£69.26	£81.17	£73.07	£76.19	£89.28	£83.03	£86.58	£101.46
1,000	£53.95	£60.76	£68.13	£59.35	£66.83	£74.94	£67.44	£75.94	£85.16
2,000	£47.72	£56.79	£64.16	£52.48	£62.46	£70.57	£59.64	£70.98	£80.20
5,000	£43.75	£52.82	£60.19	£48.12	£58.10	£66.20	£54.68	£66.02	£75.24
10,000	£42.61	£52.25	£57.35	£46.87	£57.48	£63.09	£53.26	£65.31	£71.69

Table 164. CBM sales revenue values per tonne of FW as calculated by multiplying FW to biomethane conversion yield by CBM unit sales value (medium FW to biomethane conversion scenario of BMC = 90m³/t)

Station Size	2011 baseline values			10% increase			25% increase		
	CBM	LBM	LCBM revenue (p/t FW)	CBM	LBM	LCBM revenue (p/t FW)	CBM	LBM	LCBM revenue (p/t FW)
(kg/day)	revenue (p/t FW)	revenue (p/t FW)		revenue (p/t FW)	revenue (p/t FW)		revenue (p/t FW)	revenue (p/t FW)	
500	£88.57	£92.35	£108.23	£97.43	£101.58	£119.04	£110.71	£115.43	£135.28
1,000	£71.94	£81.01	£90.84	£79.13	£89.11	£99.92	£89.92	£101.26	£113.54
2,000	£63.62	£75.72	£85.55	£69.98	£83.29	£94.10	£79.52	£94.64	£106.93
5,000	£58.33	£70.43	£80.25	£64.16	£77.46	£88.27	£72.91	£88.03	£100.31
10,000	£56.82	£69.67	£76.47	£62.50	£76.64	£84.11	£71.02	£87.08	£95.59

Below outlines total CBM sales revenue values from AD in case of low, medium and high FW to biomethane conversion scenarios (BMC = 45, 67.50 and 90m³/t FW, respectively) in both table for establishing potential revenue attainable from MOTF assuming for full capacity utilization. These comparisons applies the highest and lowest CBM sales value (£44.28 t/FW and £28.1 t/FW respectively) across all relevant scenarios as shown in respective table below (see the second row).

Table 165. Estimated total CBM sales revenue generation values from Maltings Organics Treatment Facility (MOTF) AD plant (for low FW to biomethane conversion scenario of BMC = 45m³/t)

Waste type	Feedstock capacity (tonnes/year)	Normal scenario		10% Price increase		25% price increase	
		Highest CBM unit sales price (£44.28 t/FW)	Lowest CBM unit sales price (£28.41 t/FW)	Highest CBM unit sales price (48.71 t/FW)	Lowest CBM unit sales price (£31.25 t/FW)	Highest CBM unit sales price (£55.35 t/FW)	Lowest CBM unit sales price (£35.51 t/FW)
FW	50,000	£2,214,000	£1,420,500	£2,435,400	£1,562,550	£2,767,500	£1,775,625
Other waste	32,500	£1,439,100	£923,325	£1,583,010	£1,015,658	£1,798,875	£1,154,156
FW+ Other waste	82,500	£3,653,100	£2,343,825	£4,018,410	£2,578,208	£4,566,375	£2,929,781

Table 166. Estimated total CBM sales revenue generation values from Maltings Organics Treatment Facility (MOTF) AD plant (for medium FW to biomethane conversion scenario of BMC = 67.50m³/t)

Waste type	Feedstock capacity (tonnes/year)	Normal scenario		10% Price increase		25% price increase	
		Highest CBM unit sales price (£44.28 t/FW)	Lowest CBM unit sales price (£28.41 t/FW)	Highest CBM unit sales price (48.71 t/FW)	Lowest CBM unit sales price (£31.25 t/FW)	Highest CBM unit sales price (£55.35 t/FW)	Lowest CBM unit sales price (£35.51 t/FW)
FW	50,000	£3,321,000	£2,130,750	£3,653,100	£2,343,825	£4,151,250	£2,663,438
Other waste	32,500	£2,158,650	£1,384,988	£2,374,515	£1,523,486	£2,698,313	£1,731,234
FW+ Other waste	82,500	£5,479,650	£3,515,738	£6,027,615	£3,867,311	£6,849,563	£4,394,672

Table 167. Estimated total CBM sales revenue generation values from Maltings Organics Treatment Facility (MOTF) AD plant (for high FW to biomethane conversion scenario of BMC = 90m³/t)

Waste type	Feedstock capacity (tonnes/year)	Normal scenario		10% Price increase		25% price increase	
		Highest CBM sales (£44.28 t/FW)	Lowest CBM sales (£28.41 t/FW)	Highest CBM sales (£48.71 t/FW)	Lowest CBM sales (£31.25 t/FW)	Highest CBM sales (£55.35 t/FW)	Lowest CBM sales (£35.51 t/FW)
FW	50,000	£4,428,000	£2,841,000	£4,870,800	£3,125,100	£5,535,000	£3,551,250
Other waste	32,500	£2,878,200	£1,846,650	£3,166,020	£2,031,315	£3,597,750	£2,308,313
FW+ Other waste	82,500	£7,306,200	£4,687,650	£8,036,820	£5,156,415	£9,132,750	£5,859,563

These values collectively suggest for annual biomethane sales revenue potential to be significant at both the lower and higher ranges at MOTF, which ranges from £2,214,000 to £4,428,000 (highest CBM unit sales price scenario) and £1,420,500 to £2,343,825 (lowest CBM unit sales price scenario) for the baseline FW capacity utilization only scenario. This total CBM sales revenue extends further to £3,643,100 to £7,306,200 (highest CBM unit sales price scenario) and £2,343,825 to £4,687,650 (lowest CBM unit sales price scenario) when accounting for utilization of FW and other waste capacity at MOTF. These CBM sales revenue values is further increased by 10% and 25% respectively under reasonable assumptions of normal CBM unit sales prices in 2020.

Here a more stark contrast in total revenue potential can be seen between highest to lowest value comparisons accounting for discrepancies in all 3 factors of BMC (45, 67.50 or 90m³/t FW), waste capacity inclusion (FW or FW + Other waste) and CBM unit sales prices (baseline revenue, 10% increase, 25% increase). Here the highest MOTF CBM revenue potential of 5,859,563 (BMC = 90m³/t FW, FW + Other waste, 25% price increase) is seen to be more than 4 times greater than that of the lowest MOTF BCM revenue potential of £1,420,500 (BMC = 45m³/t FW, FW only, baseline revenue), with these results evidently highlighting the importance each metric's inherent value towards affecting the final CBM revenue output (Figure 191).

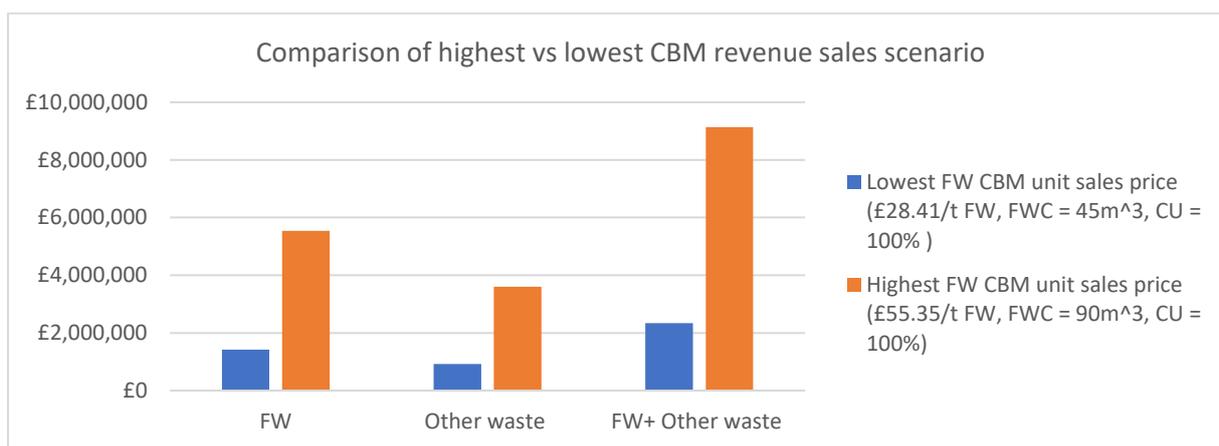


Figure 191. Comparison of highest vs lowest CBM revenue sales values attainable by MOTF at full capacity utilization or operation

Within context of real world factors, these estimated values of total CBM revenue will be subject to a number of key challenges in both the near and long term. In the near term, these include less than 100% real world operational capacity (typically 50-85%), which would proportionally reduced the production of biomethane for conversion to CBM for sale. As evident in Figure 192, this proportional reduction can be significant relative to each individual

(i.e. MOTF in this scenario) AD plant's ability to achieve its maximum CBM sales revenue potential. Also it would be assumed that the conversion process may also create some level of energy loss (though not investigated) that are translatable to sales revenue loss.

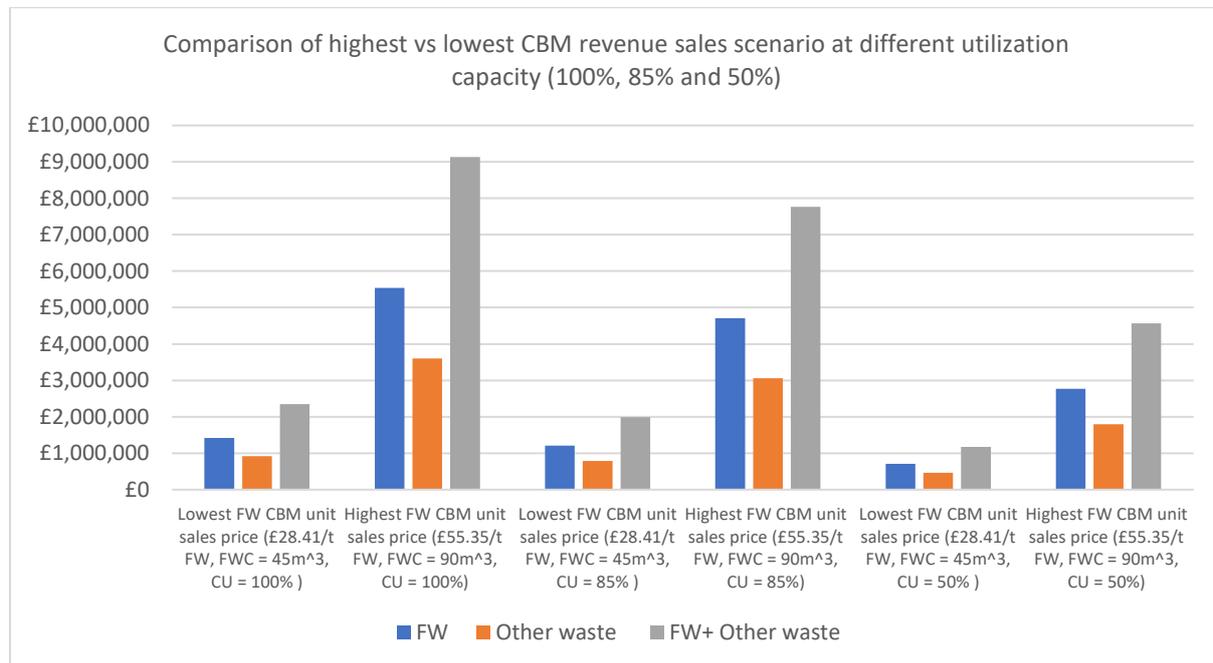


Figure 192. Comparison of highest vs lowest CBM revenue sales values attainable by MOTF at different levels of capacity utilization or operation (100%, 85% or 50%)

For the distant future, the anticipated challenges would relate more to feedstock supply should household FW collection data trends from WRAP and WDF hold true to indicate consistent and cumulative decline in the overall quantity of household FW available for collection across Leeds and most UK LA regions. Although beyond the scope of coverage under this section and research, it is worth noting that further potential adjustments such as price inflation and increased costs of operations could also significantly alter new or existing AD plant infrastructure investment and operational decisions for FWtTBC pathway deployment, as many operators will likely opt for lower risk operational routes, such as collection of commercial and industrial or other FW which exhibits trend in consistent supply and yields equal if not greater biomethane yield and potential.

The cumulative effects of each of these potential financial risks will consequently need to be mitigated and addressed by a suite of suitable government policies outlined in Table 168 below to promote dedicated long term participation from AD operators and suitable investors for deploying the FWtTBC pathway in a manner that is both scalable and profitable.

Table 168. Summary of policies designed to mitigate FWtTBC pathway deployment from a CBM sales revenue generation perspective

	Government Policy recommendation	Goals
1	Provide conditional funding and loan for conducting practices and procedures to improve their utilization capacity above suitable levels (i.e. to beyond 85%)	Help achieve greater AD operating practice to increase overall revenue
2	Provide conditional funding, loan and networking support for all AD operators to ensure they are cross accommodate intake of FW where suitable from a variety of sources,	Help achieve robust FW supply across single AD operator or between AD networks to

	including but not limited to household, commercial and industrial sources	mitigate against risk of potential FW undersupply in the future
3	To provide guarantee on the minimum sales price of biomethane (either as CBM, LBM or LCBM) or provided added incentive per unit sale of biomethane	Mitigate risk of of revenue loss from declining energy prices

Amongst these policy recommendations, the provision of government incentives on biomethane sales price is deemed to be the most direct but also costly intervention, as it would directly increase sales revenue of CBM, though with the caveat of it does not directly promote improvement in AD operational practices or mitigate for external risks of potential decline in FW supply that may prove to be a possibility in the foreseeable medium to long term future.

Consequently, the conditional funding and support in form of loan or investments to enable AD operators to adopt better operational and logistical practices to increase its own utilization capacity and flexible network of FW suppliers is also important if not essential for commanding long term business confidence in the financial viability of FWtTBC pathway deployment from the perspective of each relevant AD operators.

6.2.1j Summary, limitations and further research

The above findings collectively outline the full range of possible CBM sales revenue generation potential across NPH city region and for Maltings Organics Treatment Facility (MOTF) AD plant for all (fixed and variable) FW collection scenarios. The findings suggest a huge revenue range attainable across both fixed and variable scenarios of FW collection, with latter believed to be more accurate in portraying future real-world FW collection trend.

Here the findings suggest that revenue from CBM sales although appear to be adequate towards justifying AD operation as part of the FWtTBC pathway deployment process, the relevant real world risks of reduced AD operational capacity utilization, medium to long term FW feedstock availability and CBM unit sales prices should warrant caution and potential government policy intervention for their mitigation, as they would contribute substantially to the total CBM sales revenue output. The findings additionally suggest for such policy interventions to be direct as seen with case of added financial incentives towards sales of biomethane, or indirect via form of conditional loans or investments towards promoting improvements in AD operator practice that would enable it to achieve greater utilization capacity and FW supply network.

The findings are however limited by several that should serve to be the foundation of future integrated research. The first would be the relatively limited dataset used for biomethane sales value (2011 data), FW collection (limited WRAP and WDF data points) and biomethane conversion (BMC) yield (3 fixed levels attained from over 130 literature data), which could significantly affect the end outcome in final combined CBM sales revenue. However, the study did account for various assumptions to give a range of results for accommodating this abovementioned weakness. Other limitations include the input of case specific data from the AD operator, MOTF itself, such as its FW utilization capacity and unit sales price of biomethane produced, which could further contribute to the accuracy of the estimated CBM revenue sales findings to help better inform government policy decision making.

It is therefore advised for future studies on estimating CBM sales revenues to cooperate directly with relevant key stakeholders (MOTF, Leeds LA), which this study has not been completely successful in doing so despite repeated reach out attempts to ensure that both the input and output data more robust and completely representative of the local FWtTBC pathway deployment scenario. This can be done by adopting the analytical and calculation approach developed above, or through further suitable refinements in the above method tailored for such studies.

It is ultimately worth noting however, that the sales of biomethane constitute only one revenue stream, with additional sources being revenue derived from the adoption of Renewable Transport Fuel Certificate and landfill tax avoided. These are outlined in respective sections below to help further elucidate the overall revenue attainable from (which would help attribute often overlooked value to) all household FW collected through the deployment of the FWtTBC pathway.

6.2.2 Renewable Transport Fuel Certificate income revenues

6.2.2a RTFC tariff revenue base data - used for transport biomethane revenue calculations

Here revenue from RTFC incentives is calculated on basis of price per certificate x number of certificates reclaimable per kg of renewable transport fuel used, which for CBM derived from household FW constitutes 3.8 certificates per kg consumed (Ricardo-AEA, 2015). These calculations are made below using a lower, medium and upper RTFC value scenario of 20p, 30p and 40p per certificate to account for potential future price changes using RTFC values between 2017 and 2020 as a base reference under the assumption of certificate prices to face upward increase for the foreseeable future (Figure 193).

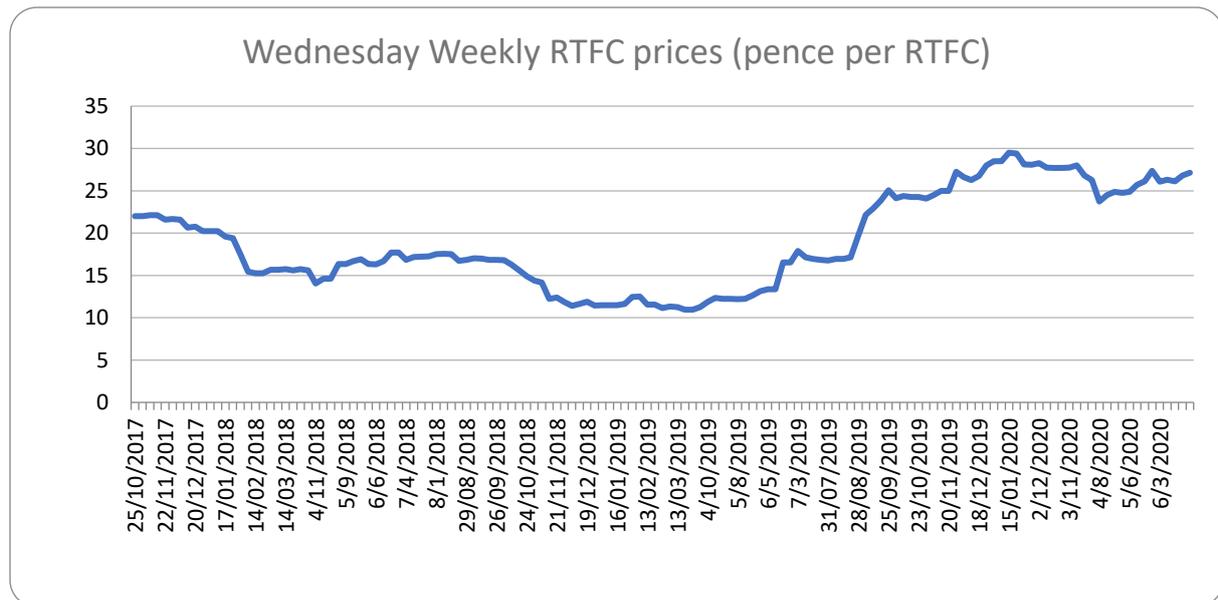


Figure 193. Weekly Renewable Transport Fuel Certificate price data from Energy census (Census, 2020)

The methodology presents the evident limitation of using a fixed RTFC value instead of weekly RTFC values as shown in Figure 193 which would give rise to more accurate results as their values are typically not strictly fixed and are accounted for by the RTFC holder at the time of redemption. To this end, the researcher also notes it being unfeasible at this time, given insufficient RTFC data, to apply weekly RTFC revenue values for estimating total RTFC values between 2010 and 2050 with sufficient confidence, thus concluding with the use of 3 fixed RTFC values as stated above.

6.2.2b RTFC tariff Revenues - all NPH city regions, fixed (20, 40 and 100 kg/person/year) FW collection data scenario

Using fixed FW collection data for RTFC calculations, results for NPH Leeds city region interesting exhibits a much greater and more consistent income generation potential of between to 338,000 to 6,754,000 in 2001 and 429,000 to 8,579,000 in 2050 (for lowest and highest RTFC revenue scenarios respectively), with the increase attributed mostly to gradual increases in population throughout the same period based on ONS data.

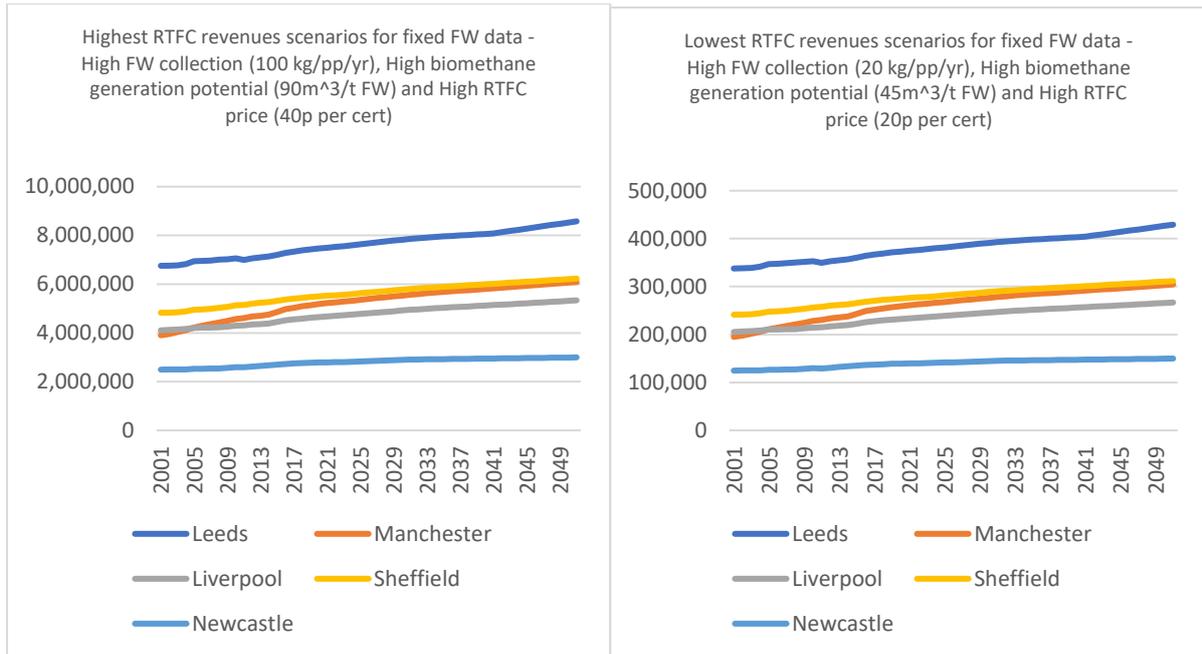


Figure 194. CBM RTFC certificate revenue potential scenario 1 - Using fixed FW collection data, showing highest (left) and lowest (right) total RTFC revenue generation potential scenarios as determined by FW collection of 20, 40, 100 kg/person/year, biomethane conversion yield (90/45m³) and RTFC value (40/20p per certificate) (see figure heading for details)

6.2.2c RTFC tariff Revenues - all NPH city regions, variable (WRAP and WDF data) FW collection data scenario

Using variable WRAP collection data for RTFC calculations, results for NPH Leeds city region interesting exhibits a much greater and more consistent income generation potential of between £1,300,000 to £5,200,000 in 2010 at its peak and £390,000 to £1,600,000 in 2050, with the decline attributed mostly to decrease in FW collection between 2010-2050 (Fig. 195).

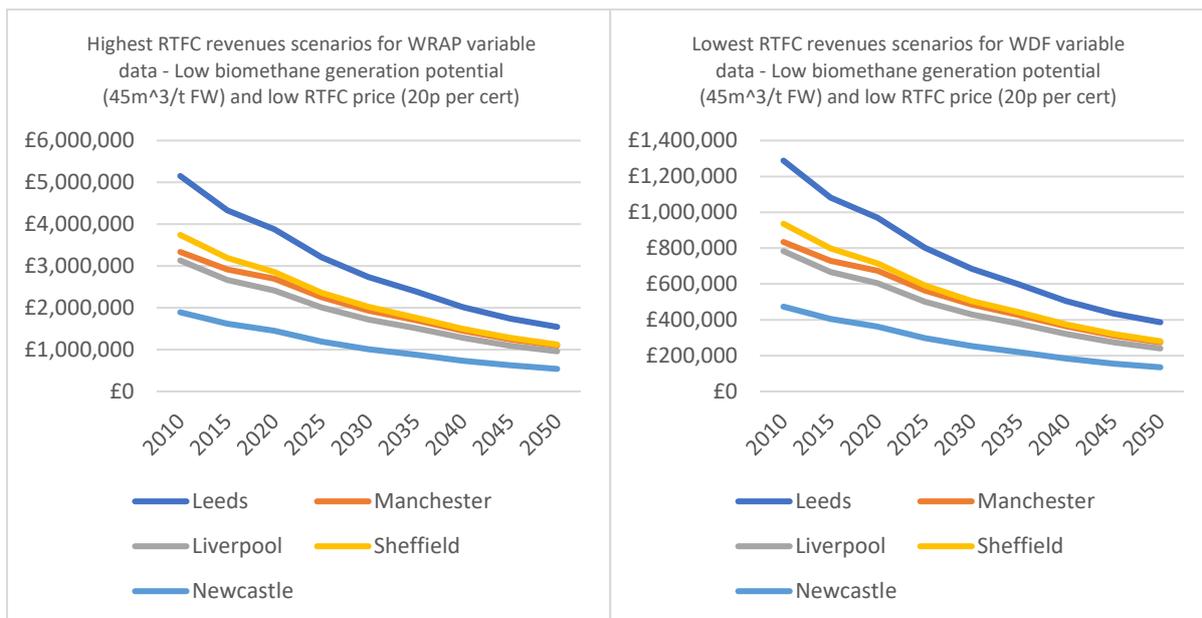


Figure 195. CBM RTFC certificate revenue potential scenario 2.1 - Using WRAP variable FW collection data, showing highest (left) and lowest (right) total RTFC revenue generation potential scenarios as determined by biomethane conversion yield (90/45m³) and RTFC value (40/20p per certificate) (see figure heading for details)

Using variable WDF collection data for RTFC calculations, results for NPH Leeds city region interestingly exhibits a much greater and more consistent income generation potential of between £805,000 to £3,250,000 in 2010 at its peak and £370,000 to £1,450,000 in 2050, with the decline attributed mostly to decrease in per capita FW collection between 2010-2050 (Figure 196).

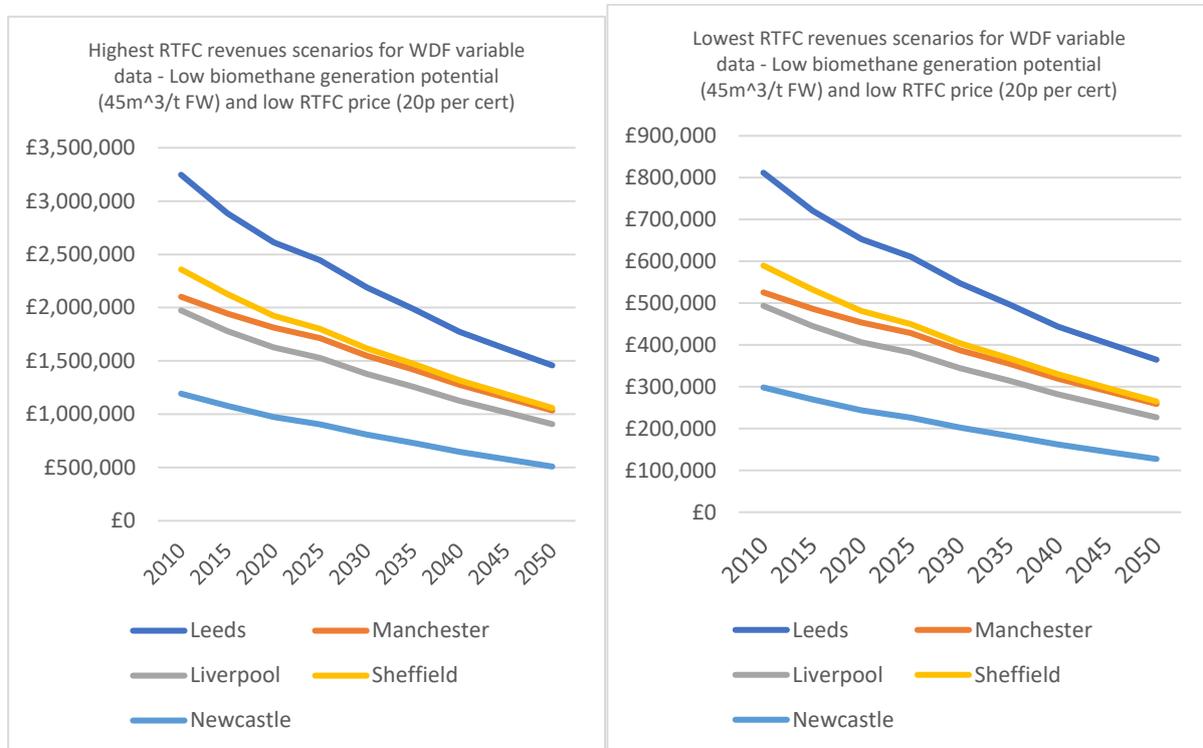


Figure 196. CBM RTFC certificate revenue potential scenario 2.2 - Using WDF variable FW collection data, showing highest (left) and lowest (right) total RTFC revenue generation potential scenarios as determined by biomethane conversion yield (90/45m³) and RTFC value (40/20p per certificate) (see figure heading for details)

Again, here it is worth noting the general trend of declining RTFC values across both scenarios are attributed to sharp decline in FW collection that is negligibly offset by slight increase in total population over the relevant 2010-2050 scenario period.

6.2.2d RTFC tariff Revenues – for Malting Organic AD plant only

Here the same revenue calculation scenarios apply to MOTF AD plant for determining the range of RTFC revenue generation potential. These are again carried out under the assumptions of full yearly capacity operation at MOTF, and by utilizing either FW capacity alone or total combined waste capacity for CBM generation and use in suitable transport vehicles, at point which the RTFC can be reclaimed at the stipulated values (of 20, 30 and 40 pence per certificate).

All findings apply the standard equation of (see Table 169 for details): FW (t) × Biomethane yield (m³/t) × Biomethane to CBM conversion yield (m³/kg) × RTFC value (p/kg) × RTFC certificate claimable per kg of CBM used (no units) = Total RTFC revenue

Table 169. Table of calculations for highest and lowest RTFC revenue generation potential at Maltings organics based on individual waste stream capacities

Scenario	FW only		Other waste		FW+Other waste		Interim output description
	Highest	Lowest	Highest	Lowest	Highest	Lowest	
FW (t)	50,000	50,000	35,000	35,000	85,000	85,000	Total FW capacity
Biomethane yield (m ³ /t)	90	45	90	45	90	45	Total biomethane yield
Conversion yield to CBM (m ³ /kg)	0.7	0.7	0.7	0.7	0.7	0.7	Total CBM yield
RTFC (£/kg)	40	20	40	20	40	20	Total RTFC revenue (without appropriate multiplier adjustment)
RTFC certificate claimable per kg CBM used (no units)	3.8	3.8	3.8	3.8	3.8	3.8	Multiplier adjustment for FW derived CBM
Total RTFC revenue (£m)	£4,79m	£1,20m	£3,35m	£0.84m	£8,14m	£2,03m	Total RTFC revenue

Here it is worth noting that fixed individual RTFC certificate values and FW to biomethane conversion yields here constitutes the sole factors affecting total RTFC revenue generation, which leads to a maximum to minimum RTFC value discrepancy of 400% (200% attributed to each of biomethane conversion yield and RTFC value discrepancy).

Table 170. MOTF plant capacity and the relevant estimated RTFC revenue generation potential.

	Plant capacity (t/year)	Estimation range	RTFC revenue generation potential
FW only	50,000	Highest	£4,788,000
	50,000	Lowest	£1,197,000
Other waste	32,500	Highest	£3,351,600
	32,500	Lowest	£837,900
FW+Other waste	82,500	Highest	£8,139,600
	82,500	Lowest	£2,034,900

Below outlines all significant RTFC revenue generation scenarios in context of maximum and minimum value achievable based on data and assumptions used in this study (see Figure 197 and Figure 198).

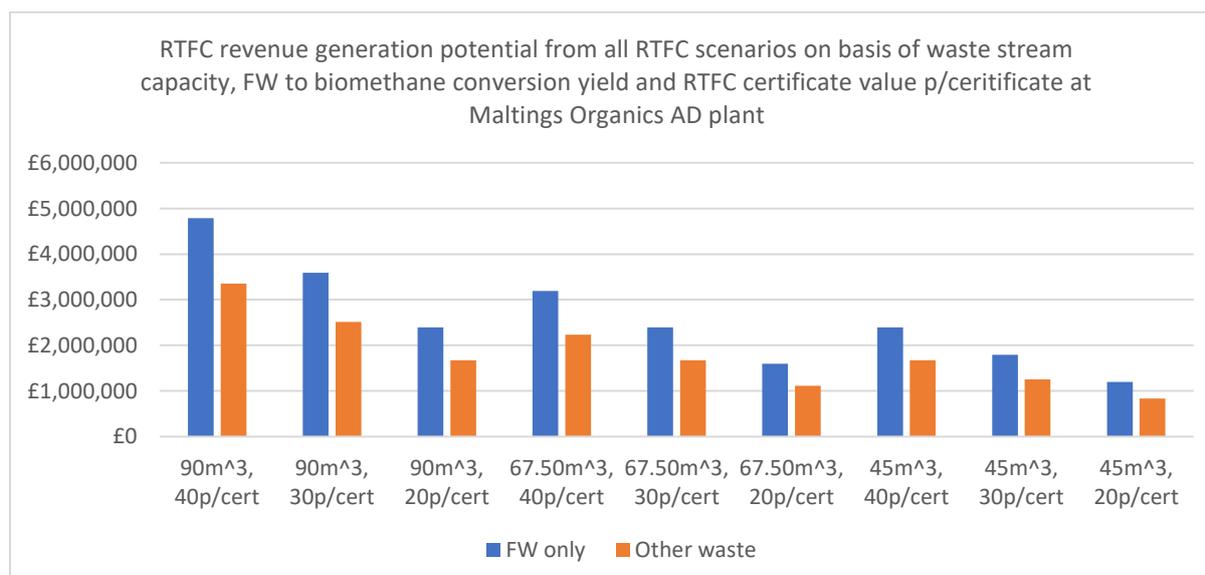


Figure 197. Range of all RTFC revenue generation potential at Maltings organics based on individual waste stream capacities, with highest and lowest generation potential shown on the most left and right graph sections, respectively. Showing values for FW and Other waste streams individually.

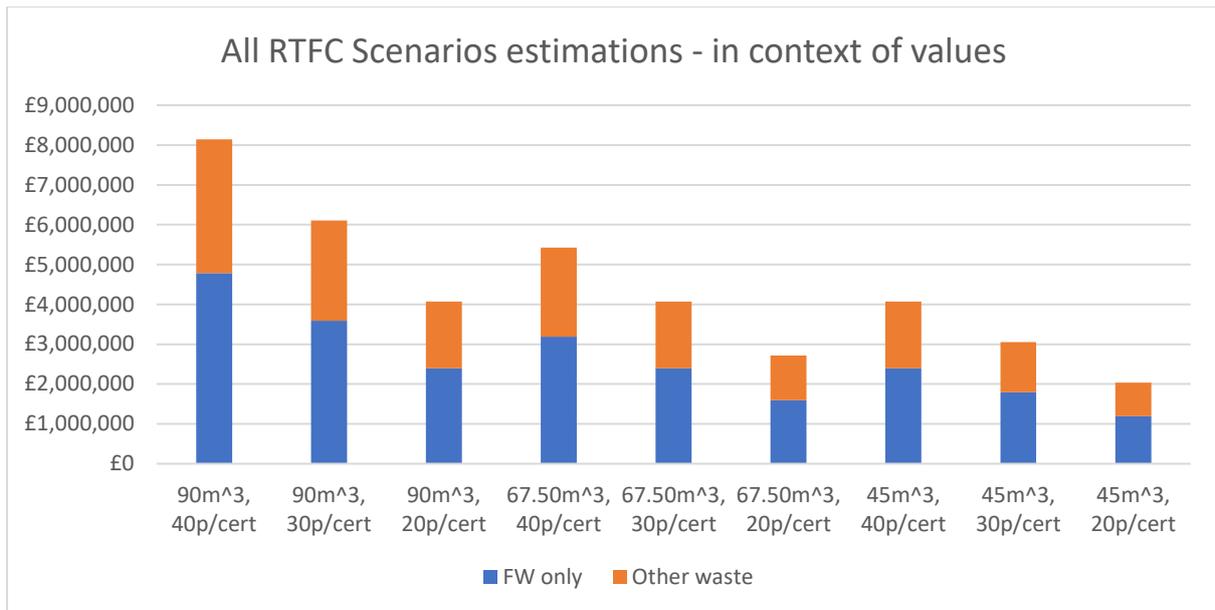


Figure 198. Range of all RTFC revenue generation potential at Maltings organics based on individual waste stream capacities, with highest and lowest generation potential shown on the most left and right graph sections, respectively. Showing stacked values from FW and Other waste streams.

Here findings for Maltings Organic AD plant demonstrate significant RTFC revenue generation potential across all scenarios, with even the lowest revenue scenario yielding a over £1 million revenue derived from utilizing FW capacity alone (of 50,000 tonnes/year), and with higher revenue generation scenarios account for over £4,500,000 (FW feedstock only) and £8,000,000 (total combined feedstock) respectively. Here it is important to note that these revenues are relatively sensitive to price fluctuations of RTFC certificate, and FW to biomethane conversion yield (BMC), with the lowest revenue scenario of BMC = 45m³/t/FW and 20p/cert to be 4 times lower in total revenue returns (£2,000,000) than the highest revenue scenario of BMC = 90m³/t FW and 40 p/cert (£4,000,000).

These revenues are similar to revenue attainable from CBM sales revenue at MOTF under the similar assumption of full capacity utilization, which is between £1,420,000 to £5,350,000 for FW only and £2,343,825 to £9,132,750 for combined total (FW + Other) waste input.

6.2.2e RTFC summary, policy recommendations and limitation

For ensuring sufficient price certainty of RTFC, suitable policy recommendations should be tailored towards mitigating extreme price fluctuations as seen with between the 2017 to 2020 data, where the lowest and the highest RTFC was shown to be 10 p/cert and 30 p/cert respectively (with a 300% impact on total RTFC revenue alone). This is especially important under scenarios of low CBM sales revenue (see above section 6.2.1 for details) to ensure at least one pillar of revenue income derived from FWtTBC pathway deployment for transport biomethane utilization is secured. These policies are more specifically summarized in Table 171 below.

Table 171. Policy recommendation for mitigating risk of RTFC price fluctuations to promote FWtTBC pathway deployment

	Policy recommendation	Goal
1	To promise specific buyout value (as to be determined pending further discussion key stakeholders) of RTFC in case of extreme RTFC market price fluctuations to ensure such fluctuations are within tolerable limits	Mitigate risk of extreme revenue losses from extreme and unpredictable RTFC price fluctuations that could deter FWtTBC pathway deployment for transport biomethane deployment – either through external intervention or internal market mechanism, or combination thereof
2	To enable market mechanism that would allow greater flexibility of RTFC trading to allow market to better mitigate risk of large RTFC price fluctuations	
3	To provide additional financial incentives for RTFC rollout that increases as unit price value of biomethane decreases	Mitigate risk against low biomethane sales prices to ensure sufficient balance of revenue is achieved through both sales of biomethane and RTFC
4	Offer significant financial or non-financial support schemes to enhance joint real world collaboration schemes between AD operators and research institutions such as universities to better share RTFC data where deemed suitable for researching more effective policies for FWtTBC pathway deployment (in addition to abovementioned policies 1-3).	Remove barriers for future collaboration efforts between various players of the FWtTBC pathway deployment to ensure effective sharing of critical data that could lead to faster and more effective policy support implementation to support development of the entire FWtTBC pathway

Key limitations arising from estimating the RTFC revenue values mainly come from the inconsistent RTFC values throughout the duration of 2017 to 2020 in which data is available, which makes a consistent RTFC value trend projection for the foreseeable future impossible. The study also only takes a point in time snapshot for potential revenue derived from RTFC at lowest, medium and highest values (of 20p/cert, 30 p/cert and 40p/cert respectively) which is useful in outlining the extreme revenue values attainable, but is not entirely reflective of the attainable RTFC values from a real world scenario.

The latter will more likely adopt the mean RTFC value attained from each unit of biomethane sales, which will vary depending on the generation and RTFC sale patterns of each individual AD operator, and consequently, its estimation will inevitably require close collaboration with MOTF or other AD suitable operators for attaining these relevant albeit highly sensitive financial data. This to-date is likely to be a large barrier which many research institutions and AD operators face (as is the case with this research project) and should be critically addressed through targeted government policy support to ensure more accurate data across all fronts (with regard to determining RTFC and all other FWtTBC pathway technical metric values) can be obtained.

The next section outlines avoided cost of FW landfill, and their respective contribution to the overall potential revenue attainable in form of avoided landfill tax expenditure.

6.2.3 Revenue from Landfill tax avoided

6.2.3a Landfill tax avoided revenue data

The significantly elevated government focus on landfill of avoidable wastes is reflected in the relatively sharp rate of increase in the cost of landfill of FW, i.e. from £84.40/tFW in 2016 to £98.60/tFW in 2022 (see Table 172).

Table 172. Table of landfill taxes between 2019 and 2021

	Standard rate (applicable to FW)	Lower rate
Rates from 1 April 2022	£98.60/tonne	3.15/tonne
Rate from 1 April 2021	£96.70/tonne	£3.10/tonne
Rate from 1 April 2020	£94.35/tonne	£3.00/tonne
Rate from 1 April 2019	£91.35/tonne	£2.90/tonne
Rate from 1 April 2018	£88.95/tonne	£2.80/tonne
Rate from 1 April 2017	£86.10/tonne	£2.70/tonne
Rate from 1 April 2016	£84.40/tonne	£2.65/tonne

(Gov.uk, 2017, 2021, 2022a)

Here it is also worth noting the non-linearity of the annual increase in FW landfill tax, which based on historical data trends presented by Figure 199 can at times be unpredictable. To elaborate, this data demonstrated an exponential increase in FW landfill tax between 2005 and 2014, followed by a more linear pattern of increase of approximately £2-3 per year in the years that followed until 2022. Based on these trends, it can be reasonable to assume that any future FW landfill tax will increase at a rate of at least £2-3 per year in a linear fashion (in the most conservative scenario estimation).

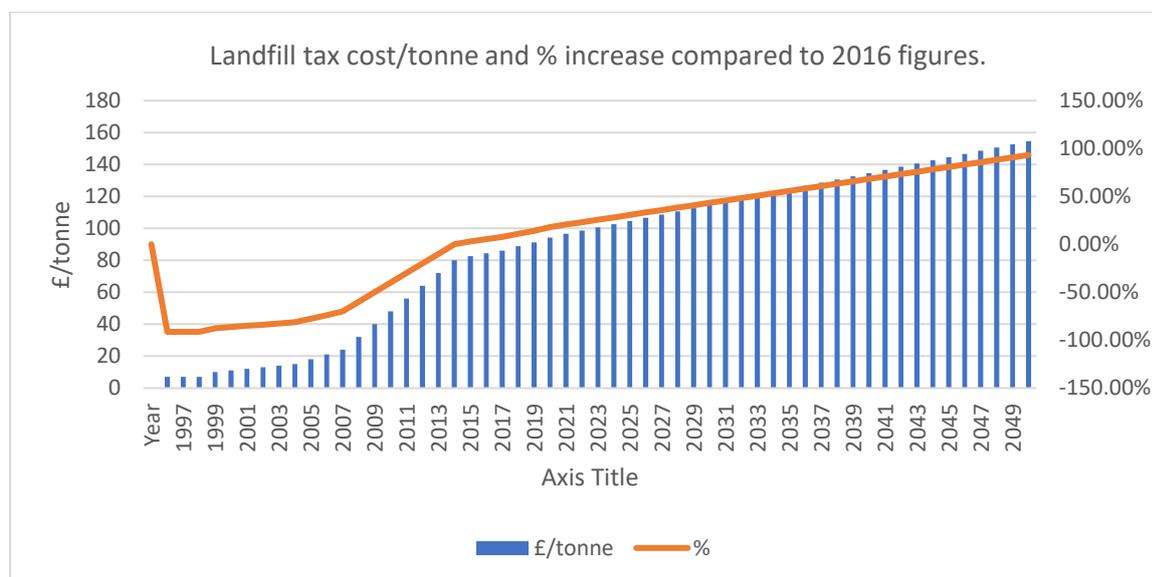


Figure 199. Past (2016-2021), present (2022, time of writing) and estimated future landfill tax values (2023-2050)

However the prospect of an exponential increase in FW landfill tax specifically, i.e. for acceleration the achievement of specific governmental goals such as zero food waste landfill by 2030, cannot be ruled out and will largely be determined by the whether current landfill tax

rates along with other relevant policy incentives are sufficient in enabling UK to achieve this set target.

Using the above rationale, a modest annual increase of £2 is assumed for landfill tax of FW for the future projected years of 2022 to 2050 for all calculations, which interestingly outlines strong financial implications in medium to long term accumulative landfill costs. This amounts to an increase of over 93.25% in the cost of each tonne of FW landfilled in 2050 (£154.6/tonne, projected) compared to the baseline value of £80/t set in 2014 (which was chosen based on it being the first value after which increases in landfill tax returns to a linear trend, see Figure 199).

Below outlines minimum and maximum revenue generation potential attributed respectively to FWtTBC pathway deployment scenarios attributed to use of (i) fixed FW collection data for NPH city regions, (ii) time-adjusted variable WRAP and WDF FW collection data for NPH city regions, and (iii) Maltings Organic Treatment Facility (MOTF) AD plant, to determine the overall range of revenue attainable in form of avoided landfill tax.

Here the total landfill tax avoided is estimated by multiplying expected total FW output by real or estimated landfill tax rate for any given year, and is underpinned by the following equation:

Revenue generated from total landfill tax avoided (£) = Landfill tax rate for FW (£/t) × Total tonnes of FW landfilled (t)

6.2.3b Revenue from avoided landfill tax revenue - all NPH city regions, fixed (20, 40 and 100 kg/person/year) FW collection data scenario

Comparison of fixed FW collection (FWC) scenarios compares differences in landfill tax cost avoided (assumed alternatively to be revenues) between highest and lowest fixed FW collection (FWC) rate of 100 and 20 kg/person/year for all NPH city regions, respectively, between 2000 and 2050 (see Figure 200).

For the low fixed FWC scenario (20 kg/person/year) for Leeds (NPH city with greatest FWC values), the landfill tax avoided amounts to £169,300 in 2001 (lowest value from dataset) which increases sharply to £350,000 in 2007 and again to £1,190,000 in 2014 before incurring a more steady incline thereafter, with the latest projection to-date to be at £1,470,000 in 2020 (where all present data in available and not extrapolated). Projection beyond this point outlines the medium, medium-long and long term avoided landfill tax cost value of £1.872,000 in 2030, £2,266,000 in 2040 and £2,754,000 in 2050 respectively. Likewise for Newcastle city (NPH city with lowest FWC values), the low fixed FWC scenario returns a avoided landfill tax cost of £127,500 in 2007, £446,900 in 2014, £548,800 in 2020, £691,700 in 2030, £827,900 in 2040 and £965,700 in 2050.

Here the findings for high FWC of 100 kg/person/year show a revenue discrepancy of 5 times multiples of the findings reported above, which ranges from £1,748,000 to 2007 and £13,770,000 in 2050 for Leeds, and from £637,700 in 2007 to £46,988,000 in 2050 for Newcastle. These results demonstrate the cost of landfill tax avoided to be significant at both low and high FWC levels in comparison to revenues derived from RTFC and CBM sales based on the magnitude of values presented.

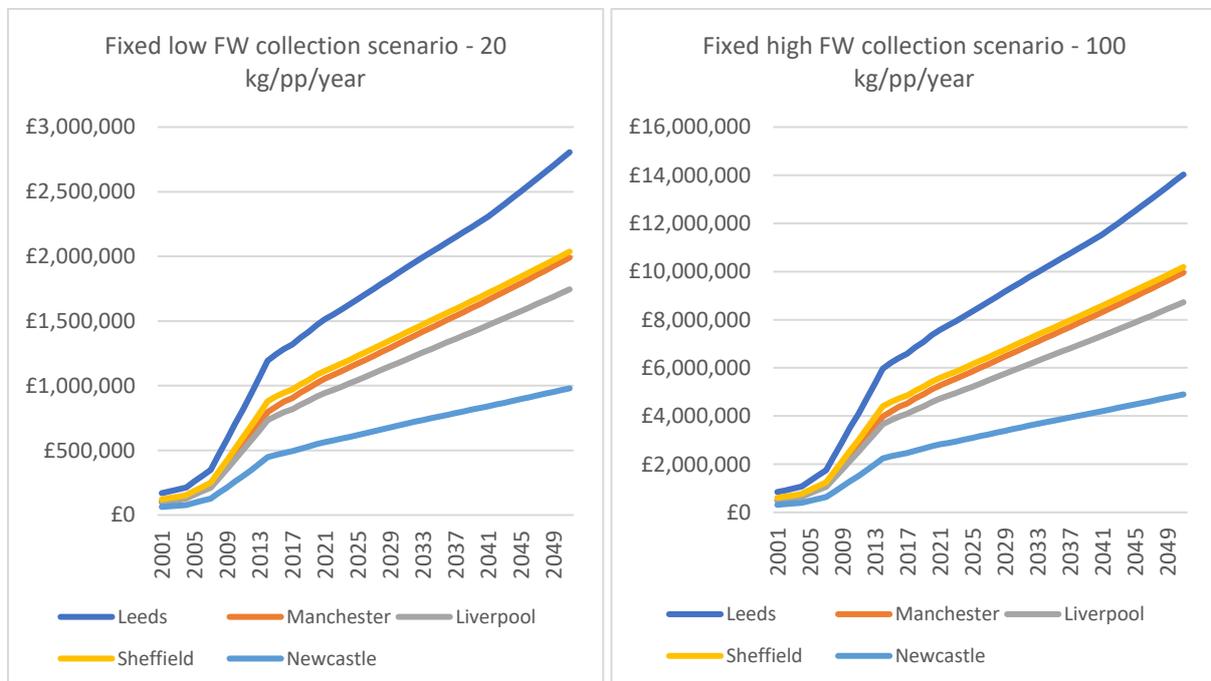


Figure 200. Estimated total revenue from landfill tax avoided for NPH city regions, comparing low fixed FW collection scenarios of 20 kg/person/year (left) and high FW collection scenario of 100 kg/person/year (right)

6.2.3c Revenue from avoided landfill tax revenue - all NPH city regions, using WDF vs WRAP variable FW collection scenario data

Comparison of variable FW collection (FWC) scenarios compares differences in landfill tax cost avoided (assumed alternatively to be revenues) between WRAP and WDF FW collection (FWC) scenarios, both which commands a high initial rate of annual FWC per individual which declines exponentially overtime (see Figure 201).

For the WRAP FWC scenario for Leeds (NPH city with greatest FWC values), the landfill tax avoided amounts to £2,600,700 in 2010 which increases sharply to £4,546,200 (greatest value) in 2015 then declines again to £3,823,000 in 2020 (where all present data in available and not extrapolated). Projection beyond this point outlines the medium, medium-long and long term avoided landfill tax cost value of £3,276,400 in 2030, £2,832,900 in 2040 and £2,425,100 in 2050, respectively. The WDF FWC scenario for Leeds by contrast demonstrates a value of £1,719,389 in 2010, £2,681,672 in 2015, £2,573,146 in 2020, £2,621,115 in 2030, £2,492,877 in 2040 and £2,290,374 in 2050, which is lower than that of WRAP results across all years.

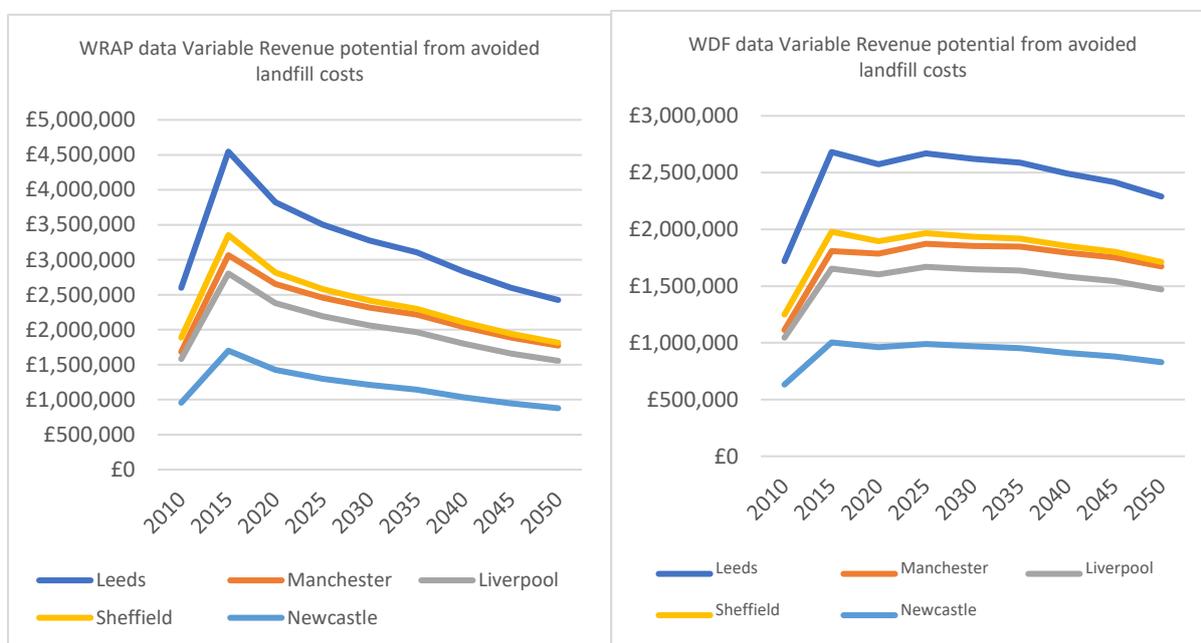


Figure 201. Landfill revenue savings arising from avoided FW landfill tax – based on fixed FW collection data scenarios, which shows high (100 kg/pp/year, left) and low (100 kg/pp/year, right) scenario graphs respectively.

Here it is worth re-iterating that these findings are due to the higher initial FWC value (that show direction correlation to landfill cost) that is seen with the WRAP scenario compared to the WDF scenario. The near convergence of both WRAP and WDF values in landfill cost avoided towards the end however is attributed to WRAP FWC values having a greater rate of exponential decline. Both WRAP and WDF FWC scenarios is also shown to exhibit different trends in their respective cost of landfill tax avoided, both which peaks at 2010, though with WRAP declining at a faster rate thereafter.

These results also suggests for the landfill tax avoided to decline at a gradual and modest rate overtime for WDF and WRAP data respectively. This is however subject to potential increases in future landfill tax rates (i.e. from linear to exponential annual increase in landfill tax rates), and is consequently likely to be an underestimation.

The next section outlines the specific case study of revenue derived from avoided landfill tax from MOTF AD plant, to benchmark revenue findings for a single large AD operator with sufficient capacity to cover annual household FW output from Leeds and West Yorkshire region, for conducting comparative analysis with CBM sales and RTFC revenue above.

6.2.3d Maltings Organic Treatment Facility (MOTF) case study

Total revenue arising from landfill tax avoided from malting organic is calculated under the assumption of it is operating under full FW capacity of 50,000 tonnes annually for time periods of 2010-2050 years, which corresponds to approximately 56 to 71 kg FW output if assumed to accommodate for the entire NPH population of Leeds (assuming for population of 705,000-890,000 from 2001-2050).

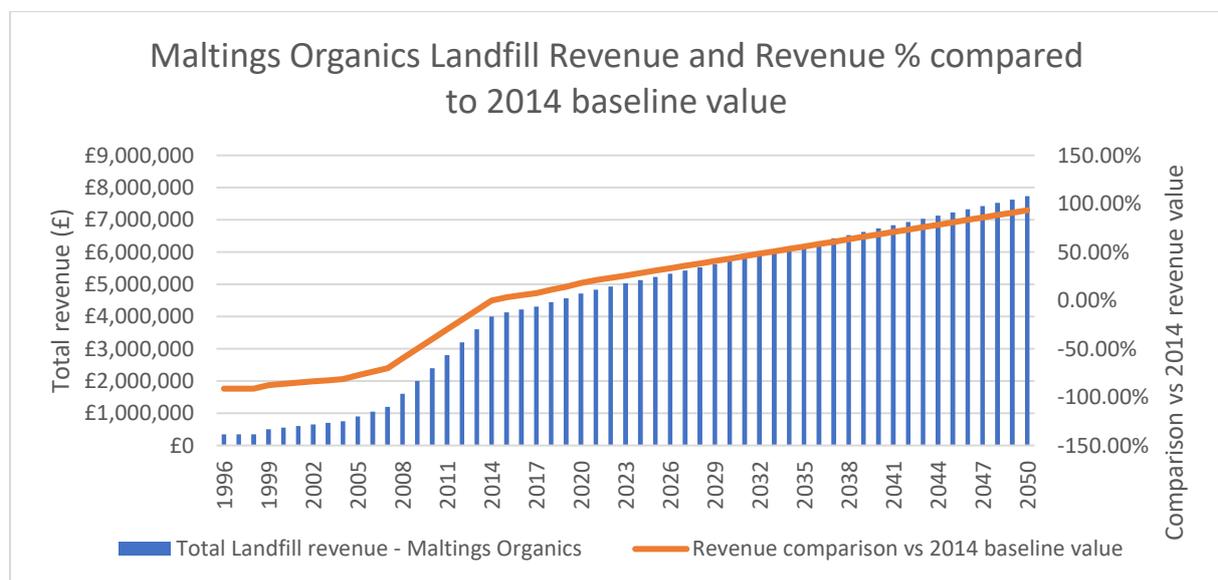


Figure 202. Melting organics landfill revenue and revenue percentage (%) compared to 2014 baseline value.

Given these parameters the landfill tax cost avoided from FW being recycled at MOTF exhibits an exponential rate of increase from £350,000 in 2001 to £4,000,000 in 2014, before slowing down to linear rate of increase to £5,800,000 in 2030, £6,900,000 in 2040 and £7,730,000 in 2050.

This when accounting for MOTF’s other (non-FW) waste capacity of 32,500 tonnes, would yield an additional 65% increase in landfill tax cost avoided, assuming either for this capacity to be used for intake of FW or other wastes with the same landfill tax rate as FW. This translates alternatively to a landfill tax avoided value of £575,000 in 2001 to £6,600,000 in 2014, before slowing down to linear rate of increase to £9,570,000 in 2030, £11,385,000 in 2040 and £12,754,000 in 2050.

The findings also re-iterate the observed trend of landfill tax rate to double in 2050 compared to 2014 baseline levels (chosen on basis of linear increase in landfill tax is applied thereafter by the government since 2014, before which such increases appears to be exponential), assuming for constant linear increase of landfill tax rates by £2 per year (chosen projection, see section beginning for rationale) following 2014. These values are quite significant in

magnitude in comparison to both the fixed and variable FWC scenarios outlined in the above sections, and is deemed to be able to contribute significantly to the overall financials of MOTF operations, either as an avoided cost or alternative revenue source (assuming for investment in the cost avoided to other areas of plant operations or for R&D).

6.2.3e Avoided FW Landfill tax cost summary, policy recommendations and limitation

This section has outlined both a reasonable and conservative projected annual rate of increase (at £2 per year) for the landfill tax beyond the current period. By applying this rate, the estimated total landfill tax avoided from both fixed and variable FW collection scenarios for the NPH city region, and that recycled at the MOTF AD plant is shown to be significant in quantity of cost that can be avoided across all projected scenarios. These findings in landfill tax avoided for all NPH city FW collection scenarios and at MOTF indicates for there to be significant cost avoidance, the latter which amounts to £350,000 in 2011 increasing to £7,730,000 in 2050.

Based on the data analysed, the study found no significant key risks that would cause significant fluctuations to the magnitude of landfill tax costs (less so compared to that CBM sales revenue or RTFC), with the only determining factor to be the actual quantity of FW diverted to landfill, which fluctuates across different LA in the real world, and is assumed to not occur in regions with no FWtTBC pathway deployment.

Consequently, any government policy that either help support, promote or strength FWtTBC pathway deployment should in theory have a significant contribution to the overall reduction in landfill of FW (see above sections for policy recommendations). Here a summary of these policy recommendations is outlined below to explain their relative contribution towards the reduction of FW landfilled.

Table 173. Policy recommendation for mitigating risk of landfill price fluctuations to promote FWtTBC pathway deployment

	Policy recommendation	Goal
1	Increase landfill price for food waste at a greater than observed linear rate of £2-3 per year, either at a greater linear rate or exponentially increasing rate.	To promote FWtTBC pathway deployment by creating greater deterrence for the landfill of FW
2	FW or can be used to set out different rates to different FW based on type and outlet (i.e. household, commercial etc).	To ensure specific FW types or categories can be more effectively targeted for recycling (via deterrence from landfill)
3	Adopt a scheme to provide additional conditional revenue incentive in form of investments or loans to AD operators that help local regions to exceed reduction in FW to landfill targets, i.e. with these incentive to be used for further improvements to AD plants and operations, or distributed to local city councils and refuel station operators	To make AD recycling of FW to be more competitive against alternative FW disposal routes by reinvesting part of avoided landfill cost as revenue back into improving AD operations
4	Apply competitive market approach to the above recommendations by AD operators to compete with each other in their respective contribution to reduction in FW landfilled, i.e. those achieving specific FW landfill reduction metrics can attain more government revenue incentive for investment into their operations or as employee bonus	To promote cross-competition in the AD sector via intrinsic market competition to help each operator to meet FW recycling metrics and for new operators to participate in FWtTBC pathway deployment (i.e. those that typically recycle other wastes)

These policies are designed to collectively promote FW recycling via the anaerobic digestion route (as part of the FWtTBC pathway) in a manner that also encourage improvements to AD

operational practices through provision of regulated incentive support and stimulation of market competition through such support.

Here one limitation to the above findings would be that the projected annual linear increase in landfill tax rate relatively modest based on past projections trends, which demonstrated periods of exponential increase (2001 to 2007 and 2007 to 2014) followed by a linear increase thereafter (post-2014). Based on past observations, It is entirely possible (if not likely) for the FW landfill tax to increase at an exponential rate for the foreseeable future to help achieve UK government's set target of eliminating FW to landfill by 2030. Consequently, it is therefore reasonable to assume that any achievable real-world landfill tax avoided should be greater than the findings illustrated above.

Another key study limitation would be a lack of inclusion of real-world operational data, such as actual FW collected from MOTF that would otherwise be landfilled and not disposed of via suitable non-landfill methods, i.e. composting that would not otherwise incur a landfill tax. These however should be subject of focus for a separate dedicated study on elucidating the flow of FW across the entire waste recycling and disposal cycle in the relevant region of interest.

6.2.4 All revenue integration for Maltings Organics

6.2.4a Base data for AD plant, FW and Refuel station cost calculations

This section presents total revenue attainable for anaerobic digestion of FW under the highest and the lowest revenue generation scenarios at Malting Organics Treatment Facility (MOTF) AD plant. These collectively includes combined revenues from biomethane energy sales revenue (i.e. CBM), Renewable Transport Fuel Certificate (RTFC) redemption revenue and from revenue that equates to the cost of landfill tax avoided (under the conditional assumptions that such costs is recouped and reinvested by the AD operator).

To this end, 5 separate total revenue generation scenarios are evaluated, which collectively accounts for original highest revenue estimations for both MOTF operating at full utilization capacity (scenario 1), followed by moderate (scenario 2) and low (scenario 3) combined revenue scenario assumptions, where all initial input metrics of AD plant utilization capacity, FW biomethane conversion (BMC) yield, CBM sales price and RTFC price are reduced to moderate levels of 75% and 50% respectively (see Table 174).

These are mainly for factoring in multiple levels of real-world operational inefficiencies associated with the deployment of the FWtTBC pathway and their cumulative impact on the final pathway output. The remaining two scenarios will respectively compare the individual effect of each factor (BCM sales, RTFC or FW landfill diversion) (scenario 4) or their combined effects (scenario 5) to the overall revenue distribution and size (see Table 174).

Table 174. Total revenue calculation scenarios with details on the relevant quantity of each FWtTBC pathway metric component used

Scenario	Scenario description / type	Utilization capacity	AD waste capacity used / waste type	FW to biomethane conversion yield	CBM sales revenue	RTFC revenues	Landfill tax
Scenario 1	Highest estimate (Real world ideal)	100%	50,000t (FW only)	High (90m ³ /t FW)	High (123.01p/m ³)	High (40p/cert)	£98.6 in 2022, increasing by £2 each year thereafter
			82,500t (FW + Other waste)				
Scenario 2	Moderate estimated (real world expected)	75%	50,000t (FW only)	Medium (67.50m ³ /t FW)	Medium (92.26p/m ³)	Medium (30p/cert)	£98.6 in 2022, increasing by £2 each year thereafter
	Low estimated (real world non-ideal)	50%	50,000t (FW only)	Low (45m ³ /t FW)	Low (61.51p/m ³)	High (20p/cert)	£98.6 in 2022, increasing by £2 each year thereafter
Scenario 3	Mixed	75%	50,000t FW only	Medium (67.50m ³ /t FW)	Medium (92.26p/m ³), compound increase of 2% each year from the previous year since 2001	Medium (30p/cert)	£98.6 in 2022, increasing by £2 each year thereafter
	Mixed	75%	50,000t FW only	Moderate (67.50m ³ /t FW)	Medium (92.26p/m ³)	Medium (30p/cert) Compound increase of 2% each year from the previous year since 2001	£98.6 in 2022, increasing by £2 each year thereafter
Scenario 3	Highest theoretical	75%	50,000t FW only	Medium (67.50m ³ /t FW)	Medium (92.26p/m ³) compound increase of 2% each year from the previous year since 2001	Medium (30p/cert) Compound increase of 2% each year from	£98.6 in 2022, increasing by £2 each year thereafter

		100%	82,500t FW only	High (90m ³ /t FW)	High (123.01p/m ³) Compound increase of 2% each year from the previous year since 2001	High (40p/cert) Compound increase of 2% each year from	£98.6 in 2022, increasing by £2 each year thereafter
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The application of this method, with specific details for each scenario summarized in Table 174, will consequently help identify key insight on how each revenue stream can be critically affected by changes to one or more key FWtTBC pathway metrics component. These can then be used to establish key policy recommendations designed to mitigate the overall risk of medium to long term declines in revenues to help ensure sustained viability of pathway deployment.

6.2.4b Scenario 1 - Highest real-world estimate of combined revenue (scenario 1, real-world ideal)

Scenario 1 illustrates the highest real-world estimations of combined revenues from RTFC ales, CBM sales and avoided FW landfill costs (see Table 174 for details on data input). Here the findings demonstrates a combined 2020 and 2050 revenue of £15 million and £18 million respectively when all FW only capacity (of 50,000 tonnes) is deployed at MOTF. This increases further to a combined 2020 and 2050 revenue of £25 million and £30 million when accounting for usage of all (82,500 tonnes, FW + Other) waste capacities at MOTF.

When excluding for avoided FW landfill cost as a revenue source, the combined revenue declines substantially to £10 million and £16.5 million throughout the entire period of 2020 to 2050, respectively when accounting for usage of FW only or all (82,500 tonnes, FW + Other) wastes (see Figure 203).

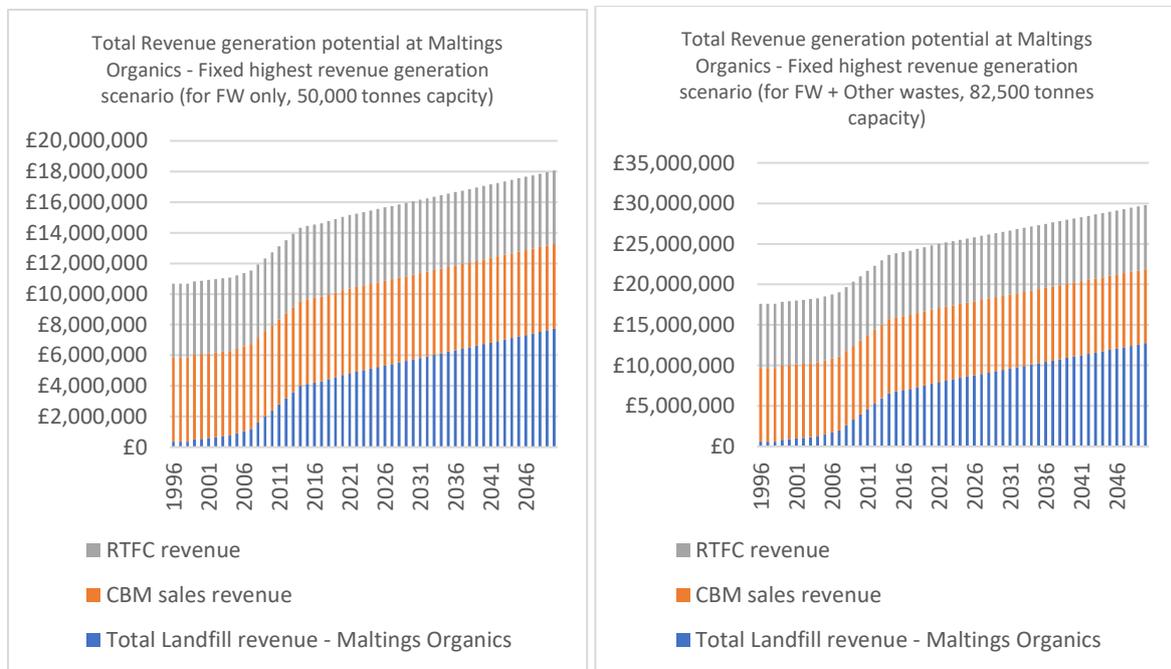


Figure 203. Highest real world estimate of combined revenue (scenario 2, real world expected and real world non-ideal) scenario, accounting for all key FWtTBC pathway input metrics to be at 100% for MOTF AD capacity of (FW only) 50,000 tonnes (left) and (Combined FW + Other waste) 82,500 tonnes (right), respectively as outlined in Table 174, operating at 100% capacity utilization.

These values of combined revenue generation are significantly and outlines the important of FW landfill tax avoided as an increasingly important source of revenue in comparison to CBM and RTFC sales revenue overtime for the default highest revenue generation scenario.

6.2.4c Scenario 2 – Moderate and Lowest real world combined revenue scenario (scenario 2, real-world expected and real-world non-ideal)

The modest and lowest real-world combined revenue scenario respectively outlines combined revenues (for FW recycling at MOTF) from RTFC sales, CBM sales and avoided FW landfill costs when only 75% and 50% of each key metric input quantity is available (see Table 174 for details on data input). This is used to outline the scenario in which each component of the FWtTBC pathway is not operating at full ideal capacity attributed to various real world factors, i.e. of operational inefficiency and logistical or technical challenges.

The results interestingly demonstrate both scenarios to have the greatest effect on reducing RTFC and CBM sales revenues, with avoided FW landfill costs being affected to a much lesser degree. This is mainly attributed to the fact that RTFC and CBM sales revenues are affected indirectly by changes to 3 separate FWtTBC pathway metric components (i.e., FW to biomethane conversion yield, MOTF AD plant utilization capacity and unit pricing value) as opposed to landfill tax avoided which is affected only by MOTF AD plant utilization capacity (see Table 174, scenario 2 for details).

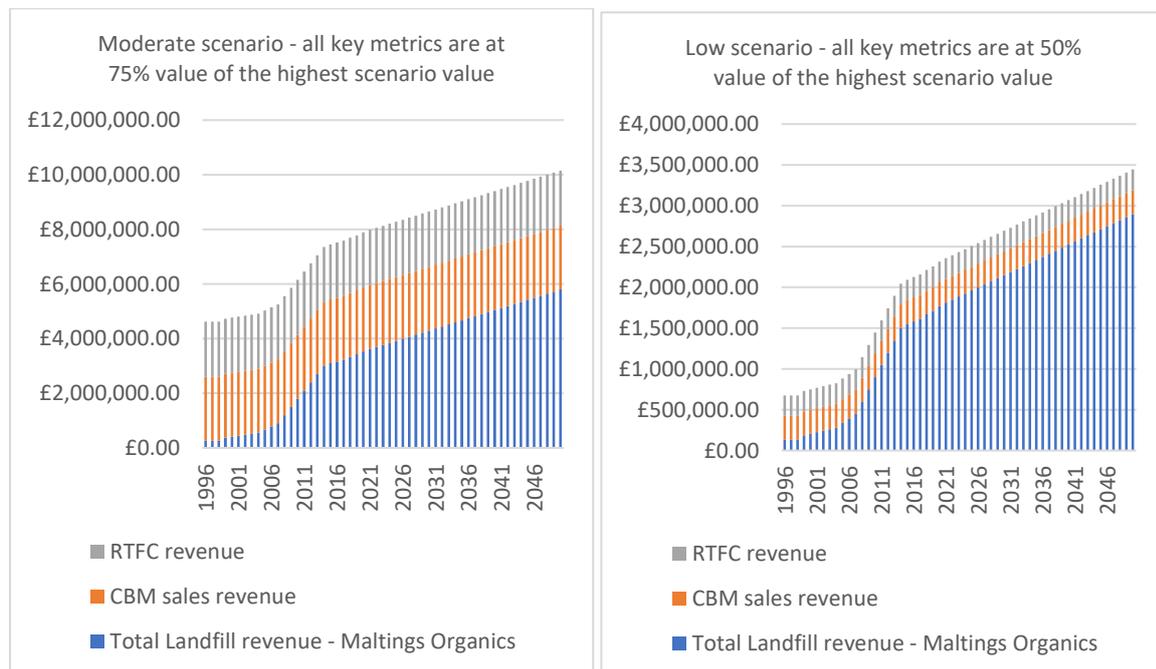


Figure 204. Moderate and Lowest real world estimate of combined revenue (scenario 2, real world expected and real world non-ideal) scenario attainable from MOTF AD plant, accounting for all key FWtTBC pathway input metrics to be at 75% (left) and 50% (right), respectively as outlined in Table 174, using values of 50,000t AD plant capacity.

Consequently, the magnitude of CBM and RTFC sales revenues will be reduced by 57.8% for the moderate scenario where all metric inputs are at 75% of the highest scenario projection value (with calculation being $1-0.75^3$). Likewise, the magnitude of CBM and RTFC sales revenues will be reduced by 87.5% ($1-0.5^3$) for the low scenario in where metric inputs are at

50% of the highest scenario projection value. As seen with the resulting graphs, revenues associated with avoided cost of FW landfill again becomes increasingly significant with increasing reductions in all key FWtTBC pathway metric component, which highlights its greatly reduced sensitivity to price fluctuation (see Figure 204).

To quantify key findings, the moderate real world combined revenue scenario demonstrates a combined revenue of £4.3 million, which increases £10 million by 2050, with approximately 2/3 of this increase being attributed to revenue arising from avoided FW landfill tax alone. Interestingly, the lowest real world combined revenue scenario demonstrates a combined revenue of £750,000 in 1996 and £3.5 million in 2050, with the avoided FW landfill costs to constitute a majority of the revenue contributions throughout. This staggeringly reduces to a much diminished combined revenue of £4 million and £600,000 respectively (to remain constant across the entire period of 1996 to 2050) for both moderate and low combined real world revenue scenarios if the avoided FW landfill cost is excluded from revenue calculations.

These observations again conveys the greater dominance in revenue contribution from FW landfill tax avoided in comparison that from CBM and RTFC sales under scenarios of FWtTBC pathway stress, where all input metrics are reduced by various real world factors. Consequently, the removal of FW landfill tax avoided as a revenue source will likely leave the FWtTBC pathway deployment extremely vulnerable to diminished revenue returns should the input metrics arising from each pathway component be sub-optimal. This should serve to be an extremely important consideration for both policy makers and AD (and other relevant, i.e. FW collection and refuel station) operators as well as investors when establishing decisions on FWtTBC pathway deployment and investment, as they significantly alter the risk profile of such deployment.

6.2.4d Scenario 3 – Real world exponential increase scenarios for RTFC and CBM sales revenue (scenario 3, mixed revenue scenario)

The third scenario compares the relative effect of exponential increase in either RTFC or CBM sales revenue (by 2% per year, year on year cumulative increase) whilst revenues of the remaining two contributing sources remain the same. This scenario uses all moderate values for each key FWtTBC pathway component (see Table 174 for details on data input).

The results demonstrates a high sensitivity for both RTFC and CBM sales revenue to this level of cumulative 2% annual increase, which for each respective scenarios would enable either component under effect to become the major revenue contributor (see Figure 205).

Again to quantify key findings, the 2% exponential increase scenario for RTFC sales value demonstrates a combined revenue of £4.8 million in 1996 and £14 million in 2050, whilst the 2% exponential increase scenario for CBM sales demonstrates a combined value of £4.4 million in 1996 and £14.7 million in 2050. Consequently, both scenarios demonstrates a similar combined total revenue, though with different distributions of individual revenue components that constitute this total (governed by the differentiating factor of exponential increase).

It therefore evident that any government policy that could consistently increase annual CBM sales price or RTFC sales revenue would be effective in enabling greater revenue returns from

FWtTBC pathway deployment, though such interventions, if ever occur, should be exercised with caution as they will likely be very costly to subsidize and implement.

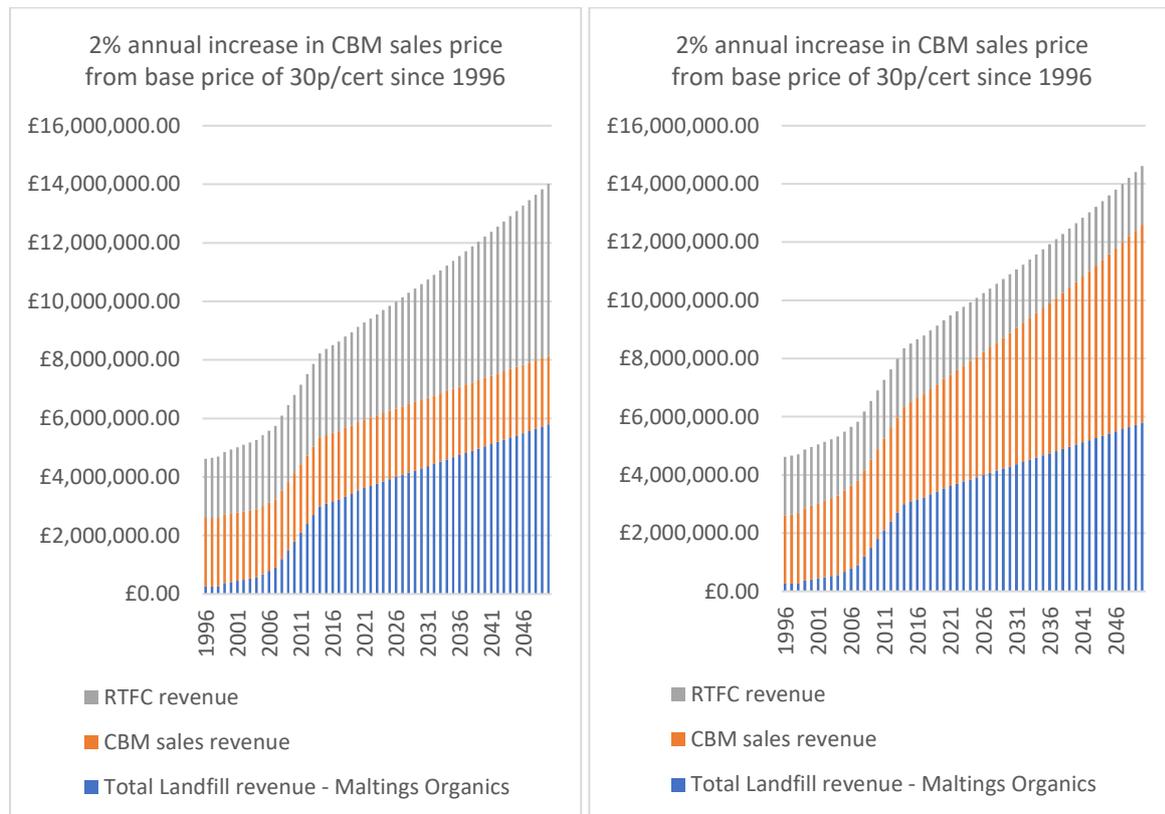


Figure 205. Mixed exponential scenario for RTFC and CBM sales revenues (scenario 3, mixed theoretical exponential) scenario attainable from MOTF AD plant, accounting for all key FWtTBC pathway input metrics to be at moderate level (of 75% of highest metric output, as outlined in Table 174, using values of 50,000t AD plant capacity).

Conversely, this also indicate both RTFC and CBM sales revenue may be equally sensitive to any cumulative year on year declines in the same (albeit reverse) manner should their price be subjected consistent year on year decline.

6.2.4e Scenario 4 – Dual exponential revenue increase scenario, theoretical estimate of greatest combined revenue attainable (scenario 4, highest theoretical scenario)

This final scenario intend to establish relevant revenue contributions from RTFC and CBM sales should both revenue streams experience a simultaneous exponential increase of 2% per year (cumulative) for the entire scenario duration of 1996 to 2050. This is highly unlikely to occur in reality and is presented as a more theoretical exercise that may only be achieved against the backdrop of consistently strong long-term government support. To this end, this scenario compares findings from both input of all moderate and highest FWtTBC pathway data metric components (see Table 174 for details on data input).

The results demonstrates a significant revenue contributions from both RTFC and CBM sales for both the moderate (left) and high (right) metric value scenario between the entire scenario duration of 1996 to 2020 (see Figure 206).

To quantify these findings, whilst the moderate FWtTBC pathway metric value scenario demonstrate a combined revenue potential of £4.8 million to £18.5 million between 1996 and 2050, the high FWtTBC pathway metric scenario demonstrate a combined revenue potential of £11 million to 37.5 million between 1996 and 2050 (which equates to approximately twice of the moderate value scenario).

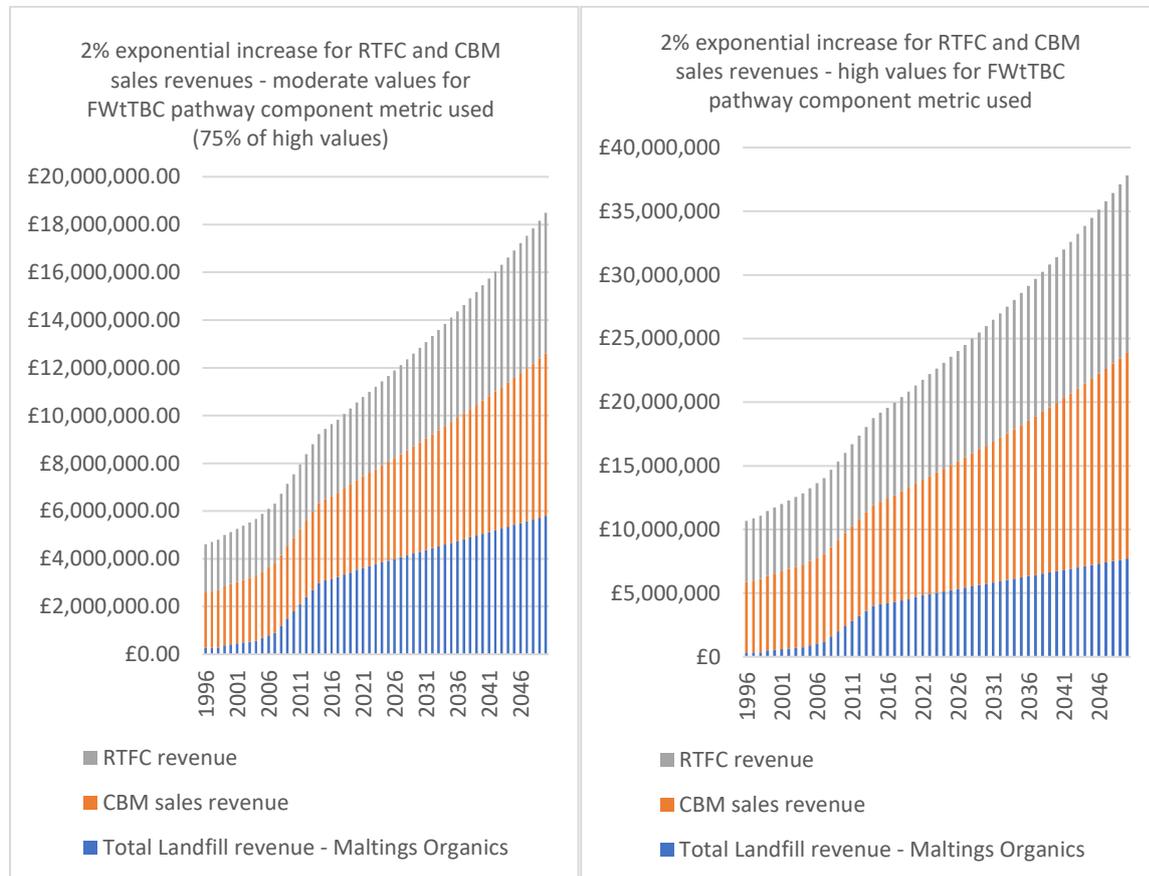


Figure 206. Dual exponential scenario for RTFC and CBM sales revenues (scenario 4, real world highest theoretical exponential) scenario attainable from MOTF AD plant, accounting for all key FWtTBC pathway input metrics to be at moderate level (of 75% left and 100% right of highest metric output, as outlined in Table 174, using values of 50,000t AD plant capacity).

Here it is interesting to note that the revenue attributed to avoided FW landfill tax costs still remain to be significant across both scenarios and account for approximately a quarter to a third of total revenue beyond 2010, which again demonstrates its consistently strong contribution to the overall revenue calculations (if considered as a revenue source).

6.2.4f Summary, limitations and further studies

This section outlined 4 separate scenarios of revenue estimation to establish key ranges of combined revenue attainable (and distribution of individual revenue streams) from FWtTBC pathway deployment using MOTF AD plant as an example. To this end, the scenario estimations established (i) the highest real world combined revenue potential (scenario 1), (ii) medium and lowest combined revenue potential (scenario 2), and combined revenues achievable from (iii) single exponential (scenario 3) or (iv) dual exponential revenue increase in RTFC and CBM sales values.

The above results established 3 important findings that could help inform policy recommendations. First and foremost, the revenue contribution from FW landfill tax avoided across all scenarios were found to be very significant in comparison to RTFC and CBM sales values, and unlike these two revenue streams, is not sensitive to the systemic challenges of FWtTBC pathway deployment (i.e. where all input metrics are reduced).

The second notable finding would be the surprisingly large impact of real world factors that may contribute to much lower than expected revenue from RTFC and CBM sales. A decrease of 75% and 50% in each of the 3 key FWtTBC metric, namely AD capacity utilization, FW to biomethane conversion yield and respect RTFC or CBM sales values for example, could reduce RTFC and CBM revenue by 57.82% and 87.5% respectively, which is extremely significant. Though perhaps unsurprisingly with revenue contribution from avoided FW landfill tax being relatively less affected as it value is directly proportional to only the quantity of FW feedstock diverted from landfill.

A final notable finding would be the strong effects of annual % increase in either RTFC or CBM sales revenue on the combined revenue. An increase of 2% for example for either RTFC or CBM sales revenue (scenario iii) would enable the relevant metric to become the most significant revenue contributor overtime, as seen with the findings. Furthermore, a simultaneous increase in both RTFC and CBM sales revenue (scenario iv) was found to be able to significantly amplify the magnitude of total combined revenues arising. In all scenarios revenues attributed to avoided FW landfill costs still remain to be significant, especially after the 2010 period owing to the greatly increased FW landfill costs (£/tonne FW).

Policy recommendations should therefore focus on the key interactions between all 3 revenue contribution factors to ensure risk of any financial payback (see next chapter) would be significantly mitigated in general with respect to FWtTBC pathway deployment for use of transport biomethane. These primarily include the safeguarding of current trend of increase in FW landfill costs and a suitable policy to apportion a significant % (if not the entire avoided costs) of FW landfill tax savings as an alternative revenue stream to help further improve AD development and operations. Further recommendations relate to the specific interaction between CBM sales revenue and RTFC revenue in a manner that could mitigate risk of simultaneous decline in both revenue metrics, as specifically outlined in Table 175 below.

Table 175. Policy recommendation to help mitigate decline in combined revenue associated with deployment of FWtBC pathway under unexpected and extreme scenarios

	Policy recommendation	Goal
1	Ensure low CBM sales revenues are coupled with sufficient RTFC certificate guarantees to offset 50% to 75% reduction in the CBM sales price, for AD operators that demonstrates good practices through sufficient utilization of their overall FW capacity (i.e. 70% and above) and with achievement of high FW capture rates from the FW collection process (i.e. over 75% of total household FW)	Hedge risk of each revenue stream, i.e. CBM sales, RTFC and landfill cost against each other to ensure overall combined revenue is sufficiently safeguarded against significant fluctuations in each individual revenue stream.
2	Conditionally apportion significant % avoided landfill tax savings to improve and further expand AD operations and critical FWtBC pathway components deemed to be key weak points for the deployment of the entire pathway	Ensure suitable apportioning of avoided landfill tax as revenues to enhance the FWtBC pathway deployment as a whole
3	Ensure CBM and RTFC prices are sufficiently safe guarded via promise of a mechanism that adds supplementary value to CBM or RTFC values in case of sudden fall in overall CBM or RTFC revenue, i.e. attributed to decreasing FW biomethane yield, CBM or RTFC sales prices, reduced AD utilization capacity or combination thereof.	Safeguard price of CBM and RTFC via market support mechanism or direct financial support mechanism to ensure sufficient revenue are met to promote FWtBC pathway deployment and development

These policy recommendations are designed logically to (i) firstly safeguard most reliable potential revenue stream derived from avoided FW landfill tax, as well as to (ii) ensure it is can be converted to a key revenue source for optimizing and promoting FWtBC pathway development, and finally to (iii) ensure a sufficiently robust and flexible support mechanism is available for accommodate for extreme scenarios that could significantly reduce CBM and RTFC sales revenues, i.e by over 57.82% of highest expected values.

Here it is the ultimate aim of these recommendations to help create for financially self-sufficient FWtBC pathway deployment strategies within the context of available current support, but one that is not limited by the utilization of additional support if deemed necessary to help further promote pathway deployment.

Here the risk in payback uncertainty as mentioned above is primarily attributed to the changes to RTFC followed by that of CBM sales revenue, as these constitute factors with greatest price fluctuation and also dependent highly on the demand of biomethane sales and use within the transport sector. Cost avoided from landfill of FW however constitute a more certain source of avoided cost (or revenue equivalent, assuming for reinvestment of these avoided costs) that is almost guaranteed to be steady in their contribution towards the payback period due to a fixed rate of increase that does not decline.

Finally, it is worth noting that this study is limited by the use of best estimate but not completely representative operational data in its combined revenue scenario projections owing to inherent barriers to third party collaboration as mentioned throughout this research. Consequently, whilst every effort had been made towards establishing best estimates of combined revenue projections using different price assumptions, i.e. for MOTF, the results are nonetheless not fully representative of precise real world operation. Future studies should address this through direct collaborations with key stakeholders such as AD plant operators and local city councils for obtaining and using more representative FWtBC pathway metric data in the combined revenue projections, either by using the same or a revised version of the method outlined above.

6.2.5 Cost and breakeven findings overview - CAPEX and OPEX analysis in context of FWtTBC pathway deployment

6.2.5a AD CAPEX graph, trend and findings

For cost estimations, various online data pertaining to AD plant size relative to cost are collected from relevant online AD news sites and are cross-assessed against their FW and total (FW + Other waste) capacity for estimating output cost per unit generation capacity (see Figure 207). These are estimated using current data on reported total AD costs of construction and operation against estimated revenue, and is most relevant towards helping determining financial feasibility from an AD operators perspective, and less relevant for other stakeholders.

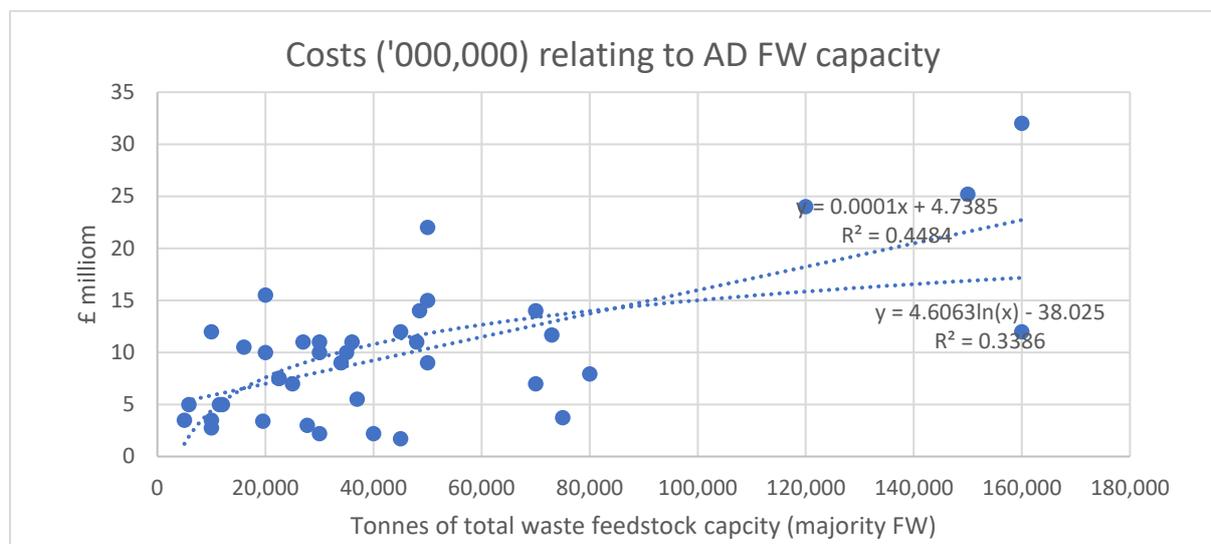


Figure 207. AD capacity against all wastes (FW + Other waste), for AD plants where data is available, of which majority is FW (see Appendix table 66)

The result shows a weak to moderate positive correlation between AD plant FW capacity size and CAPEX cost, which for Maltings Organics translates to a low to high estimated capital cost of £9 million to £22 million, and with both regression trendlines to (linear and polynomial) hover around the £10 million to £12 million value range.

6.2.5b AD plant Breakeven period using CAPEX values only

This translates to a cost per tonne of FW to be between £180 and £440, which interestingly when factoring in the above findings on revenue per tonne of FW of £143-£215 and £230-£253 (mean revenue value per tonne FW registered between 2010 and 2050 for fixed and variable data, respectively), suggests a CAPEX payback period of 0.89 years to 3.41 years, which appears to be unreasonably high.

One potential reason for this would be the assumption of landfill tax avoided as a 'revenue stream', inclusion of CAPEX only values without considering Operation costs (OPEX) and assumes that AD operates at 100% capacity all year long without necessary shutdown periods for maintenance.

When discarding landfill tax avoided value, the mean revenue generation per tonne FW for between 2010-2050 period decreases significantly to £119 and £121-253 for fixed and variable

revenue scenarios, respectively. This translates to a corresponding breakeven period of 1.51-3.70 years and 0.71-3.70 years for these two respective scenarios, which is still relative high (see Table 176).

Table 176. Table of breakeven period calculations in context of AD cost (CAPEX only) and revenue per tonne of FW processed

Revenue		Breakeven period – considering CAPEX only		Cost/Revenue per t/FW = breakeven period
RTFC + CBM sales + Including landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period	440/143 = 3.08	
		Fastest payback period	180/215 = 0.84	
	Variable scenario values	Slowest payback period	440/250 = 1.76	
		Fastest payback period	180/253 = 0.71	
RTFC + CBM sales + Excluding landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period	440/119 = 3.70	
		Fastest payback period	180/119 = 1.51	
	Variable scenario values	Slowest payback period	440/121 = 3.70	
		Fastest payback period	180/253 = 0.71	

6.2.5c Breakeven period factoring in CAPEX and OPEX

In context of real world AD operations, additional operational costs (OPEX) must be factored in and is typically considered as a % of CAPEX. Here a value of 3%, 5% and 7% is used, which collectively results in an average CAPEX increase of 160%, 200% and 240% throughout the 2010-2050 period (Figure 208).

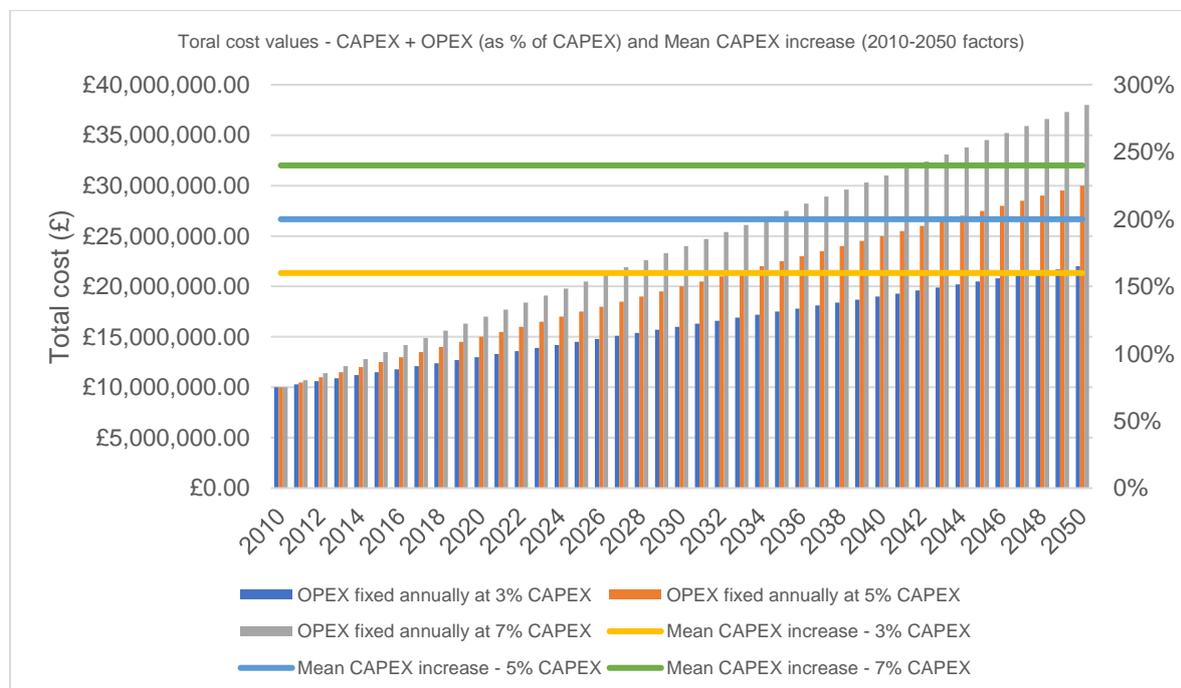


Figure 208. OPEX costs fixed annually as 3%, 5% and 7% total CAPEX,

This consequently increases the CAPEX only breakeven period proportionally to 1.136 to 8.88 years across all scenarios, with specific breakdowns outlined in Figure 209.

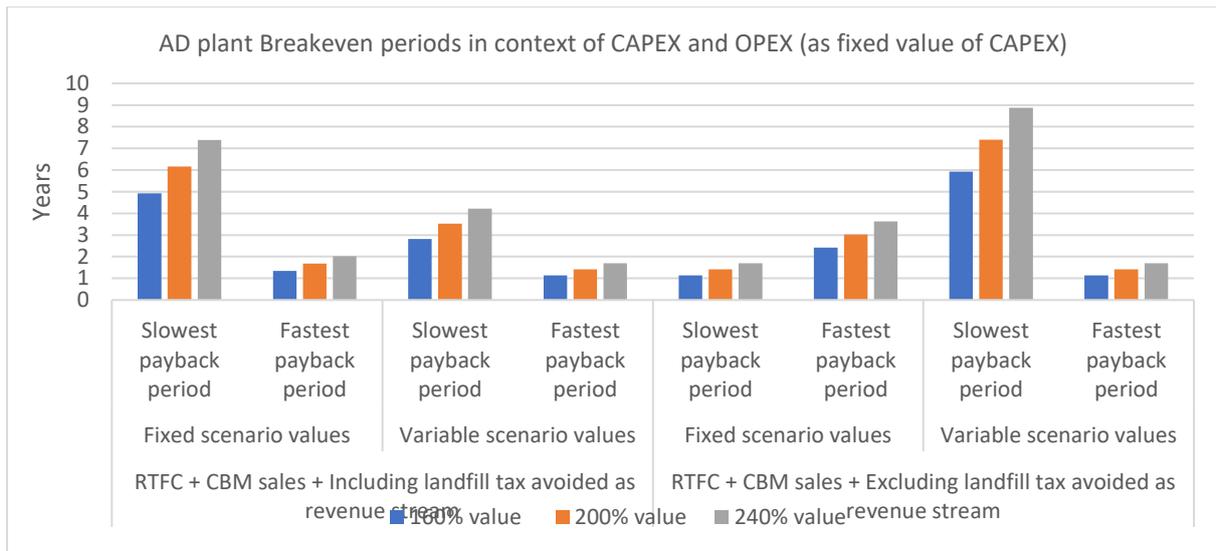


Figure 209. Breakeven period considering AD cost CAPEX and OPEX against revenue per tonne of FW processed

Table 177. Table of breakeven period calculations in context of AD cost (CAPEX and OPEX as fixed % of CAPEX) against revenue per tonne of FW processed

Revenue		Breakeven period – considering CAPEX and OPEX		OPEX as 3% CAPEX	OPEX as 5% CAPEX	OPEX as 7% CAPEX
RTFC + CBM sales + Including landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period		4.928	6.16	7.392
		Fastest payback period		1.344	1.68	2.016
	Variable scenario values	Slowest payback period		2.816	3.52	4.224
		Fastest payback period				
RTFC + CBM sales + Excluding landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period		1.136	1.42	1.704
		Fastest payback period		2.416	3.02	1.704
	Variable scenario values	Slowest payback period		5.92	7.4	8.88
		Fastest payback period				

The results interestingly show the largest difference between fastest and slowest payback periods (calculated by dividing total cost by highest and lowest combined revenues, respectively) across all scenarios, which ranges from 1.5 to 5 times in magnitude. This discrepancy in payback period for different OPEX values by contrast is more modest and varies between 1.25 to 1.5 times between the OPEX as 3% CAPEX and OPEX as 7% CAPEX revenue scenario. These payback periods across all criteria ranges from a lowest of 1.136 years to a highest of 7.392 years as outlined in Table 177 above. Although when accounting for each cost category, it is shown that higher OPEX values (i.e. 7% CAPEX) would return a significantly longer pay payback period compared to lower OPEX values (i.e. 3% CAPEX) even when for the same scenario type, which outlines the importance of operational costs in general on considerations on financial return on investment.

When factoring in an assumed total AD waste capacity utilization rate of 50% and 75% (accounting for cumulative real world inefficiencies and downtime for maintenance or upgrade), the breakeven period range further increases proportionally by 50% and 75% across all scenarios, with specific breakdown of values being outlined in Figure 210 below. For

breakeven period considering AD cost CAPEX and OPEX against revenue per tonne of FW processed please refer to Table 178. These payback periods across all categories vary between 1.51 years and 12.53 years, and again demonstrate the trend of longer payback periods for scenarios with highest OPEX values (i.e. 7%) relative to CAPEX, and lowest utilization capacity (i.e. 50%).

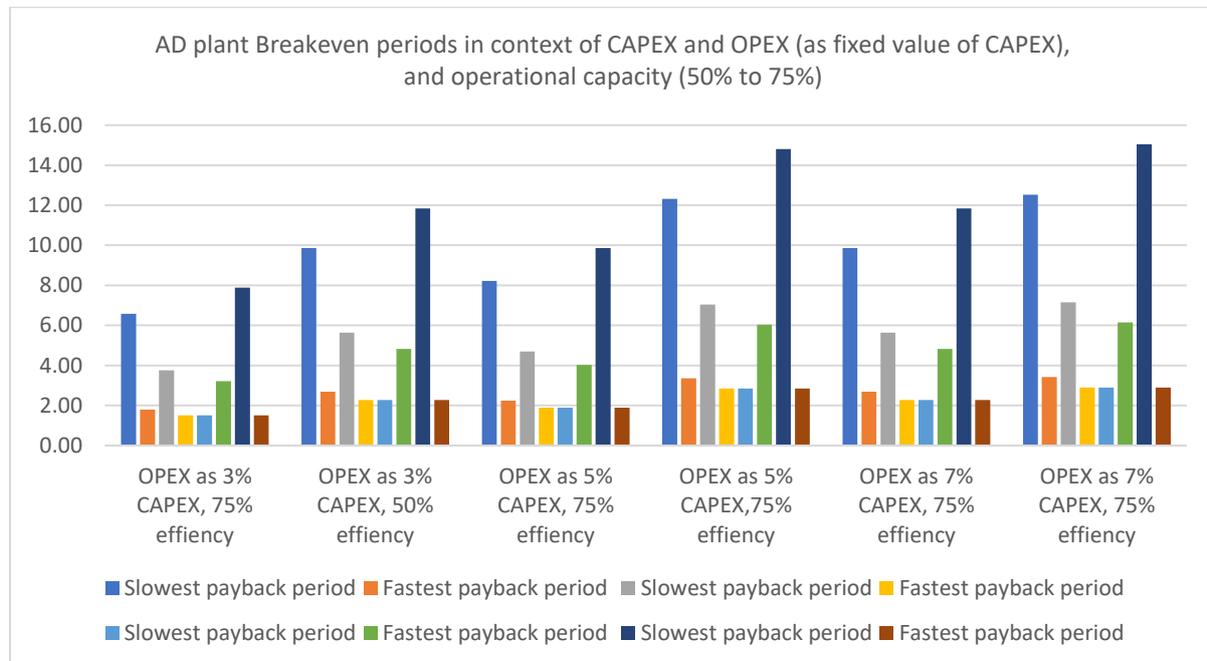


Figure 210. Breakeven period considering AD cost CAPEX and OPEX plus AD operational waste capacity utilization against revenue per tonne of FW processed. Here efficiency also refers to utilization capacity.

Table 178. Table of breakeven period calculations in context of AD cost CAPEX + OPEX plus AD operational waste capacity utilization against revenue per tonne of FW processed

Revenue		Breakeven period – considering CAPEX and OPEX	OPEX as 3% CAPEX, 75% capacity utilization	OPEX as 3% CAPEX, 50% capacity utilization	OPEX as 5% CAPEX, 75% capacity utilization	OPEX as 5% CAPEX, 50% capacity utilization	OPEX as 7% CAPEX, 75% capacity utilization	OPEX as 7% CAPEX, 50% capacity utilization
RTFC + CBM sales + Including landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period	6.57	9.86	8.21	12.32	9.86	12.53
		Fastest payback period	1.79	2.69	2.24	3.36	2.69	3.42
	Variable scenario values	Slowest payback period	3.75	5.63	4.69	7.04	5.63	7.16
		Fastest payback period	1.51	2.27	1.89	2.84	2.27	2.89
RTFC + CBM sales + Excluding landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period	1.51	2.27	1.89	2.84	2.27	2.89
		Fastest payback period	3.22	4.83	4.03	6.04	4.83	6.14
	Variable scenario values	Slowest payback period	7.89	11.84	9.87	14.80	11.84	15.05
		Fastest payback period	1.51	2.27	1.89	2.84	2.27	2.89

This above estimations however do not give account for extra costs (CAPEX and OPEX) associated with deployment of FW collection and transport refuelling. Consequently, an added

final cost factor of additional 25%, 50% and 100% is applied to the above AD only CAPEX and OPEX, with results outlined in Table 179 below (using AD OPEX as 7% CAPEX values in Table 178 above).

Here the results outline a further increase to the payback period that is proportional to the assumed additional cost of FW collection (FWC) and transport refuel station (RS) deployment. A 25%, 50% and 100% increase for example increases general lowest and highest payback period to 2.84 and 18.81 years, 3.41 to 22.58 years and 4.54 to 30.10 years, respectively. Here it is important to note without accurate data associated with true FWC and RS costs, these results constitute a general estimate and should be considered with some level of caution.

Table 179. Table of breakeven period calculations in context of AD cost CAPEX + OPEX plus AD operational waste capacity utilization against revenue per tonne of FW processed

		25% increase		50% increase		100% increase		
Revenue		Breakeven period – considering CAPEX and OPEX	OPEX as 7% CAPEX, 75% capacity utilization	OPEX as 7% CAPEX, 50% capacity utilization	OPEX as 7% CAPEX, 75% capacity utilization	OPEX as 7% CAPEX, 50% capacity utilization	OPEX as 7% CAPEX, 75% capacity utilization	
RTFC + CBM sales + Including landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period	12.33	15.66	14.79	18.80	19.72	25.06
		Fastest payback period	3.36	4.28	4.04	5.13	5.38	6.84
	Variable scenario values	Slowest payback period	7.04	8.95	8.45	10.74	11.26	14.32
		Fastest payback period	2.84	3.61	3.41	4.34	4.54	5.78
RTFC + CBM sales + Excluding landfill tax avoided as revenue stream	Fixed scenario values	Slowest payback period	2.84	3.61	3.41	4.34	4.54	5.78
		Fastest payback period	6.04	7.68	7.25	9.21	9.66	12.28
	Variable scenario values	Slowest payback period	14.80	18.81	17.76	22.58	23.68	30.10
		Fastest payback period	2.84	3.61	3.41	4.34	4.54	5.78

6.2.5d Summary, limitations and further studies

The 3 separate findings above also illustrates the complexity of calculating payback periods, which could show a considerable range when factoring real world factors of reduced utilization capacity in context of operational (OPEX as % of CAPEX) and additional costs, i.e. those for FWC and RS deployment. Evidently these values are affected by both the combined cost against revenues for each relevant scenario and can be optimized by focusing on utilization of suitable AD plants with a low CAPEX + OPEX cost relative to FW feedstock capacity for combined revenue generation (i.e. from CBM and RTFC sales and avoided FW landfill tax).

Consequently, key policy recommendations are in line with that is mentioned in earlier sections of this chapter, and involves specific focus on ensuring each AD plant is operating at optimal real world conditions with sufficient utilization capacity with adequate FW to biomethane conversion rate, and that both CBM and RTFC unit pricing should be safeguarded to a reasonable degree alongside mechanism to recoup significant proportion of avoided FW landfill tax for reinvestment back into improving and expanding AD operations.

In the context, it is worth noting that the study is again limited by the use of real world operating data despite reasonable assumptions to factor in likely possible scenarios through use of different CAPEX and OPEX values (estimated in % as CAPEX). Future studies should therefore involve closer collaboration with all stakeholders and investors FWtTBC pathway deployment for establishing and inputting more precise cost and revenue data to ensure such calculations made would be more accurate and real world representative, and consequently can help better inform government policy recommendations, i.e. via combination of financial and non-financial incentive support.

Finally, it is worth noting that the cost pertaining to each FW collection and refuel station deployment scenario will vary largely based on availability of existing infrastructure and the efficiency of deployment, and thus whilst the above results outline potential breakeven timeframes on FWtTBC pathway deployment, more accurate breakeven timeframes will need to be validated by future studies by integrating more specific real world data as they become available.

Chapter 7. Whole Systems Analysis and Findings

This chapter outlines results of the whole systems analysis to evaluate the readiness with which FWtTBC pathway can be deployed across NPH city region of Leeds and metropolitan county region of West Yorkshire, and whether if these deployments can be scalable to cover other NPH regions.

The analysis draws on summary of all quantitative and qualitative findings established in all previous sections where relevant, in support of key discussions and evaluations on the current state of FWtTBC pathway deployment across NPH regions with respect to each whole system analysis criteria presented.

These will also be evaluated from perspective of a number of key stakeholders involved, including local city council, AD plant (ADP) operators (assumed to also be responsible for FW collection and transport refuelling), local household participants of FW collection and central government, to assess barrier to against drivers of pathway deployment.

To elaborate, relevant barriers associated with the whole system assessment criteria of (i) goals/metrics, (ii) people/culture, (iii) techno-economics, (iv) infrastructure/investment, (v) policy/environment, and (vi) process/procedures are evaluated against existing drivers of FWtTBC pathway deployment. The collective interactions of these 6 criteria will also be discussed as part of an integrated analytical approach to highlight possible approaches in support of FWtTBC pathway deployment given the known benefits attainable from the findings in the previous chapters (see Chapter 5 and 6). These are summarized in Table 180 below and further expanded upon within each discussion section.

To this end, a key outcome would be to evaluate and consolidate key policy findings and recommendations to ensure they are suitably equipped to overcome surmountable barriers, challenges and risks associated with FWtTBC pathway development, and that any useful outputs can be suitably reinvested back to further establish and strengthen pathway deployment for the foreseeable future to come.

Table 180. Revised Whole systems analysis of relevant barriers for each of the socio-techno-economic categories pertaining to FWtTBC pathway deployment at Leeds NPH city region using key research findings,

Framework component	Food waste	Anaerobic digestion	Biomethane refuelling and use in HDV vehicles (in biomethane propulsion systems)
Goal/metrics	Low Barriers Findings demonstrate at least Moderate level of annual FW collection (40kg/person) based on Rothwell data, though this other regional data suggest this can be further improved to 80-100kg/person	Very low barriers Sufficient FW capacity at nearby AD plants to accommodate for collected FW, with strong potential to meet all environmental and financial targets as outlined in relevant findings	Low barriers Strong presumed financial incentive for transport biomethane use due to RTFC incentive, that couples well with meeting FW reduction and clean in-city air emission targets
People/Culture	Low barriers Inferred high participation rate from at select local regions with reasonable to high local FW collection rate (although converse maybe true for regions with low FW collection rates), with anticipation of further participation if support by government policy incentives		
Techno-economics	Low barriers The combined findings of revenues, costs and technical biomethane conversion yields associated with FWtTBC pathway deployment established low payback period of FWtTBC pathway development, which suggests that at least on the macro-scale, the techno-economic of pathway deployment is financially feasible should sufficient relevant information and knowledge be obtained. Here it is worth noting whilst the deployment barrier maybe low, the initial barrier of information access and insight establishment is very high given the complexity of the calculation and data involved.		
Infrastructure / Investment	Low-Moderate barriers Existing deployment of FWtTBC pathway in the Rothwell region, and consequently upscale to NPH Leeds city region (or sub-region) should not be overly challenging	Low barriers Existing strong AD infrastructure capacity at Maltings Organics plant that can accommodate for FW arising from entire population of Leeds and West Yorkshire (with 3 additional AD located to South, North and East of Leeds)	Moderate barriers Existing operation of a very small trial biomethane refuel station at Leeds, with full refuel station deployment requiring significant up-scalability and present a moderate albeit not insurmountable challenge
Policy/Environment	Low FW landfill tax regulation offers strong incentive for FW recycling and diversion from landfill	Low Benefits strongly from indirect policy incentives such as landfill tax, RTF and RHI incentive	Low RTFC reclaim for HDV biomethane use constitute a strong policy finance incentive
Process/Procedures	Low Process and procedures can be learnt from Rothwell food waste collection trial and existing waste collection trials	Moderate Process and procedures can be Rothwell trial in terms of transport logistics and plant operations, but require establishing new or finding existing local AD plant to accommodate increase in food waste capacity input	Moderate Process and procedures can be Rothwell trial in terms of transport logistics and plant operations, but require establishing new or finding existing local refuel stations to accommodate increase in biomethane HDV refuelling

7.1 Goals and metrics analysis

The whole systems analysis of goals and metrics aims to assess a number of key goals and metrics associated with the complex logistical, operational and financial processes relating to deployment of the FWtTBC pathway.

From perspective of key stakeholders and in context of this research, this mainly centres on whether if key environmental and financial targets, i.e. of FW collection or reduction and revenue generation can be met to ensure the pathway is adequately financially self-sustainable and beneficial to both businesses, local city council and the society in general. This assessment falls within the macro-economic backdrop of diminishing funding to local city councils and increasing environmental awareness to reduce waste and pollution.

Here it is important to note the separation of focus with respect to different metrics presented and analysed in this study to different stakeholders. Here the most important metric in perspective of all stakeholders will most likely be the overall financial feasibility of FWtTBC pathway development (top down evaluation approach) to ensure that the FWtTBC pathway can be financially sustainable. Conversely, it is also critical to consider the key metric of local FW availability (bottom up approach) for strategic and future planning purposes, assuming for local infrastructure availability to accommodate for the necessary logistical and operational processes, i.e. of FW collection and recycling. Finally, more technical data such as those associated with AD plant capacity, FW to biomethane conversion yield and AD plant utilization capacity may also be considered important from the perspective of researchers and AD plant operators as they directly affect the revenue outputs. The assessment of metrics can also be conducted with respect to each FWtTBC pathway component, which involves FW collection, anaerobic digestion and transport refuelling.

For FW collection, the research was able to identify representative household FW collection (FWC) data trends derived from WDF and WRAP datasets for estimating both FW output per individual and collective FW availability within given local city and metropolitan counties. Here the findings show 2 separate data scenarios which both demonstrate there to be enough household FW for collection in the near to medium term (of at least 40 kg/person/year being the median estimation), though with some data suggesting for diminished household FW in the long term beyond 2035 (see WDF and WRAP FW collection data). These are collectively outlined in Chapter 5 by using reasonable evidence based assumptions and inferences, and demonstrates low barrier to FWtTBC pathway deployment as far as FW feedstock availability is concerned.

For technical AD operations, the technical metric barriers towards pathway deployment, as found by the findings presented in Chapter 5.3, is also deemed to be low owing multiple experimental studies demonstrating the adequate biomethane conversion yield of household FW, which can be further improved through mixing with commercial and industrial FW. More specifically these typically range between 45m³ to 90m³ biomethane produced per tonne household FW (with a medium value of 67.50m³/t FW) which proved to be more than adequate.

With regard to AD infrastructure availability, the findings also established there to be sufficient FW capacity at MOTF to accommodate for all household FW collected at Leeds and West Yorkshire region (assuming for medium level of FW collection used), which additionally

outlines the low infrastructure metric barrier (of FW intake capacity for biomethane generation against expected supply from collection).

For all 3 FWtTBC pathway components with respect to key financials, relevant financial calculations for revenue against cost has demonstrated the possibility of sufficiently short payback periods of between (2 and 10 years) for combined capital and operation of an entire AD plant using Maltings Organic Treatment Facility (MOTF) AD plant as an example in consideration of real world factors of plant utilization capacity and input of moderate FWtTBC pathway parameters. These are further attributed to contributions from key revenue streams of biomethane sales, RTFC sales and avoided FW landfill tax which collectively ensure the relatively strong financial self-sufficiency of FWtTBC pathway deployment under most real world conditions government by existing policy support incentives and market mechanism (i.e. that determine biomethane and RTFC sales prices). These are collectively outlined in see Chapter 6 again by using evidence based reasonable assumptions and inferences to demonstrate low financial barrier towards pathway deployment once it is fully operational.

The combined assessment of the above findings collectively indicates a low barrier to FWtTBC pathway deployment as far as key stakeholder goals and metrics as concerned, as the findings of each pathway metric component more than satisfies the overall minimum values required to ensure the financial viability of FWtTBC pathway deployment, and that there exist sufficient evidence and proof that these metrics can be realistically obtained from real-world pathway deployment, i.e. at Leeds city region (based on the Rothwell data collection trials).

It is also worth noting that these findings are inferred mainly from subsets of existing data that are reasonably assumed to be representative to the FWtTBC pathway scenario under investigation, and is limited largely by the input of data from a single truly representative study. This is likely to be attainable only through real world collaborations with both the local city council and relevant operators of FW collection, AD operations and biomethane refuel stations, which is not achieved by this research despite repeated attempts at doing so. Consequently, a more accurate analysis for future research purposes should aim for closer real world collaborations with key stakeholders in local regions of FWtTBC pathway deployment to further validate whether if barriers associated with the goals/metrics aspect of this whole system analysis is indeed low (i.e. from estimations of FW collected, FW to biomethane conversion yield and financials).

Here it is critical to note that the above findings holds most true for the near term deployment of FWtTBC pathway, whose key metrics values (as outlined above) is likely to be subjected to change overtime. An example would be the likely diminishing source of household FW as seen from WDF and WRAP data which shows annual reduction in household FW collection that will prove to be significantly high FW collection barrier in the distance future. This alongside other risk factors are collectively addressed by specific policy recommendations to ensure the continued financial and operational viability of FWtTBC pathway deployment.

7.2 People and Culture

The whole systems analysis of people and culture assesses the overall FWtTBC pathway deployment processes in context of key participants and local cultural acceptance towards the FWtTBC pathway at all levels and stages of deployment. These are mainly directly inferred based on substantial evidence of UK's current practices on enabling FW collection, AD operation and transport refuelling at local, regional and national level. This is based on the notion of a successful FWtTBC pathway deployment scenario would be highly dependent on strong participation from local households where there is a general cultural acceptance and behavioural affinity towards conducting dedicated FW recycling for collection (which constitute the first pathway component).

To this end, the assessment consolidates a number of key findings and trends, which from the WDF data and WRAP study demonstrates that UK does possess a substantially strong national FW household participation and cultural acceptance towards FW collection. This is mainly attributed to the finding of there being over 60 participating regions of FW data collection from WRAP studies that demonstrates significant household participation from which significant yield of per capita household FW output is obtained to feasibly enable the deployment of the entire FWtTBC pathway (see Chapter 5.2.2).

What is more unclear however is the extent of household participation and cultural acceptance towards AD digestion of FW, although in reality it is more likely to be a business or market oriented question of whether if AD operators are sufficiently competitive in procuring FW compared to other procurers. To end this, UK's AD plant infrastructure data interestingly had shown a consistent increase in the establishment of AD plants over the past 2 decades, which in turn demonstrated strong industry participation and business culture acceptance for the deployment of AD plants for recycling FW and other wastes.

Here the people/cultural barrier for refuel station deployment is more obscure based on the limited use of transport biomethane, i.e. in form of CBM, LBM or LCBM. Here the study is not able to draw on sufficient data to establish a reasonable assessment of whether deployment of such stations is popular, although based on the introduction of supporting policy incentives for promoting use of renewable transport fuel, i.e. the RTFC. It can however be inferred based on the continued adoption of these policies that there is significant political and financial will in at least the short term to help improve people's perception and cultural acceptance towards using biomethane as an alternative road transport fuel. In reality, this is mainly applicable to heavy duty or heavy goods vehicles and far less so for consumer passenger vehicles as the latter is mainly monopolized by petrol or diesel and increasingly, electrical vehicles, which will most likely serve to significantly reduce individual participation from a consumer usage perspective.

On the basis of the above, here it can be argued that the deployment of FWtTBC pathway by means of an external incentive can be useful for increasing people participation and eventually cultural acceptance (as seen with the RTFC incentive introduced to promote use of biomethane as an alternative transport fuel) or that an inherent cultural acceptance and willingness could give rise to greater success of people participation in, i.e. in FW collection and AD construction schemes.

Both factors are assumed to be at play in assessing FWtTBC pathway deployment at Leeds city region, owing to a decent history of local FW collection efforts with future plan to upscale this to the city level, in addition to past efforts made towards establishing a local AD plant and transport biomethane refuel station. It is also worth noting the alternative availability of MOTF AD plant in close proximity to Leeds to help enable the FWtTBC pathway deployment process, albeit with slightly more complex cost and logistical challenges compared to the utilizing an AD plant based closer to the city centre (which Leeds city council previously attempted and not succeeded in).

On this basis, it can be assumed that people and cultural barriers towards FWtTBC pathway deployment at Leeds city region is reasonably low to moderate and is certainly sufficient to enable the successful deployment of the FWtTBC pathway, given that part of the city has been local FW collection scheme deployment or heard of plans for citywide upscale, but with a majority of its urban population not participated in any FW collection trial (apart from those in the Rothwell region) to date to the extent indicated by the research data. The same rationale can be applied to conclude that UK also possess a low to at most a moderate barrier for FWtTBC pathway deployment at the regional and national level owing to the reasons above.

Further uncertainties in the data however, pertains to the decline in FW collection between 2010 and 2050 as demonstrated by the WDF and WRAP regression analysis data trends, which could be attributed to a number of factors including reduced FW output for collection, reduced FW capture rate or drop of in local household participation (i.e. due to underlying effects of decreasing cultural acceptance). This consequently can constitute an interesting field of further research investigation, for uncovering the potentially changing dynamics in the future of FW recycling.

Base on the above inferences, it can be assumed that there is sufficient cooperation from local individuals and an absence of general societal or cultural distain that would significantly hamper FW collection rate (kg per individual per year) to the extent of invalidating FWtTBC pathway deployment across the NPH region under study, Consequently, people and culture barriers are seemed to be sufficiently low for the pathway deployment, but only in knowledge of this requires urgent research to elucidate key attributing factors responsible for anticipated future decline in FW collection that should and must be addressed.

Table 181. Revised Summary of rationale in support of low to medium barrier of FWtTBC pathway deployment from perspective of people participation and cultural acceptance (associated with people and culture criteria of the whole systems analysis) at the case study region of Leeds in addition to other UK city and counties.

	Local - Leeds	Other UK cities and counties
FW collection	Existing Rothwell FW collection trial	Existing FW collection trial at 60 other local authority regions
AD infrastructure	Past attempts of establishing AD infrastructure in city, and with local MOTF AD plant nearby	History of popularization of AD plant construction and AD industry development within the past one to two decades
Refuel station	Past attempts of establishing biomethane refuel stations albeit at a smaller scale, designed mainly for commercial uses	Extent of biomethane station establishment and usage appear to be small and not generally used by public

7.3 Techno-economics

In context of FWtTBC pathway deployment, the techno-economics pertaining mainly to both the technical conversion of FW to biomethane (i.e. the quantity of which is governed by FW to biomethane conversion yield) in addition to the costs and returns associated with this conversion process. The assessment of barriers associated with the techno-economics of FWtTBC pathway deployment consequently involves drawing information from a number of technical and financial metrics found through this study.

Namely these include technical FW to biomethane conversion data, revenue data for all AD revenue streams, in addition to capital and operation cost data in relation to the construction and operation of AD plant and other infrastructure that constitute to the part of the FWtTBC deployment pathway.

Here the technical data on FW to biomethane conversion is derived from research literature review on AD operations is used for cross-examining the possible technical conversion yields attainable from different combinations of FW types (i.e. mixed, commercial, household, commercial and household) and AD plant types (thermophilic, mesophilic) given specific operational conditions (i.e. process temperature, OLR). The results of this finding, which returned a FW to biomethane conversion range of 45-90m³ per tonne of FW is further compared with and found to be in reasonably close agreement with the data from NFCCC's Excel database (see Chapter 5 for details).

Insights surrounding key revenue streams and data were attained from specialist databases and reports such as the RTFC market database and alternative fuel industry report for establishing data on RTFC and biomethane unit sales prices respectively. Here it is worth noting that the latter data only constitute a point in time data (reported in 2011) and should be replaced by more modern data where possible. The market data of RTFC by contrast suggested for a consistent range of 10-30p per certificate between 2017 and 2020 (weekly data), and is veering towards the upper end of this range by 2020.

Lastly, data associated with the AD construction costs against their waste intake capacity (or AD plant size) for a number of small and large AD plant is attained through dedicated industry news sites, which helped to establish a linear and exponential trend correlation between the two. Use of the linear relationship for example, found an average construction cost of £3.75 million is required to provide a AD waste intake capacity of 10,000 tonne, and with smaller AD plants being generally more expensive relative to size than larger AD plants (see Chapter 6 for details).

By combining these 3 data streams, an integrated payback or breakeven period under a number of reasonable scenarios is established for assessing the techno-economics associated with hypothetically deploying FWtTBC pathway for Leeds city and West Yorkshire metropolitan county region using MOTF AD plant. Here the results established low payback periods of between 2 and 10 years across a significant number of modest scenario estimations (see Chapter 6.2.5) which highlighted the sufficiently strong techno-economic of FWtTBC pathway at Leeds and West Yorkshire.

These estimations however does not account for the techno-economics of specific operations within each FWtTBC pathway component which is beyond the scope of this study, but do in

general outline that under circumstances of normal operation (where each pathway input metric remains to be moderate or high in value), the techno-economics of FWtTBC pathway deployment is more than financially self-sufficient. Consequently, whilst the information barriers towards determining the precise techno-economics of FWtTBC pathway for each deployment scenario maybe high (as shown here where it requires the establishment of key technical and financial data from several sources), its actual barrier with respect to pathway deployment is by contrast reasonably low once the findings can be ascertained with reasonable degree of certainty (as with outcome of this research, outlined in summary of Chapter 6).

For a more accurate assessment, future studies should further consider both the techno-economics that is associated within each FWtTBC pathway component, whilst also using more representative case specific operational data obtained through collaboration with key stakeholders for the implementation of a specific FWtTBC pathway in question to help put insights derived from this research into practice.

7.4 Infrastructure and investment

The infrastructure and investment assessment criteria aims to assess whether there exist sufficient AD infrastructure capacity to accommodate for intake of collected FW within relevant NPH city and metropolitan county regions, and whether corresponding investments in these infrastructure is deemed to be profitable from the perspective of AD operator or external investor.

To this end, the research adopted a city level case study analysis, which used data provided by the NFCCC and AD biogas map to identify 4 AD plants within close proximity to Leeds city. These mainly include South Kirby Business Park, Maltings Organic Treatment Plant (MOTF), Greencore Grocery and Allerton Waste Recovery Park, which was found to possess a combined dedicated FW capacity of 122,125 tonnes and can accommodate for FW collected from a population range of 3,000,000 to 6,000,000, that can comfortably cover the entire West Yorkshire region with significant capacity to spare (assuming for low to moderate FW collection rate of 20 to 40 kg/person/year). The study also found that the dedicated FW intake capacity of 50,000 tonnes per year at MOTF alone is more than sufficient for accommodating all FW collected by the entire population of Leeds (see Chapter 5.3.5).

To elaborate, the 4 respective AD plants was also found to be situated within relative close proximity to Leeds and West Yorkshire region (extending into South, North and East of Leeds city), which can be used to enable effective deployment of FW for FWtTBC pathway across these surrounding regions. Here it is important to note that the region towards the North of Leeds is likely to be most at risk of running out of AD FW capacity, due to it being covered only by the small Greencore Grocery AD plant (which possess a dedicated FW capacity of 9,125 tonnes).

Furthermore, the research established indications of further infrastructure investment at Leeds in form of upscaling current FW collection to the entire city as well as to further expand the capacity of the existing small-scale biomethane refuel station. These collectively outlined strong political will and investment by Leeds city council towards deploying the FWtTBC pathway to a reasonable degree.

Assessment on AD infrastructure investment is based on similar techno-economic findings outlined in the section above (see Chapter 7.3 above) likewise have established a reasonably low payback or breakeven period of 2 to 10 years under scenarios of normal operations for MOTF AD plant (Capital and Operational). This trend by logic should indicate low barrier to investment for AD plant construction and operation for FWtTBC pathway deployment on the above basis.

It can be argued that in typical circumstances, such barriers maybe greater than expected owing to limited local city council funding, precedence of previously failed attempt in AD deployment at Leeds and the recent establishment of a (Veolia) waste incineration plant based near Leeds city centre. However, the reverse argument that there still exist significant wiliness by Leeds city council to reattempt FWtTBC pathway deployment if they are given the opportunity, as seen with their plans to upscale FW collection and transport refuel station operation as outlined above.

By combining the two above findings, it can be reasonably deduced that the barrier towards FWtTBC pathway deployment from an AD infrastructure and investment perspective across Leeds city region is low owing to existing infrastructure availability and strong political will by Leeds city council (a key stakeholder) to further plan for upscaling of relevant infrastructure that are critical to FWtTBC pathway deployment.

7.5 Policy and environment

The policy and environment assessment criteria primarily focus on FWtTBC pathway deployment barriers in context of supporting policy and environment set out by the UK government. Here the research presents a number of irrefutable findings that indicates there is extremely strong policy support for FWtTBC pathway deployment from a financial and environmental standpoint that will likely extend to the medium and long term future.

Here the most notable finding includes the development and enforcement of FW landfill tax and RTFC policies, which have proven to be extremely effective in promoting FWtTBC pathway deployment through provision of strong financial incentives (or disincentives). This is evidently seen in the calculation of combined revenues and breakeven periods associated with FWtTBC pathway deployment (see Chapter 6 for details).

Given UK's current stance on further accelerating FW elimination from landfill (with target set by 2030 as established by the study), it is likely that the strength of incentive offered by such policies may increase further in the foreseeable future.

The research further analysed each key metric component of the FWtTBC pathway, from which a number of key policy recommendations is established. To elaborate, this research outlined policy recommendations aimed at improving each component of the FWtTBC pathway, which includes those associated with (i) FW collection, (ii) FW to biomethane conversion, (iii) AD operation and biomethane sales, to ensure the pathway can be optimized with respect to its input-output metrics.

Here it is worth noting these policies are ultimately designed to help mitigate the financial risk of FWtTBC pathway deployment, and largely includes different forms of conditional loans and investments designed to assist with the development or optimization of specific pathway components. A number of policy recommendation is also designed for mitigating the risk of extreme price fluctuation in key FWtTBC pathway revenue streams, i.e. that of RTFC and biomethane sales revenue, by providing safeguard guarantees in the minimum value attributed to these respective metrics (see Chapter 5 and 6, policy table at end of each section).

In light of the above, it is believed that deployment of FWtTBC pathway at Leeds city and similar regions is entirely feasible with the help of current policies and those established as part of this study (as key supporting policy recommendations).

7.6 Process and procedures

In context of FWtTBC pathway process and procedures adopted, tangible research elements relates to the process operational diagrams that refer to material, energy and financial metric conversion values. Whilst it is not feasible to comment on specific real-world AD plant operational processes and procedures used due to lack of real world facility and data access, aspects of general process AD operations such as FW type, AD plant type (i.e. by temperature used or size), is fully utilized to ensure the modelling is as real-world relevant as it can be, notwithstanding the aforementioned limitations.

A similar conclusion is drawn for household FW collection and refuelling station component of the FWtTBC pathway deployment, which accounts for aggregate material, energy and revenue potential arising from collected FW and resulting transport biomethane but does not include details surrounding specific physical processes involved.

It is also worth noting that modelling of each FWtTBC pathway component has inherent loss factors arising from real world operational inefficiencies built in as reflected by the scope of real-world data used. This is both true for variable WRAP and Waste Data Flow (WDF) FW collection data obtained from actual FW collection trials and that of FW to biomethane conversion data attained from actual anaerobic digestion of FW under typical AD operational process conditions. For financial estimations of the FWtTBC pathway also accounted for variations in the upper and lower value of each revenue and cost component, respectively as well as the overall breakdown period for pathway deployment, albeit on a simplified basis by using revenue and cost against per tonne of FW digested.

The above data collectively suggests a low barrier for implementing the necessary FWtTBC pathway process operations for achieving sufficiently reasonable FW collection, FW to biomethane conversion and revenue generation values that justifies pathway deployment. Although in context of limitations outlined above, this conclusion should be further cross-validated with findings from future research collaborations using more accurate and specific real-world facility oriented operational processes and procedural data when they become available or accessible.

Chapter 8. Summary and conclusions

8.1 Summary of research outcome and challenges

This doctoral thesis has presented a novel research approach for establishing key qualitative and quantitative metrics associated with deployment of the Food Waste to Transport Biomethane Conversion (FWtTBC) pathway, and evaluating whether the deployment of this pathway is viable across Leeds on basis of values of these key metrics. To this end, a combination of material-energy and financial conversion metrics were used (see Chapter 4).

The results indicate that there exist sufficient evidence to suggest that deployment of FWtTBC pathway under normal operational conditions is financially self-sustainable based on the relatively short payback period (of 2 to 10 years) established.

The study also established key risk factors that could significantly undermine the successful deployment of the FWtTBC pathway in a financially self-sustainable manner. These namely includes removal of RTFC and landfill tax avoidance policies, consistent decline in household FW supply for the foreseeable future and systemic disruptions to the entire pathway that would reduce the value of each input metric by more than 25%.

To this end, the research also established relevant capital and operational costs of AD operations in addition to the deployment of entire FWtTBC pathway by using publicly available data and reasonable methods of cost estimation (OPEX as reasonable % of CAPEX, and total pathway deployment cost as % of total AD total cost).

Using NPH regions and Leeds city as a case study, the research further outlined sufficient AD infrastructure availability (arising from 4 AD plants) and political will for the FWtTBC pathway to be deployed at the local Leeds city and possibly further expanded to the West Yorkshire metropolitan county level.

Finally, the research established a number of policy recommendations across each relevant chapters (see end of each section for Chapters 5 and 6) that is thought to be effective in mitigation key risk factors that could undermine successful pathway deployment either financially or operationally. Namely, these include policy recommendations to optimize household FW disposal and capture rate, FW supply flexibility and FW collection logistics in addition to those that endeavour to safeguard RTFC, biomethane sales and avoided FW landfill tax revenues.

8.2 Limitations

In context of key research challenges and limitations surrounding facility and data access, it is strongly advised to conduct further relevant studies under conditions where precise operational data is applicable for integrated into the existing methodological approach or an upgraded version of it, to help cross-verify findings arising from this research.

Namely, this includes data arising from specific FW collection trial or schemes, relevant FW to biomethane conversion in context of specific operational processes used at the corresponding

recipient AD plant, and that of final transport biomethane output available for biomethane fleet refuelling.

For financial calculations, more specific combined cost (CAPEX and OPEX) and revenue stream data pertaining to individual components of the specific FWtTBC pathway deployment in question, namely, that of FW collection, anaerobic digestion alongside refuel station and fleet operation, should also be accounted for to give rise to more accurate breakeven and other return on investment findings.

To this end, additional cost and revenue factors such as from material and energy price inflation, and digestate sales could also be accounted for to portray a more accurate estimation of relevant financials metrics to the end user or stakeholder.

8.3 Proposal of further research

It would also be interesting to consequently, should conditions permit, draw on several such studies across high potential regions where FWtTBC pathway deployment is already undergoing local trial but with interest for broader city or region wide expansion, for comparative analysis and to aid in the expansion process as to-date, no such comparisons appear to be available.

These collective findings should then be used to inform specific modelling on impact of relevant policies (i.e. RTFO) and regulations (i.e. landfill tax) to further elucidate, on basis of updated and more precise information, their relative effects on cost-benefit trade-off pertaining to specific FWtTBC pathway deployment in question.

Here a final concluding remark would be that all above research findings and further study suggestions pertaining to this doctoral thesis is aimed at, first, to provide new knowledge and insight towards informing suitable strategies and support mechanisms for FWtTBC pathway deployment, and second, to help support real-world pathway deployment process to occur at region of interest in hope of establishing successful case studies to inspire further relevant research and similar deployments in the foreseeable future.

To this end, whilst relevant foundational work pertaining to evaluating cost-benefit trade-off and strategies surrounding FWtTBC pathway deployment is outlined within the body of this thesis, much research will still require on a consistent and evolutionary basis to elucidate the full extent of benefits attainable (relative to cost) for such deployments to make this a reality in operation.

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Appendix

Appendix table 1. Summary of food waster research publications

Study titles	Number of individual data points
1 Sustainable food waste and energy systeMS- p175-176	22
2 J. P. Lee, J. S. Lee, and S. C. Park, "Two-phase methanization of food wastes in pilot scale," <i>Applied Biochemistry and Biotechnol- ogy</i> , vol. 77–79, pp. 585–593, 1999.	1
3 V. N. Gunaseelan, "Biochemical methane potential of fruits and vegetable solid waste feedstocks," <i>Biomass and Bioenergy</i> , vol. 26, no. 4, pp. 389–399, 2004.	1
4 J.-H. Youn and H.-S. Shin, "Comparative performance between temperature-phased and conventional mesophilic two-phased processes in terMSof anaerobically produced bioenergy from food waste," <i>Waste Management and Research</i> , vol. 23, no. 1, pp. 32–38, 2005.	6
5 C. J. Banks, M. Chesshire, S. Heaven, and R. Arnold, "Anaerobic digestion of source-segregated domestic food waste: perfor- mance assessment by mass and energy balance," <i>Bioresource Technology</i> , vol. 102, no. 2, pp. 612–620, 2011.	1
6 X. Dai, N. Duan, B. Dong, and L. Dai, "High-solids anaerobic co-digestion of sewage sludge and food waste in comparison with mono digestions: stability and performance," <i>Waste Man- agement</i> , vol. 33, no. 2, pp. 308–316, 2013.	10
7 C. Zhang, G. Xiao, L. Peng, H. Su, and T. Tan, "The anaerobic co-digestion of food waste and cattle manure," <i>Bioresource Technology</i> , vol. 129, pp. 170–176, 2013.	10
8 T. Forster-Carneiro, M. Pe´rez, and L. I. Romero, "Influence of total solid and inoculum contents on performance of anaerobic reactors treating food waste," <i>Bioresource Technology</i> , vol. 99, no. 15, pp. 6994–7002, 2008.	1
9 J. K. Kim, G. H. Han, B. R. Oh, Y. N. Chun, C.-Y. Eom, and S. W. Kim, "Volumetric scale-up of a three stage fermentation system for food waste treatment," <i>Bioresource Technology</i> , vol. 99, no. 10, pp. 4394–4399, 2008.	2
10 Zhang, R., El-Mashad, H. M., Hartmann, K., Wang, F., Liu, G., Choate, C., & Gamble, P. (2007). Characterization of food waste as feedstock for anaerobic digestion. <i>Bioresource Technology</i> , 98, 929–935. http://dx.doi.org/10.1016/j.biortech.2006.02.039	2
11 Bouallagui, H., Rachdi, B., Gannoun, H., & Hamdi, M. (2009). Mesophilic and thermophilic anaerobic co-digestion of abattoir wastewater and fruit and vegetable waste in anaerobic sequencing batch reactors. <i>Biodegradation</i> , 20, 401–409. http://dx.doi.org/10.1007/s10532-008-9231-1	8
12 im, J. K., Oh, B. R., Chun, Y. N., & Kim, S. W. (2006). Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. <i>Journal of Bioscience and Bioengineering</i> , 102, 328–332. doi:10.1263/jbb.102.328	8
13 Prema et al. (1991) (reference not shown in literature) Likely: 38-6-1 Anaerobic digestionwaste of fruit and vegetable processing wastes for biogas production	9
14 Krishna, N., Devi, S. S., Viswnath, P., Deepak, S., & Sarada, R. (1991). Anaerobic digestion of canteen wastes for biogas production: Process optimization. <i>Process Biochemistry</i> , 26, 1–5	4
15 Ortega, L., Barrington, S., & Guiot, S. R. (2008). Thermophilic adaptation of a mesophilic anaerobic sludge for food waste treatment. <i>Journal of Environmental Management</i> , 88, 517–525. http://dx.doi.org/10.1016/j.jenvman.2007.03.032	2
16 Berlian, S., Sukandar, & Seno, D. P. (2013). Biogas recovery from anaerobic digestion process of mixed fruit-vegetable wastes energy. <i>Procedia</i> , 32, 176–182	1
17 Bouallagui, H., Haouari, O., Touhami, Y., Ben Cheikh, R., & Marouani, L., & Hamdi, M. (2004). Effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste. <i>Process Biochemistry</i> , 39, 2143–2148. http://dx.doi.org/10.1016/j.procbio.2003.11.022	10
18 Chen, X., Romano, R. T., & Zhang, R. (2010). Anaerobic digestion of food wastes for biogas production. <i>International Journal of Agricultural & Biological Engineering</i> , 3, 61. Retrieved from http://www.ijabe.org	5
19 Zhang, L., Lee, Y., Jahng, D., 2011. Anaerobic co-digestion of food waste and piggery wastewater:	1
20 Zhang, C., Su, H., Tan, T., 2013. Batch and semi-continuous anaerobic digestion of food waste in a dual solid-liquid system. <i>Bioresour. Technol.</i> 145, 10–16.	3
21 Gunaseelan, V.N., 2004. Biochemical methane potential of fruits and vegetable solid waste feedstocks. <i>Biomass Bioenergy</i> 26, 389–399.	1
22 Trzcinski, A.P., Stuckey, D.C., 2011. Parameters affecting the stability of the digestate from a two-stage anaerobic process treating the organic fraction of municipal solid waste. <i>Waste Manage.</i> 31, 1480–1487.	3
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Total		161

Appendix table 2 Time adjusted population data for NPH city regions of Leeds, Manchester, Liverpool, Sheffield and Newcastle, with total total shown

	Leeds	pManchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	705,337	407,482	428,696	504,082	260,463	2,306,060
2002	706,094	412,654	430,652	505,153	261,182	2,315,735
2003	707,329	421,181	431,860	506,313	261,040	2,327,723
2004	712,792	429,396	434,987	510,631	261,062	2,348,868
2005	724,729	440,223	439,144	516,705	263,761	2,384,562
2006	725,823	448,249	439,896	518,574	264,402	2,396,944
2007	728,170	455,074	440,397	520,823	265,712	2,410,176
2008	731,333	462,012	441,284	524,968	265,798	2,425,395
2009	733,534	468,425	444,285	529,290	267,573	2,443,107
2010	737,149	477,254	448,112	535,483	270,819	2,468,817
2011	730,571	480,805	449,326	538,122	270,127	2,468,951
2012	737,358	488,346	453,779	543,566	272,884	2,495,933
2013	740,687	491,567	455,543	546,487	276,793	2,511,077
2014	745,186	496,710	458,129	549,697	279,283	2,529,005
2015	752,924	507,744	464,488	555,406	281,735	2,562,297
2016	760,750	519,281	471,331	560,253	284,668	2,596,283
2017	765,825	525,679	475,286	564,257	286,583	2,617,630
2018	770,765	531,520	478,975	568,052	288,366	2,637,678
2019	775,250	536,690	482,300	571,360	289,810	2,655,410
2020	779,210	541,138	485,249	574,197	290,851	2,670,645
2021	782,640	544,993	487,861	576,655	291,583	2,683,732
2022	786,035	548,619	490,414	579,120	292,306	2,696,494
2023	789,613	552,097	493,003	581,711	293,141	2,709,565
2024	793,408	555,696	495,788	584,502	294,163	2,723,557
2025	797,426	559,435	498,740	587,546	295,397	2,738,544
2026	801,530	563,205	501,765	590,703	296,734	2,753,937
2027	805,646	566,984	504,835	593,912	298,114	2,769,491
2028	809,503	570,612	507,814	596,949	299,394	2,784,272
2029	813,210	574,145	510,708	599,908	300,617	2,798,588
2030	816,852	577,684	513,572	602,878	301,799	2,812,785
2031	820,392	581,213	516,362	605,839	302,929	2,826,735
2032	823,451	584,488	518,922	608,484	303,806	2,839,151
2033	826,134	587,509	521,253	610,881	304,454	2,850,231
2034	828,592	590,375	523,403	613,131	304,983	2,860,484
2035	830,968	593,180	525,495	615,376	305,484	2,870,503
2036	833,130	595,824	527,448	617,481	305,888	2,879,771
2037	835,225	598,413	529,329	619,583	306,268	2,888,818
2038	837,386	600,990	531,215	621,717	306,671	2,897,979
2039	839,597	603,537	533,095	623,873	307,083	2,907,185
2040	841,847	606,036	534,958	626,023	307,488	2,916,352
2041	844,084	608,456	536,782	628,143	307,876	2,925,341

Appendix table 3. Time adjusted population data for NPH metropolitan county of West Yorkshire, Liverpool, Sheffield and Newcastle, with total total shown

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2001	2,054,017	2,477,933	1,343,312	1,248,946	1,069,736	8,193,944
2002	2,063,996	2,484,854	1,341,909	1,253,631	1,069,339	8,213,729
2003	2,073,482	2,500,262	1,341,482	1,258,781	1,067,482	8,241,489
2004	2,088,988	2,511,444	1,342,416	1,265,697	1,065,444	8,273,989
2005	2,112,710	2,525,556	1,343,636	1,275,332	1,067,887	8,325,121
2006	2,124,528	2,543,614	1,343,260	1,281,659	1,068,866	8,361,927
2007	2,139,047	2,559,925	1,342,367	1,288,162	1,071,665	8,401,166
2008	2,155,341	2,581,403	1,343,666	1,297,282	1,073,310	8,451,002
2009	2,167,768	2,601,125	1,346,424	1,305,570	1,076,711	8,497,598
2010	2,182,411	2,622,864	1,350,265	1,314,386	1,081,933	8,551,859
2011	2,189,481	2,642,558	1,354,695	1,321,341	1,086,009	8,594,084
2012	2,202,184	2,658,219	1,360,047	1,329,378	1,089,355	8,639,183
2013	2,212,364	2,670,425	1,361,867	1,335,442	1,094,143	8,674,241
2014	2,223,256	2,686,569	1,366,943	1,342,775	1,098,801	8,718,344
2015	2,239,230	2,710,328	1,374,896	1,352,144	1,101,988	8,778,586
2016	2,256,285	2,736,945	1,384,493	1,361,932	1,107,801	8,847,456
2017	2,267,397	2,753,631	1,389,494	1,369,034	1,110,993	8,890,549
2018	2,278,763	2,770,616	1,394,736	1,376,227	1,114,354	8,934,696
2019	2,289,466	2,786,963	1,399,822	1,382,947	1,117,394	8,976,592
2020	2,299,337	2,802,146	1,404,688	1,389,095	1,119,953	9,015,219
2021	2,308,178	2,816,268	1,409,195	1,394,710	1,122,050	9,050,401
2022	2,316,505	2,829,424	1,413,545	1,400,110	1,123,963	9,083,547
2023	2,324,620	2,841,644	1,417,856	1,405,399	1,125,881	9,115,400
2024	2,332,745	2,853,531	1,422,315	1,410,709	1,127,945	9,147,245
2025	2,340,848	2,865,032	1,426,847	1,416,126	1,130,156	9,179,009
2026	2,348,908	2,876,255	1,431,339	1,421,561	1,132,437	9,210,500
2027	2,356,639	2,886,848	1,435,724	1,426,852	1,134,624	9,240,687
2028	2,363,963	2,897,103	1,439,956	1,431,870	1,136,632	9,269,524
2029	2,371,012	2,907,041	1,444,044	1,436,758	1,138,544	9,297,399
2030	2,377,871	2,916,676	1,448,027	1,441,578	1,140,354	9,324,506
2031	2,384,492	2,926,125	1,451,778	1,446,319	1,142,080	9,350,794
2032	2,390,420	2,935,055	1,455,204	1,450,661	1,143,435	9,374,775
2033	2,395,936	2,943,729	1,458,399	1,454,763	1,144,525	9,397,352
2034	2,401,203	2,952,311	1,461,440	1,458,694	1,145,448	9,419,096
2035	2,406,385	2,960,754	1,464,419	1,462,572	1,146,303	9,440,433
2036	2,411,398	2,969,171	1,467,236	1,466,363	1,147,034	9,461,202
2037	2,416,133	2,977,190	1,469,849	1,470,054	1,147,603	9,480,829
2038	2,421,003	2,985,311	1,472,504	1,473,789	1,148,192	9,500,799
2039	2,425,999	2,993,529	1,475,195	1,477,556	1,148,811	9,521,090
2040	2,431,109	3,001,826	1,477,928	1,481,343	1,149,439	9,541,645
2041	2,436,242	3,010,165	1,480,643	1,485,092	1,150,056	9,562,198

Appendix table 4. Table of data for population multiplier difference between NPH county region and city region data (for individual regions and total 5-NPH region total)

	West Yorkshire vs. Leeds	Greater Manchester vs. Manchester	Merseyside vs. Liverpool	South Yorkshire vs. Sheffield	Tyne and Wear vs. Newcastle	NPH 5-metropolitan county vs. city region
2001	2.912107	6.081086	3.133484	2.477664	4.107056	3.553222
2002	2.923118	6.02164	3.115994	2.481686	4.094229	3.546921
2003	2.931425	5.936312	3.106289	2.486172	4.089343	3.54058
2004	2.930712	5.848783	3.086106	2.478692	4.081191	3.522543
2005	2.915172	5.736992	3.059671	2.468201	4.048692	3.491258

2006	2.927061	5.674556	3.053585	2.471506	4.042579	3.488578
2007	2.937565	5.625294	3.048084	2.47332	4.033183	3.485706
2008	2.94714	5.587307	3.044901	2.471164	4.038067	3.484382
2009	2.955239	5.552917	3.030541	2.466644	4.02399	3.478193
2010	2.96061	5.49574	3.013231	2.45458	3.995041	3.46395
2011	2.996945	5.496112	3.014949	2.455467	4.020364	3.480865
2012	2.986587	5.443311	2.997157	2.445661	3.992008	3.461304
2013	2.986908	5.432474	2.989547	2.443685	3.952929	3.454391
2014	2.983491	5.408727	2.983751	2.442755	3.934364	3.447342
2015	2.974045	5.337981	2.960025	2.434515	3.911435	3.426061
2016	2.965869	5.270643	2.937411	2.430923	3.891554	3.407739
2017	2.960725	5.238237	2.92349	2.42626	3.876688	3.396412
2018	2.956495	5.212628	2.911918	2.422713	3.864374	3.387334
2019	2.953197	5.192873	2.902389	2.420448	3.855609	3.380492
2020	2.950857	5.178247	2.894778	2.419196	3.850607	3.375671
2021	2.949221	5.167531	2.888517	2.418621	3.848132	3.372319
2022	2.947076	5.157357	2.88235	2.417651	3.845159	3.368651
2023	2.943999	5.147001	2.875958	2.415975	3.840749	3.364156
2024	2.940158	5.135058	2.868797	2.413523	3.834422	3.358566
2025	2.935505	5.121296	2.860903	2.410239	3.825889	3.351784
2026	2.93053	5.106942	2.852608	2.406558	3.816337	3.344485
2027	2.925154	5.091586	2.843947	2.402464	3.806007	3.336601
2028	2.920265	5.077186	2.835597	2.398647	3.796442	3.329245
2029	2.915621	5.063252	2.827534	2.394964	3.787357	3.322175
2030	2.911018	5.048913	2.819521	2.39116	3.778521	3.315044
2031	2.906528	5.034514	2.811551	2.387299	3.770124	3.307984
2032	2.902929	5.021583	2.804283	2.384058	3.763701	3.301964
2033	2.900178	5.010526	2.797872	2.381418	3.759271	3.297049
2034	2.897932	5.000739	2.792189	2.37909	3.755777	3.292833
2035	2.895882	4.991325	2.786742	2.376713	3.752416	3.288773
2036	2.894384	4.983302	2.781764	2.37475	3.74985	3.285401
2037	2.892793	4.975143	2.776816	2.372651	3.747055	3.281906
2038	2.891143	4.967322	2.771955	2.370514	3.744051	3.278422
2039	2.88948	4.959976	2.767227	2.36836	3.741044	3.27502
2040	2.887828	4.953214	2.762699	2.366276	3.738159	3.271774
2041	2.886255	4.947219	2.758369	2.364258	3.735452	3.268746

Appendix table 5. Total food waste collection data using ONS 2018 population data and minimum acceptable (based on all real-world collection data used) per capita food waste data value of 20kg/person/year across all NPH city regions

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	14,107	8,150	8,574	10,082	5,209	46,121
2002	14,122	8,253	8,613	10,103	5,224	46,315
2003	14,147	8,424	8,637	10,126	5,221	46,554
2004	14,256	8,588	8,700	10,213	5,221	46,977
2005	14,495	8,804	8,783	10,334	5,275	47,691
2006	14,516	8,965	8,798	10,371	5,288	47,939
2007	14,563	9,101	8,808	10,416	5,314	48,204
2008	14,627	9,240	8,826	10,499	5,316	48,508
2009	14,671	9,369	8,886	10,586	5,351	48,862
2010	14,743	9,545	8,962	10,710	5,416	49,376
2011	14,611	9,616	8,987	10,762	5,403	49,379
2012	14,747	9,767	9,076	10,871	5,458	49,919
2013	14,814	9,831	9,111	10,930	5,536	50,222
2014	14,904	9,934	9,163	10,994	5,586	50,580
2015	15,058	10,155	9,290	11,108	5,635	51,246
2016	15,215	10,386	9,427	11,205	5,693	51,926
2017	15,317	10,514	9,506	11,285	5,732	52,353
2018	15,415	10,630	9,580	11,361	5,767	52,754
2019	15,505	10,734	9,646	11,427	5,796	53,108
2020	15,584	10,823	9,705	11,484	5,817	53,413
2021	15,653	10,900	9,757	11,533	5,832	53,675
2022	15,721	10,972	9,808	11,582	5,846	53,930
2023	15,792	11,042	9,860	11,634	5,863	54,191
2024	15,868	11,114	9,916	11,690	5,883	54,471
2025	15,949	11,189	9,975	11,751	5,908	54,771
2026	16,031	11,264	10,035	11,814	5,935	55,079
2027	16,113	11,340	10,097	11,878	5,962	55,390
2028	16,190	11,412	10,156	11,939	5,988	55,685
2029	16,264	11,483	10,214	11,998	6,012	55,972
2030	16,337	11,554	10,271	12,058	6,036	56,256
2031	16,408	11,624	10,327	12,117	6,059	56,535
2032	16,469	11,690	10,378	12,170	6,076	56,783
2033	16,523	11,750	10,425	12,218	6,089	57,005
2034	16,572	11,808	10,468	12,263	6,100	57,210
2035	16,619	11,864	10,510	12,308	6,110	57,410
2036	16,663	11,916	10,549	12,350	6,118	57,595
2037	16,705	11,968	10,587	12,392	6,125	57,776
2038	16,748	12,020	10,624	12,434	6,133	57,960
2039	16,792	12,071	10,662	12,477	6,142	58,144
2040	16,837	12,121	10,699	12,520	6,150	58,327
2041	16,882	12,169	10,736	12,563	6,158	58,507

Appendix table 6. Total food waste collection data using ONS 2018 population data and Leeds Rothwell representative (based on all real-world collection data used) per capita food waste data value of 40kg/person/year across all NPH city regions

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	28,213	16,299	17,148	20,163	10,419	92,242
2002	28,244	16,506	17,226	20,206	10,447	92,629
2003	28,293	16,847	17,274	20,253	10,442	93,109
2004	28,512	17,176	17,399	20,425	10,442	93,955
2005	28,989	17,609	17,566	20,668	10,550	95,382
2006	29,033	17,930	17,596	20,743	10,576	95,878

2007	29,127	18,203	17,616	20,833	10,628	96,407
2008	29,253	18,480	17,651	20,999	10,632	97,016
2009	29,341	18,737	17,771	21,172	10,703	97,724
2010	29,486	19,090	17,924	21,419	10,833	98,753
2011	29,223	19,232	17,973	21,525	10,805	98,758
2012	29,494	19,534	18,151	21,743	10,915	99,837
2013	29,627	19,663	18,222	21,859	11,072	100,443
2014	29,807	19,868	18,325	21,988	11,171	101,160
2015	30,117	20,310	18,580	22,216	11,269	102,492
2016	30,430	20,771	18,853	22,410	11,387	103,851
2017	30,633	21,027	19,011	22,570	11,463	104,705
2018	30,831	21,261	19,159	22,722	11,535	105,507
2019	31,010	21,468	19,292	22,854	11,592	106,216
2020	31,168	21,646	19,410	22,968	11,634	106,826
2021	31,306	21,800	19,514	23,066	11,663	107,349
2022	31,441	21,945	19,617	23,165	11,692	107,860
2023	31,585	22,084	19,720	23,268	11,726	108,383
2024	31,736	22,228	19,832	23,380	11,767	108,942
2025	31,897	22,377	19,950	23,502	11,816	109,542
2026	32,061	22,528	20,071	23,628	11,869	110,157
2027	32,226	22,679	20,193	23,756	11,925	110,780
2028	32,380	22,824	20,313	23,878	11,976	111,371
2029	32,528	22,966	20,428	23,996	12,025	111,944
2030	32,674	23,107	20,543	24,115	12,072	112,511
2031	32,816	23,249	20,654	24,234	12,117	113,069
2032	32,938	23,380	20,757	24,339	12,152	113,566
2033	33,045	23,500	20,850	24,435	12,178	114,009
2034	33,144	23,615	20,936	24,525	12,199	114,419
2035	33,239	23,727	21,020	24,615	12,219	114,820
2036	33,325	23,833	21,098	24,699	12,236	115,191
2037	33,409	23,937	21,173	24,783	12,251	115,553
2038	33,495	24,040	21,249	24,869	12,267	115,919
2039	33,584	24,141	21,324	24,955	12,283	116,287
2040	33,674	24,241	21,398	25,041	12,300	116,654
2041	33,763	24,338	21,471	25,126	12,315	117,014

Appendix table 7. Total food waste collection data using ONS 2018 population data and maximum achievable (based on all real-world collection data used) per capita food waste data value of 100kg/person/year across all NPH city regions

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	70,534	40,748	42,870	50,408	26,046	230,606
2002	70,609	41,265	43,065	50,515	26,118	231,574
2003	70,733	42,118	43,186	50,631	26,104	232,772
2004	71,279	42,940	43,499	51,063	26,106	234,887
2005	72,473	44,022	43,914	51,671	26,376	238,456
2006	72,582	44,825	43,990	51,857	26,440	239,694
2007	72,817	45,507	44,040	52,082	26,571	241,018
2008	73,133	46,201	44,128	52,497	26,580	242,540
2009	73,353	46,843	44,429	52,929	26,757	244,311
2010	73,715	47,725	44,811	53,548	27,082	246,882
2011	73,057	48,081	44,933	53,812	27,013	246,895
2012	73,736	48,835	45,378	54,357	27,288	249,593
2013	74,069	49,157	45,554	54,649	27,679	251,108
2014	74,519	49,671	45,813	54,970	27,928	252,901
2015	75,292	50,774	46,449	55,541	28,174	256,230
2016	76,075	51,928	47,133	56,025	28,467	259,628

2017	76,583	52,568	47,529	56,426	28,658	261,763
2018	77,077	53,152	47,898	56,805	28,837	263,768
2019	77,525	53,669	48,230	57,136	28,981	265,541
2020	77,921	54,114	48,525	57,420	29,085	267,065
2021	78,264	54,499	48,786	57,666	29,158	268,373
2022	78,604	54,862	49,041	57,912	29,231	269,649
2023	78,961	55,210	49,300	58,171	29,314	270,957
2024	79,341	55,570	49,579	58,450	29,416	272,356
2025	79,743	55,944	49,874	58,755	29,540	273,854
2026	80,153	56,321	50,177	59,070	29,673	275,394
2027	80,565	56,698	50,484	59,391	29,811	276,949
2028	80,950	57,061	50,781	59,695	29,939	278,427
2029	81,321	57,415	51,071	59,991	30,062	279,859
2030	81,685	57,768	51,357	60,288	30,180	281,279
2031	82,039	58,121	51,636	60,584	30,293	282,674
2032	82,345	58,449	51,892	60,848	30,381	283,915
2033	82,613	58,751	52,125	61,088	30,445	285,023
2034	82,859	59,038	52,340	61,313	30,498	286,048
2035	83,097	59,318	52,550	61,538	30,548	287,050
2036	83,313	59,582	52,745	61,748	30,589	287,977
2037	83,523	59,841	52,933	61,958	30,627	288,882
2038	83,739	60,099	53,122	62,172	30,667	289,798
2039	83,960	60,354	53,310	62,387	30,708	290,719
2040	84,185	60,604	53,496	62,602	30,749	291,635
2041	84,408	60,846	53,678	62,814	30,788	292,534

Appendix table 8. Total food waste collection data using ONS 2018 population data and time-adjusted WRAP data across all NPH city regions (based on data availability) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2007	63,559	40,041	40,060	45,902	24,110	213,681
2010	51,861	33,588	32,745	37,900	19,602	175,562
2012	51,147	33,598	32,224	37,680	19,251	173,698
2014	53,676	35,461	33,459	39,459	20,269	182,143
2015	53,282	35,621	33,251	39,202	20,122	181,309
2017	52,875	36,070	33,132	38,939	20,030	180,919
2018	49,533	33,912	31,060	36,490	18,746	169,604
2020	39,178	26,979	24,555	28,863	14,839	134,300
2025	32,757	22,856	20,550	24,099	12,267	112,482
2030	28,047	19,781	17,656	20,649	10,448	96,576
2035	24,563	17,473	15,546	18,135	9,102	84,810
2040	20,787	14,901	13,225	15,411	7,661	71,972
2045	17,932	12,792	11,314	13,173	6,482	61,682
2050	15,831	11,207	9,878	11,489	5,599	53,997

*Values for 2020-2050 years are estimated via best regression trendline analysis in Excel using original data

Appendix table 9. Total food waste collection data using ONS 2018 population data and time-adjusted Waste Data Flow (WDF) data across all NPH city regions (based on data availability) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	35,821	23,191	21,775	26,021	13,160	119,968
2011	33,041	21,745	20,321	24,337	12,217	111,661
2012	29,320	19,419	18,044	21,614	10,851	99,249
2013	32,435	21,526	19,949	23,931	12,121	109,962
2014	29,742	19,825	18,285	21,940	11,147	100,939
2015	32,466	21,894	20,029	23,949	12,148	110,485
2016	36,395	24,843	22,549	26,803	13,619	124,210
2017	29,011	19,914	18,005	21,376	10,856	99,163
2018	29,470	20,323	18,314	21,719	11,026	100,851
2020	27,272	18,940	16,984	20,097	10,180	93,473
2025	25,518	17,902	15,960	18,801	9,453	87,633
2030	22,872	16,175	14,380	16,881	8,450	78,758
2035	20,774	14,830	13,137	15,384	7,637	71,763
2040	18,521	13,333	11,769	13,773	6,765	64,160
2045	16,863	12,077	10,627	12,423	6,042	58,032
2050	15,141	10,761	9,438	11,020	5,310	51,669

*Values for 2020-2050 years are estimated via best regression trendline analysis in Excel using original data

Appendix table 10. Total food waste collection data using ONS 2018 population data and time-adjusted wrap data across all NPH metropolitan county regions (based on data availability) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2007	186,710	225,244	122,107	113,529	97,239	744,830
2010	153,541	184,591	98,668	93,029	78,310	608,138
2012	152,754	182,886	96,580	92,151	76,851	601,223
2014	160,142	191,798	99,834	96,388	79,747	627,909
2015	158,464	190,142	98,424	95,437	78,708	621,174
2017	156,548	188,943	96,861	94,476	77,650	614,477
2018	146,445	176,772	90,443	88,404	72,442	574,506
2020	115,609	139,702	71,081	69,824	57,138	453,354
2025	96,158	117,052	58,793	58,084	46,931	377,017
2030	81,646	99,874	49,781	49,375	39,478	320,154
2035	71,130	87,211	43,321	43,103	34,156	278,922
2040	60,030	73,808	36,536	36,467	28,636	235,477
2045	50,946	62,864	30,979	31,029	24,125	199,943
2050	44,132	54,637	26,807	26,941	20,744	173,261

*Values for 2020-2050 years are estimated via best regression trendline analysis in Excel using original data

Appendix table 11. Total food waste collection data using ONS 2018 population data and time-adjusted Waste Data Flow (WDF) data across all NPH regions (based on data availability) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2010	106,051	127,454	65,614	63,871	52,575	415,564
2011	99,021	119,512	61,267	59,759	49,116	388,675
2012	87,568	105,702	54,081	52,862	43,317	343,530
2013	96,881	116,940	59,637	58,480	47,913	379,852
2014	88,735	107,227	54,558	53,593	43,856	347,970
2015	96,555	116,868	59,285	58,304	47,517	378,529
2016	107,944	130,940	66,236	65,157	52,999	423,276
2017	85,895	104,315	52,638	51,863	42,087	336,797
2018	87,128	105,934	53,327	52,620	42,607	341,617
2020	80,477	98,075	49,164	48,618	39,198	315,533
2025	74,907	91,681	45,659	45,316	36,165	293,728
2030	66,580	81,667	40,545	40,364	31,930	261,086
2035	60,160	74,019	36,610	36,564	28,658	236,011
2040	53,484	66,040	32,514	32,590	25,288	209,916
2045	47,910	59,354	29,098	29,262	22,488	188,112
2050	42,208	52,459	25,613	25,840	19,673	165,792

*Values for 2020-2050 years are estimated via best regression trendline analysis in Excel using original data

Appendix table 12. Total food waste collection data using ONS 2018 population data and time-adjusted WRAP data across all NPH city regions (based on data availability) for 2010-2050 at 5 year intervals

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	53,811,877	34,839,542	32,712,176	39,090,259	19,769,787	180,223,641
2015	45,175,440	30,464,640	27,869,280	33,324,360	16,904,100	153,737,820
2020	40,518,920	28,139,176	25,232,948	29,858,244	15,124,252	138,873,540
2025	33,491,892	23,496,270	20,947,080	24,676,932	12,406,674	115,018,848
2030	28,589,820	20,218,940	17,975,020	21,100,730	10,562,965	98,447,475
2035	24,929,040	17,795,400	15,764,850	18,461,280	9,164,520	86,115,090
2040	21,046,175	15,150,900	13,373,950	15,650,575	7,687,200	72,908,800

*Values for 2020-2050 years are estimated via best regression trendline analysis in Excel using original data

Appendix table 13. Total food waste collection data using ONS 2018 population data and time-adjusted Waste Data Flow (WDF) data across all NPH city regions (based on data availability) for 2010-2050 at 5 year intervals

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	33,908,854	21,953,684	20,613,152	24,632,218	12,457,674	113,565,582
2015	30,116,960	20,309,760	18,579,520	22,216,240	11,269,400	102,491,880
2020	27,272,350	18,939,830	16,983,715	20,096,895	10,179,785	93,472,575
2025	25,517,632	17,901,920	15,959,680	18,801,472	9,452,704	87,633,408
2030	22,871,856	16,175,152	14,380,016	16,880,584	8,450,372	78,757,980
2035	20,774,200	14,829,500	13,137,375	15,384,400	7,637,100	71,762,575
2040	18,520,634	13,332,792	11,769,076	13,772,506	6,764,736	64,159,744

*Values for 2020-2050 years are estimated via best regression trendline analysis in Excel using original data

Appendix table 14. Table of data outlining total food waste data for each NPH region based on both Waste Data Flow (WDF) and WRAP time-adjusted food waste collection data of 46 to 17 over relevant time durations of 2010 to 2050.

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	33,908,854	21,953,684	20,613,152	24,632,218	12,457,674	113,565,582	53,811,877	34,839,542	32,712,176	39,090,259	19,769,787	180,223,641
2015	30,116,960	20,309,760	18,579,520	22,216,240	11,269,400	102,491,880	45,175,440	30,464,640	27,869,280	33,324,360	16,904,100	153,737,820
2020	27,272,350	18,939,830	16,983,715	20,096,895	10,179,785	93,472,575	40,518,920	28,139,176	25,232,948	29,858,244	15,124,252	138,873,540
2025	25,517,632	17,901,920	15,959,680	18,801,472	9,452,704	87,633,408	33,491,892	23,496,270	20,947,080	24,676,932	12,406,674	115,018,848
2030	22,871,856	16,175,152	14,380,016	16,880,584	8,450,372	78,757,980	28,589,820	20,218,940	17,975,020	21,100,730	10,562,965	98,447,475
2035	20,774,200	14,829,500	13,137,375	15,384,400	7,637,100	71,762,575	24,929,040	17,795,400	15,764,850	18,461,280	9,164,520	86,115,090
2040	18,520,634	13,332,792	11,769,076	13,772,506	6,764,736	64,159,744	21,046,175	15,150,900	13,373,950	15,650,575	7,687,200	72,908,800

Appendix table 15. Total food waste outputs for all NPH regions and all single data food waste collection scenarios

	Leeds (20kg)	Manchester (20kg)	Liverpool (20kg)	Sheffield (20kg)	Newcastle (20kg)	Leeds (40kg)	Manchester (40kg)	Liverpool (40kg)	Sheffield (40kg)	Newcastle (40kg)	Leeds (100kg)	Manchester (100kg)	Liverpool (100kg)	Sheffield (100kg)	Newcastle (100kg)
2001	14,107	8,150	8,574	10,082	5,209	28,213	16,299	17,148	20,163	10,419	70,534	40,748	42,870	50,408	26,046
2002	14,122	8,253	8,613	10,103	5,224	28,244	16,506	17,226	20,206	10,447	70,609	41,265	43,065	50,515	26,118
2003	14,147	8,424	8,637	10,126	5,221	28,293	16,847	17,274	20,253	10,442	70,733	42,118	43,186	50,631	26,104
2004	14,256	8,588	8,700	10,213	5,221	28,512	17,176	17,399	20,425	10,442	71,279	42,940	43,499	51,063	26,106
2005	14,495	8,804	8,783	10,334	5,275	28,989	17,609	17,566	20,668	10,550	72,473	44,022	43,914	51,671	26,376
2006	14,516	8,965	8,798	10,371	5,288	29,033	17,930	17,596	20,743	10,576	72,582	44,825	43,990	51,857	26,440
2007	14,563	9,101	8,808	10,416	5,314	29,127	18,203	17,616	20,833	10,628	72,817	45,507	44,040	52,082	26,571
2008	14,627	9,240	8,826	10,499	5,316	29,253	18,480	17,651	20,999	10,632	73,133	46,201	44,128	52,497	26,580
2009	14,671	9,369	8,886	10,586	5,351	29,341	18,737	17,771	21,172	10,703	73,353	46,843	44,429	52,929	26,757

2010	14,743	9,545	8,962	10,710	5,416	29,486	19,090	17,924	21,419	10,833	73,715	47,725	44,811	53,548	27,082
2011	14,611	9,616	8,987	10,762	5,403	29,223	19,232	17,973	21,525	10,805	73,057	48,081	44,933	53,812	27,013
2012	14,747	9,767	9,076	10,871	5,458	29,494	19,534	18,151	21,743	10,915	73,736	48,835	45,378	54,357	27,288
2013	14,814	9,831	9,111	10,930	5,536	29,627	19,663	18,222	21,859	11,072	74,069	49,157	45,554	54,649	27,679
2014	14,904	9,934	9,163	10,994	5,586	29,807	19,868	18,325	21,988	11,171	74,519	49,671	45,813	54,970	27,928
2015	15,058	10,155	9,290	11,108	5,635	30,117	20,310	18,580	22,216	11,269	75,292	50,774	46,449	55,541	28,174
2016	15,215	10,386	9,427	11,205	5,693	30,430	20,771	18,853	22,410	11,387	76,075	51,928	47,133	56,025	28,467
2017	15,317	10,514	9,506	11,285	5,732	30,633	21,027	19,011	22,570	11,463	76,583	52,568	47,529	56,426	28,658
2018	15,415	10,630	9,580	11,361	5,767	30,831	21,261	19,159	22,722	11,535	77,077	53,152	47,898	56,805	28,837
2019	15,505	10,734	9,646	11,427	5,796	31,010	21,468	19,292	22,854	11,592	77,525	53,669	48,230	57,136	28,981
2020	15,584	10,823	9,705	11,484	5,817	31,168	21,646	19,410	22,968	11,634	77,921	54,114	48,525	57,420	29,085
2021	15,653	10,900	9,757	11,533	5,832	31,306	21,800	19,514	23,066	11,663	78,264	54,499	48,786	57,666	29,158
2022	15,721	10,972	9,808	11,582	5,846	31,441	21,945	19,617	23,165	11,692	78,604	54,862	49,041	57,912	29,231
2023	15,792	11,042	9,860	11,634	5,863	31,585	22,084	19,720	23,268	11,726	78,961	55,210	49,300	58,171	29,314
2024	15,868	11,114	9,916	11,690	5,883	31,736	22,228	19,832	23,380	11,767	79,341	55,570	49,579	58,450	29,416
2025	15,949	11,189	9,975	11,751	5,908	31,897	22,377	19,950	23,502	11,816	79,743	55,944	49,874	58,755	29,540
2026	16,031	11,264	10,035	11,814	5,935	32,061	22,528	20,071	23,628	11,869	80,153	56,321	50,177	59,070	29,673
2027	16,113	11,340	10,097	11,878	5,962	32,226	22,679	20,193	23,756	11,925	80,565	56,698	50,484	59,391	29,811
2028	16,190	11,412	10,156	11,939	5,988	32,380	22,824	20,313	23,878	11,976	80,950	57,061	50,781	59,695	29,939
2029	16,264	11,483	10,214	11,998	6,012	32,528	22,966	20,428	23,996	12,025	81,321	57,415	51,071	59,991	30,062
2030	16,337	11,554	10,271	12,058	6,036	32,674	23,107	20,543	24,115	12,072	81,685	57,768	51,357	60,288	30,180
2031	16,408	11,624	10,327	12,117	6,059	32,816	23,249	20,654	24,234	12,117	82,039	58,121	51,636	60,584	30,293
2032	16,469	11,690	10,378	12,170	6,076	32,938	23,380	20,757	24,339	12,152	82,345	58,449	51,892	60,848	30,381
2033	16,523	11,750	10,425	12,218	6,089	33,045	23,500	20,850	24,435	12,178	82,613	58,751	52,125	61,088	30,445
2034	16,572	11,808	10,468	12,263	6,100	33,144	23,615	20,936	24,525	12,199	82,859	59,038	52,340	61,313	30,498
2035	16,619	11,864	10,510	12,308	6,110	33,239	23,727	21,020	24,615	12,219	83,097	59,318	52,550	61,538	30,548
2036	16,663	11,916	10,549	12,350	6,118	33,325	23,833	21,098	24,699	12,236	83,313	59,582	52,745	61,748	30,589
2037	16,705	11,968	10,587	12,392	6,125	33,409	23,937	21,173	24,783	12,251	83,523	59,841	52,933	61,958	30,627
2038	16,748	12,020	10,624	12,434	6,133	33,495	24,040	21,249	24,869	12,267	83,739	60,099	53,122	62,172	30,667
2039	16,792	12,071	10,662	12,477	6,142	33,584	24,141	21,324	24,955	12,283	83,960	60,354	53,310	62,387	30,708
2040	16,837	12,121	10,699	12,520	6,150	33,674	24,241	21,398	25,041	12,300	84,185	60,604	53,496	62,602	30,749
2041	16,882	12,169	10,736	12,563	6,158	33,763	24,338	21,471	25,126	12,315	84,408	60,846	53,678	62,814	30,788

Appendix table 16. Total biomethane production data using low fixed FW collection data (20kg/person/year) and low FW to biomethane conversion yield (45m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	634,803	366,734	385,826	453,674	234,417	634,803
2002	635,485	371,389	387,587	454,638	235,064	635,485
2003	636,596	379,063	388,674	455,682	234,936	636,596
2004	641,513	386,456	391,488	459,568	234,956	641,513
2005	652,256	396,201	395,230	465,035	237,385	652,256
2006	653,241	403,424	395,906	466,717	237,962	653,241
2007	655,353	409,567	396,357	468,741	239,141	655,353
2008	658,200	415,811	397,156	472,471	239,218	658,200
2009	660,181	421,583	399,857	476,361	240,816	660,181
2010	663,434	429,529	403,301	481,935	243,737	663,434
2011	657,514	432,725	404,393	484,310	243,114	657,514
2012	663,622	439,511	408,401	489,209	245,596	663,622
2013	666,618	442,410	409,989	491,838	249,114	666,618
2014	670,667	447,039	412,316	494,727	251,355	670,667
2015	677,632	456,970	418,039	499,865	253,562	677,632
2016	684,675	467,353	424,198	504,228	256,201	684,675
2017	689,243	473,111	427,757	507,831	257,925	689,243
2018	693,689	478,368	431,078	511,247	259,529	693,689
2019	697,725	483,021	434,070	514,224	260,829	697,725
2020	701,289	487,024	436,724	516,777	261,766	701,289
2021	704,376	490,494	439,075	518,990	262,425	704,376
2022	707,432	493,757	441,373	521,208	263,075	707,432
2023	710,652	496,887	443,703	523,540	263,827	710,652
2024	714,067	500,126	446,209	526,052	264,747	714,067
2025	717,683	503,492	448,866	528,791	265,857	717,683
2026	721,377	506,885	451,589	531,633	267,061	721,377
2027	725,081	510,286	454,352	534,521	268,303	725,081
2028	728,553	513,551	457,033	537,254	269,455	728,553
2029	731,889	516,731	459,637	539,917	270,555	731,889
2030	735,167	519,916	462,215	542,590	271,619	735,167
2031	738,353	523,092	464,726	545,255	272,636	738,353
2032	741,106	526,039	467,030	547,636	273,425	741,106
2033	743,521	528,758	469,128	549,793	274,009	743,521
2034	745,733	531,338	471,063	551,818	274,485	745,733
2035	747,871	533,862	472,946	553,838	274,936	747,871
2036	749,817	536,242	474,703	555,733	275,299	749,817
2037	751,703	538,572	476,396	557,625	275,641	751,703
2038	753,647	540,891	478,094	559,545	276,004	753,647
2039	755,637	543,183	479,786	561,486	276,375	755,637
2040	757,662	545,432	481,462	563,421	276,739	757,662
2041	759,676	547,610	483,104	565,329	277,088	759,676
2042	764,333	550,062	484,942	567,336	277,534	764,333
2043	768,991	552,514	486,779	569,343	277,979	768,991
2044	773,648	554,966	488,617	571,351	278,424	773,648
2045	778,306	557,418	490,455	573,358	278,869	778,306
2046	782,963	559,870	492,293	575,366	279,315	782,963
2047	787,621	562,322	494,131	577,373	279,760	787,621
2048	792,278	564,773	495,968	579,380	280,205	792,278
2049	796,936	567,225	497,806	581,388	280,650	796,936
2050	801,593	569,677	499,644	583,395	281,095	801,593

*2042-2050 data estimated using regression trendline data

Appendix table 17. Total biomethane generation potential data using Low fixed FW collection data (20kg/person/year) and low FW to biomethane conversion yield (45m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	1,848,615	2,230,140	1,208,981	1,124,051	962,762	7,374,550
2002	1,857,596	2,236,369	1,207,718	1,128,268	962,405	7,392,356
2003	1,866,134	2,250,236	1,207,334	1,132,903	960,734	7,417,340
2004	1,880,089	2,260,300	1,208,174	1,139,127	958,900	7,446,590
2005	1,901,439	2,273,000	1,209,272	1,147,799	961,098	7,492,609
2006	1,912,075	2,289,253	1,208,934	1,153,493	961,979	7,525,734
2007	1,925,142	2,303,933	1,208,130	1,159,346	964,499	7,561,049
2008	1,939,807	2,323,263	1,209,299	1,167,554	965,979	7,605,902
2009	1,950,991	2,341,013	1,211,782	1,175,013	969,040	7,647,838
2010	1,964,170	2,360,578	1,215,239	1,182,947	973,740	7,696,673
2011	1,970,533	2,378,302	1,219,226	1,189,207	977,408	7,734,676
2012	1,981,966	2,392,397	1,224,042	1,196,440	980,420	7,775,265
2013	1,991,128	2,403,383	1,225,680	1,201,898	984,729	7,806,817
2014	2,000,930	2,417,912	1,230,249	1,208,498	988,921	7,846,510
2015	2,015,307	2,439,295	1,237,406	1,216,930	991,789	7,900,727
2016	2,030,657	2,463,251	1,246,044	1,225,739	997,021	7,962,710
2017	2,040,657	2,478,268	1,250,545	1,232,131	999,894	8,001,494
2018	2,050,887	2,493,554	1,255,262	1,238,604	1,002,919	8,041,226
2019	2,060,519	2,508,267	1,259,840	1,244,652	1,005,655	8,078,933
2020	2,069,403	2,521,931	1,264,219	1,250,186	1,007,958	8,113,697
2021	2,077,360	2,534,641	1,268,276	1,255,239	1,009,845	8,145,361
2022	2,084,855	2,546,482	1,272,191	1,260,099	1,011,567	8,175,192
2023	2,092,158	2,557,480	1,276,070	1,264,859	1,013,293	8,203,860
2024	2,099,471	2,568,178	1,280,084	1,269,638	1,015,151	8,232,521
2025	2,106,763	2,578,529	1,284,162	1,274,513	1,017,140	8,261,108
2026	2,114,017	2,588,630	1,288,205	1,279,405	1,019,193	8,289,450
2027	2,120,975	2,598,163	1,292,152	1,284,167	1,021,162	8,316,618
2028	2,127,567	2,607,393	1,295,960	1,288,683	1,022,969	8,342,572
2029	2,133,911	2,616,337	1,299,640	1,293,082	1,024,690	8,367,659
2030	2,140,084	2,625,008	1,303,224	1,297,420	1,026,319	8,392,055
2031	2,146,043	2,633,513	1,306,600	1,301,687	1,027,872	8,415,715
2032	2,151,378	2,641,550	1,309,684	1,305,595	1,029,092	8,437,298
2033	2,156,342	2,649,356	1,312,559	1,309,287	1,030,073	8,457,617
2034	2,161,083	2,657,080	1,315,296	1,312,825	1,030,903	8,477,186
2035	2,165,747	2,664,679	1,317,977	1,316,315	1,031,673	8,496,390
2036	2,170,258	2,672,254	1,320,512	1,319,727	1,032,331	8,515,082
2037	2,174,520	2,679,471	1,322,864	1,323,049	1,032,843	8,532,746
2038	2,178,903	2,686,780	1,325,254	1,326,410	1,033,373	8,550,719
2039	2,183,399	2,694,176	1,327,676	1,329,800	1,033,930	8,568,981
2040	2,187,998	2,701,643	1,330,135	1,333,209	1,034,495	8,587,481
2041	2,192,618	2,709,149	1,332,579	1,336,583	1,035,050	8,605,978
2042	2,197,275	2,716,712	1,335,177	1,340,072	1,035,768	8,616,768
2043	2,201,933	2,724,276	1,337,774	1,343,562	1,036,486	8,627,592
2044	2,206,590	2,731,839	1,340,372	1,347,052	1,037,204	8,638,450
2045	2,211,248	2,739,403	1,342,970	1,350,541	1,037,922	8,649,342
2046	2,215,905	2,746,967	1,345,568	1,354,031	1,038,640	8,660,266
2047	2,220,563	2,754,530	1,348,166	1,357,520	1,039,357	8,671,224
2048	2,225,220	2,762,094	1,350,764	1,361,010	1,040,075	8,682,214
2049	2,229,878	2,769,657	1,353,362	1,364,499	1,040,793	8,693,237
2050	2,234,535	2,777,221	1,355,959	1,367,989	1,041,511	8,704,290

Appendix table 18. Total biomethane generation potential data using Medium fixed FW collection data (40kg/person/year) and low FW to biomethane conversion yield (45m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	1,269,607	733,468	771,653	907,348	468,833	4,150,908
2002	1,270,969	742,777	775,174	909,275	470,128	4,168,323
2003	1,273,192	758,126	777,348	911,363	469,872	4,189,901
2004	1,283,026	772,913	782,977	919,136	469,912	4,227,962
2005	1,304,512	792,401	790,459	930,069	474,770	4,292,212
2006	1,306,481	806,848	791,813	933,433	475,924	4,314,499
2007	1,310,706	819,133	792,715	937,481	478,282	4,338,317
2008	1,316,399	831,622	794,311	944,942	478,436	4,365,711
2009	1,320,361	843,165	799,713	952,722	481,631	4,397,593
2010	1,326,868	859,057	806,602	963,869	487,474	4,443,871
2011	1,315,028	865,449	808,787	968,620	486,229	4,444,112
2012	1,327,244	879,023	816,802	978,419	491,191	4,492,679
2013	1,333,237	884,821	819,977	983,677	498,227	4,519,939
2014	1,341,335	894,078	824,632	989,455	502,709	4,552,209
2015	1,355,263	913,939	836,078	999,731	507,123	4,612,135
2016	1,369,350	934,706	848,396	1,008,455	512,402	4,673,309
2017	1,378,485	946,222	855,515	1,015,663	515,849	4,711,734
2018	1,387,377	956,736	862,155	1,022,494	519,059	4,747,820
2019	1,395,450	966,042	868,140	1,028,448	521,658	4,779,738
2020	1,402,578	974,048	873,448	1,033,555	523,532	4,807,161
2021	1,408,752	980,987	878,150	1,037,979	524,849	4,830,718
2022	1,414,863	987,514	882,745	1,042,416	526,151	4,853,689
2023	1,421,303	993,775	887,405	1,047,080	527,654	4,877,217
2024	1,428,134	1,000,253	892,418	1,052,104	529,493	4,902,403
2025	1,435,367	1,006,983	897,732	1,057,583	531,715	4,929,379
2026	1,442,754	1,013,769	903,177	1,063,265	534,121	4,957,087
2027	1,450,163	1,020,571	908,703	1,069,042	536,605	4,985,084
2028	1,457,105	1,027,102	914,065	1,074,508	538,909	5,011,690
2029	1,463,778	1,033,461	919,274	1,079,834	541,111	5,037,458
2030	1,470,334	1,039,831	924,430	1,085,180	543,238	5,063,013
2031	1,476,706	1,046,183	929,452	1,090,510	545,272	5,088,123
2032	1,482,212	1,052,078	934,060	1,095,271	546,851	5,110,472
2033	1,487,041	1,057,516	938,255	1,099,586	548,017	5,130,416
2034	1,491,466	1,062,675	942,125	1,103,636	548,969	5,148,871
2035	1,495,742	1,067,724	945,891	1,107,677	549,871	5,166,905
2036	1,499,634	1,072,483	949,406	1,111,466	550,598	5,183,588
2037	1,503,405	1,077,143	952,792	1,115,249	551,282	5,199,872
2038	1,507,295	1,081,782	956,187	1,119,091	552,008	5,216,362
2039	1,511,275	1,086,367	959,571	1,122,971	552,749	5,232,933
2040	1,515,325	1,090,865	962,924	1,126,841	553,478	5,249,434
2041	1,519,351	1,095,221	966,208	1,130,657	554,177	5,265,614
2042	1,528,666	1,100,125	969,883	1,134,672	555,067	5,283,363
2043	1,537,981	1,105,028	973,559	1,138,687	555,958	5,301,112
2044	1,547,296	1,109,932	977,234	1,142,702	556,848	5,318,861
2045	1,556,611	1,114,836	980,910	1,146,716	557,739	5,336,610
2046	1,565,926	1,119,740	984,586	1,150,731	558,629	5,354,359
2047	1,575,241	1,124,643	988,261	1,154,746	559,520	5,372,108
2048	1,584,556	1,129,547	991,937	1,158,760	560,410	5,389,857
2049	1,593,871	1,134,451	995,612	1,162,775	561,300	5,407,606
2050	1,603,186	1,139,354	999,288	1,166,790	562,191	5,425,356

Appendix table 19. Total biomethane generation potential data using medium fixed FW collection data (40kg/person/year) and low FW to biomethane conversion yield (45m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	3,697,231	4,460,279	2,417,962	2,248,103	1,925,525	14,749,099
2002	3,715,193	4,472,737	2,415,436	2,256,536	1,924,810	14,784,712
2003	3,732,268	4,500,472	2,414,668	2,265,806	1,921,468	14,834,680
2004	3,760,178	4,520,599	2,416,349	2,278,255	1,917,799	14,893,180
2005	3,802,878	4,546,001	2,418,545	2,295,598	1,922,197	14,985,218
2006	3,824,150	4,578,505	2,417,868	2,306,986	1,923,959	15,051,469
2007	3,850,285	4,607,865	2,416,261	2,318,692	1,928,997	15,122,099
2008	3,879,614	4,646,525	2,418,599	2,335,108	1,931,958	15,211,804
2009	3,901,982	4,682,025	2,423,563	2,350,026	1,938,080	15,295,676
2010	3,928,340	4,721,155	2,430,477	2,365,895	1,947,479	15,393,346
2011	3,941,066	4,756,604	2,438,451	2,378,414	1,954,816	15,469,351
2012	3,963,931	4,784,794	2,448,085	2,392,880	1,960,839	15,550,529
2013	3,982,255	4,806,765	2,451,361	2,403,796	1,969,457	15,613,634
2014	4,001,861	4,835,824	2,460,497	2,416,995	1,977,842	15,693,019
2015	4,030,614	4,878,590	2,474,813	2,433,859	1,983,578	15,801,455
2016	4,061,313	4,926,501	2,492,087	2,451,478	1,994,042	15,925,421
2017	4,081,315	4,956,536	2,501,089	2,464,261	1,999,787	16,002,988
2018	4,101,773	4,987,109	2,510,525	2,477,209	2,005,837	16,082,453
2019	4,121,039	5,016,533	2,519,680	2,489,305	2,011,309	16,157,866
2020	4,138,807	5,043,863	2,528,438	2,500,371	2,015,915	16,227,394
2021	4,154,720	5,069,282	2,536,551	2,510,478	2,019,690	16,290,722
2022	4,169,709	5,092,963	2,544,381	2,520,198	2,023,133	16,350,385
2023	4,184,316	5,114,959	2,552,141	2,529,718	2,026,586	16,407,720
2024	4,198,941	5,136,356	2,560,167	2,539,276	2,030,301	16,465,041
2025	4,213,526	5,157,058	2,568,325	2,549,027	2,034,281	16,522,216
2026	4,228,034	5,177,259	2,576,410	2,558,810	2,038,387	16,578,900
2027	4,241,950	5,196,326	2,584,303	2,568,334	2,042,323	16,633,237
2028	4,255,133	5,214,785	2,591,921	2,577,366	2,045,938	16,685,143
2029	4,267,822	5,232,674	2,599,279	2,586,164	2,049,379	16,735,318
2030	4,280,168	5,250,017	2,606,449	2,594,840	2,052,637	16,784,111
2031	4,292,086	5,267,025	2,613,200	2,603,374	2,055,744	16,831,429
2032	4,302,756	5,283,099	2,619,367	2,611,190	2,058,183	16,874,595
2033	4,312,685	5,298,712	2,625,118	2,618,573	2,060,145	16,915,234
2034	4,322,165	5,314,160	2,630,592	2,625,649	2,061,806	16,954,373
2035	4,331,493	5,329,357	2,635,954	2,632,630	2,063,345	16,992,779
2036	4,340,516	5,344,508	2,641,025	2,639,453	2,064,661	17,030,164
2037	4,349,039	5,358,942	2,645,728	2,646,097	2,065,685	17,065,492
2038	4,357,805	5,373,560	2,650,507	2,652,820	2,066,746	17,101,438
2039	4,366,798	5,388,352	2,655,351	2,659,601	2,067,860	17,137,962
2040	4,375,996	5,403,287	2,660,270	2,666,417	2,068,990	17,174,961
2041	4,385,236	5,418,297	2,665,157	2,673,166	2,070,101	17,211,956
2042	4,394,551	5,433,424	2,670,353	2,680,145	2,071,536	17,233,535
2043	4,403,866	5,448,551	2,675,549	2,687,124	2,072,972	17,255,183
2044	4,413,181	5,463,679	2,680,745	2,694,103	2,074,408	17,276,900
2045	4,422,496	5,478,806	2,685,940	2,701,082	2,075,844	17,298,683
2046	4,431,811	5,493,933	2,691,136	2,708,061	2,077,279	17,320,533
2047	4,441,126	5,509,060	2,696,332	2,715,040	2,078,715	17,342,449
2048	4,450,441	5,524,187	2,701,527	2,722,020	2,080,151	17,364,429
2049	4,459,756	5,539,315	2,706,723	2,728,999	2,081,586	17,386,473
2050	4,469,071	5,554,442	2,711,919	2,735,978	2,083,022	17,408,581

*2042-2050 data estimated using regression trendline data

Appendix table 20. Total biomethane generation potential data using high fixed FW collection data (100kg/person/year) and low FW to biomethane conversion yield (45m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	3,174,017	1,833,669	1,929,132	2,268,369	1,172,084	10,377,270
2002	3,177,423	1,856,943	1,937,934	2,273,189	1,175,319	10,420,808
2003	3,182,981	1,895,315	1,943,370	2,278,409	1,174,680	10,474,754
2004	3,207,564	1,932,282	1,957,442	2,297,840	1,174,779	10,569,906
2005	3,261,281	1,981,004	1,976,148	2,325,173	1,186,925	10,730,529
2006	3,266,204	2,017,121	1,979,532	2,333,583	1,189,809	10,786,248
2007	3,276,765	2,047,833	1,981,787	2,343,704	1,195,704	10,845,792
2008	3,290,999	2,079,054	1,985,778	2,362,356	1,196,091	10,914,278
2009	3,300,903	2,107,913	1,999,283	2,381,805	1,204,079	10,993,982
2010	3,317,171	2,147,643	2,016,504	2,409,674	1,218,686	11,109,677
2011	3,287,570	2,163,623	2,021,967	2,421,549	1,215,572	11,110,280
2012	3,318,111	2,197,557	2,042,006	2,446,047	1,227,978	11,231,699
2013	3,333,092	2,212,052	2,049,944	2,459,192	1,245,569	11,299,847
2014	3,353,337	2,235,195	2,061,581	2,473,637	1,256,774	11,380,523
2015	3,388,158	2,284,848	2,090,196	2,499,327	1,267,808	11,530,337
2016	3,423,375	2,336,765	2,120,990	2,521,139	1,281,006	11,683,274
2017	3,446,213	2,365,556	2,138,787	2,539,157	1,289,624	11,779,335
2018	3,468,443	2,391,840	2,155,388	2,556,234	1,297,647	11,869,551
2019	3,488,625	2,415,105	2,170,350	2,571,120	1,304,145	11,949,345
2020	3,506,445	2,435,121	2,183,621	2,583,887	1,308,830	12,017,903
2021	3,521,880	2,452,469	2,195,375	2,594,948	1,312,124	12,076,794
2022	3,537,158	2,468,786	2,206,863	2,606,040	1,315,377	12,134,223
2023	3,553,259	2,484,437	2,218,514	2,617,700	1,319,135	12,193,043
2024	3,570,336	2,500,632	2,231,046	2,630,259	1,323,734	12,256,007
2025	3,588,417	2,517,458	2,244,330	2,643,957	1,329,287	12,323,448
2026	3,606,885	2,534,423	2,257,943	2,658,164	1,335,303	12,392,717
2027	3,625,407	2,551,428	2,271,758	2,672,604	1,341,513	12,462,710
2028	3,642,764	2,567,754	2,285,163	2,686,271	1,347,273	12,529,224
2029	3,659,445	2,583,653	2,298,186	2,699,586	1,352,777	12,593,646
2030	3,675,834	2,599,578	2,311,074	2,712,951	1,358,096	12,657,533
2031	3,691,764	2,615,459	2,323,629	2,726,276	1,363,181	12,720,308
2032	3,705,530	2,630,196	2,335,149	2,738,178	1,367,127	12,776,180
2033	3,717,603	2,643,791	2,345,639	2,748,965	1,370,043	12,826,040
2034	3,728,664	2,656,688	2,355,314	2,759,090	1,372,424	12,872,178
2035	3,739,356	2,669,310	2,364,728	2,769,192	1,374,678	12,917,264
2036	3,749,085	2,681,208	2,373,516	2,778,665	1,376,496	12,958,970
2037	3,758,513	2,692,859	2,381,981	2,788,124	1,378,206	12,999,681
2038	3,768,237	2,704,455	2,390,468	2,797,727	1,380,020	13,040,906
2039	3,778,187	2,715,917	2,398,928	2,807,429	1,381,874	13,082,333
2040	3,788,312	2,727,162	2,407,311	2,817,104	1,383,696	13,123,584
2041	3,798,378	2,738,052	2,415,519	2,826,644	1,385,442	13,164,035
2042	3,821,666	2,750,311	2,424,708	2,836,680	1,387,668	13,208,407
2043	3,844,953	2,762,571	2,433,897	2,846,717	1,389,894	13,252,780
2044	3,868,241	2,774,830	2,443,086	2,856,754	1,392,120	13,297,153
2045	3,891,528	2,787,089	2,452,275	2,866,791	1,394,347	13,341,525
2046	3,914,816	2,799,349	2,461,464	2,876,828	1,396,573	13,385,898
2047	3,938,103	2,811,608	2,470,653	2,886,864	1,398,799	13,430,271
2048	3,961,391	2,823,867	2,479,842	2,896,901	1,401,025	13,474,643
2049	3,984,678	2,836,127	2,489,031	2,906,938	1,403,251	13,519,016
2050	4,007,966	2,848,386	2,498,220	2,916,975	1,405,477	13,563,389

*2042-2050 data estimated using regression trendline data

Appendix table 21. Total biomethane generation potential data using high fixed FW collection data (100kg/person/year) and low FW to biomethane conversion yield (45m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2054

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	9,243,077	11,150,699	6,044,904	5,620,257	4,813,812	36,872,748
2002	9,287,982	11,181,843	6,038,591	5,641,340	4,812,026	36,961,781
2003	9,330,669	11,251,179	6,036,669	5,664,515	4,803,669	37,086,701
2004	9,400,446	11,301,498	6,040,872	5,695,637	4,794,498	37,232,951
2005	9,507,195	11,365,002	6,046,362	5,738,994	4,805,492	37,463,045
2006	9,560,376	11,446,263	6,044,670	5,767,466	4,809,897	37,628,672
2007	9,625,712	11,519,663	6,040,652	5,796,729	4,822,493	37,805,247
2008	9,699,035	11,616,314	6,046,497	5,837,769	4,829,895	38,029,509
2009	9,754,956	11,705,063	6,058,908	5,875,065	4,845,200	38,239,191
2010	9,820,850	11,802,888	6,076,193	5,914,737	4,868,699	38,483,366
2011	9,852,665	11,891,511	6,096,128	5,946,035	4,887,041	38,673,378
2012	9,909,828	11,961,986	6,120,212	5,982,201	4,902,098	38,876,324
2013	9,955,638	12,016,913	6,128,402	6,009,489	4,923,644	39,034,085
2014	10,004,652	12,089,561	6,151,244	6,042,488	4,944,605	39,232,548
2015	10,076,535	12,196,476	6,187,032	6,084,648	4,958,946	39,503,637
2016	10,153,283	12,316,253	6,230,219	6,128,694	4,985,105	39,813,552
2017	10,203,287	12,391,340	6,252,723	6,160,653	4,999,469	40,007,471
2018	10,254,434	12,467,772	6,276,312	6,193,022	5,014,593	40,206,132
2019	10,302,597	12,541,334	6,299,199	6,223,262	5,028,273	40,394,664
2020	10,347,017	12,609,657	6,321,096	6,250,928	5,039,789	40,568,486
2021	10,386,801	12,673,206	6,341,378	6,276,195	5,049,225	40,726,805
2022	10,424,273	12,732,408	6,360,953	6,300,495	5,057,834	40,875,962
2023	10,460,790	12,787,398	6,380,352	6,324,296	5,066,465	41,019,300
2024	10,497,353	12,840,890	6,400,418	6,348,191	5,075,753	41,162,603
2025	10,533,816	12,892,644	6,420,812	6,372,567	5,085,702	41,305,541
2026	10,570,086	12,943,148	6,441,026	6,397,025	5,095,967	41,447,250
2027	10,604,876	12,990,816	6,460,758	6,420,834	5,105,808	41,583,092
2028	10,637,834	13,036,964	6,479,802	6,443,415	5,114,844	41,712,858
2029	10,669,554	13,081,685	6,498,198	6,465,411	5,123,448	41,838,296
2030	10,700,420	13,125,042	6,516,122	6,487,101	5,131,593	41,960,277
2031	10,730,214	13,167,563	6,533,001	6,508,436	5,139,360	42,078,573
2032	10,756,890	13,207,748	6,548,418	6,527,975	5,145,458	42,186,488
2033	10,781,712	13,246,781	6,562,796	6,546,434	5,150,363	42,288,084
2034	10,805,414	13,285,400	6,576,480	6,564,123	5,154,516	42,385,932
2035	10,828,733	13,323,393	6,589,886	6,581,574	5,158,364	42,481,949
2036	10,851,291	13,361,270	6,602,562	6,598,634	5,161,653	42,575,409
2037	10,872,599	13,397,355	6,614,321	6,615,243	5,164,214	42,663,731
2038	10,894,514	13,433,900	6,626,268	6,632,051	5,166,864	42,753,596
2039	10,916,996	13,470,881	6,638,378	6,649,002	5,169,650	42,844,905
2040	10,939,991	13,508,217	6,650,676	6,666,044	5,172,476	42,937,403
2041	10,963,089	13,545,743	6,662,894	6,682,914	5,175,252	43,029,891
2042	10,986,377	13,583,561	6,675,883	6,700,362	5,178,841	43,083,838
2043	11,009,664	13,621,379	6,688,872	6,717,810	5,182,430	43,137,958
2044	11,032,952	13,659,197	6,701,861	6,735,258	5,186,020	43,192,249
2045	11,056,239	13,697,015	6,714,851	6,752,705	5,189,609	43,246,708
2046	11,079,527	13,734,833	6,727,840	6,770,153	5,193,198	43,301,332
2047	11,102,814	13,772,651	6,740,829	6,787,601	5,196,787	43,356,121
2048	11,126,102	13,810,469	6,753,818	6,805,049	5,200,376	43,411,072
2049	11,149,389	13,848,287	6,766,808	6,822,497	5,203,966	43,466,183
2050	11,172,677	13,886,105	6,779,797	6,839,945	5,207,555	43,521,452

*2042-2050 data estimated using regression trendline data

Appendix table 22. Total biomethane generation potential data using low fixed FW collection data (20kg/person/year) and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	952,205	550,101	578,740	680,511	351,625	3,113,181
2002	953,227	557,083	581,380	681,957	352,596	3,126,242
2003	954,894	568,594	583,011	683,523	352,404	3,142,426
2004	962,269	579,685	587,232	689,352	352,434	3,170,972
2005	978,384	594,301	592,844	697,552	356,077	3,219,159
2006	979,861	605,136	593,860	700,075	356,943	3,235,874
2007	983,030	614,350	594,536	703,111	358,711	3,253,738
2008	987,300	623,716	595,733	708,707	358,827	3,274,283
2009	990,271	632,374	599,785	714,542	361,224	3,298,194
2010	995,151	644,293	604,951	722,902	365,606	3,332,903
2011	986,271	649,087	606,590	726,465	364,671	3,333,084
2012	995,433	659,267	612,602	733,814	368,393	3,369,510
2013	999,927	663,615	614,983	737,757	373,671	3,389,954
2014	1,006,001	670,559	618,474	742,091	377,032	3,414,157
2015	1,016,447	685,454	627,059	749,798	380,342	3,459,101
2016	1,027,013	701,029	636,297	756,342	384,302	3,504,982
2017	1,033,864	709,667	641,636	761,747	386,887	3,533,801
2018	1,040,533	717,552	646,616	766,870	389,294	3,560,865
2019	1,046,588	724,532	651,105	771,336	391,244	3,584,804
2020	1,051,934	730,536	655,086	775,166	392,649	3,605,371
2021	1,056,564	735,741	658,612	778,484	393,637	3,623,038
2022	1,061,147	740,636	662,059	781,812	394,613	3,640,267
2023	1,065,978	745,331	665,554	785,310	395,740	3,657,913
2024	1,071,101	750,190	669,314	789,078	397,120	3,676,802
2025	1,076,525	755,237	673,299	793,187	398,786	3,697,034
2026	1,082,066	760,327	677,383	797,449	400,591	3,717,815
2027	1,087,622	765,428	681,527	801,781	402,454	3,738,813
2028	1,092,829	770,326	685,549	805,881	404,182	3,758,767
2029	1,097,834	775,096	689,456	809,876	405,833	3,778,094
2030	1,102,750	779,873	693,322	813,885	407,429	3,797,260
2031	1,107,529	784,638	697,089	817,883	408,954	3,816,092
2032	1,111,659	789,059	700,545	821,453	410,138	3,832,854
2033	1,115,281	793,137	703,692	824,689	411,013	3,847,812
2034	1,118,599	797,006	706,594	827,727	411,727	3,861,653
2035	1,121,807	800,793	709,418	830,758	412,403	3,875,179
2036	1,124,726	804,362	712,055	833,599	412,949	3,887,691
2037	1,127,554	807,858	714,594	836,437	413,462	3,899,904
2038	1,130,471	811,337	717,140	839,318	414,006	3,912,272
2039	1,133,456	814,775	719,678	842,229	414,562	3,924,700
2040	1,136,493	818,149	722,193	845,131	415,109	3,937,075
2041	1,139,513	821,416	724,656	847,993	415,633	3,949,210
2042	1,146,500	825,093	727,412	851,004	416,300	3,962,522
2043	1,153,486	828,771	730,169	854,015	416,968	3,975,834
2044	1,160,472	832,449	732,926	857,026	417,636	3,989,146
2045	1,167,458	836,127	735,683	860,037	418,304	4,002,458
2046	1,174,445	839,805	738,439	863,048	418,972	4,015,769
2047	1,181,431	843,482	741,196	866,059	419,640	4,029,081
2048	1,188,417	847,160	743,953	869,070	420,308	4,042,393
2049	1,195,403	850,838	746,709	872,081	420,975	4,055,705
2050	1,202,390	854,516	749,466	875,092	421,643	4,069,017

*2042-2050 data estimated using regression trendline data

Appendix table 23. Total biomethane generation potential data using low fixed FW collection data (20kg/person/year) and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	2,772,923	3,345,210	1,813,471	1,686,077	1,444,144	11,061,824
2002	2,786,395	3,354,553	1,811,577	1,692,402	1,443,608	11,088,534
2003	2,799,201	3,375,354	1,811,001	1,699,354	1,441,101	11,126,010
2004	2,820,134	3,390,449	1,812,262	1,708,691	1,438,349	11,169,885
2005	2,852,159	3,409,501	1,813,909	1,721,698	1,441,647	11,238,913
2006	2,868,113	3,433,879	1,813,401	1,730,240	1,442,969	11,288,601
2007	2,887,713	3,455,899	1,812,195	1,739,019	1,446,748	11,341,574
2008	2,909,710	3,484,894	1,813,949	1,751,331	1,448,969	11,408,853
2009	2,926,487	3,511,519	1,817,672	1,762,520	1,453,560	11,471,757
2010	2,946,255	3,540,866	1,822,858	1,774,421	1,460,610	11,545,010
2011	2,955,799	3,567,453	1,828,838	1,783,810	1,466,112	11,602,013
2012	2,972,948	3,588,596	1,836,063	1,794,660	1,470,629	11,662,897
2013	2,986,691	3,605,074	1,838,520	1,802,847	1,477,093	11,710,225
2014	3,001,396	3,626,868	1,845,373	1,812,746	1,483,381	11,769,764
2015	3,022,961	3,658,943	1,856,110	1,825,394	1,487,684	11,851,091
2016	3,045,985	3,694,876	1,869,066	1,838,608	1,495,531	11,944,066
2017	3,060,986	3,717,402	1,875,817	1,848,196	1,499,841	12,002,241
2018	3,076,330	3,740,332	1,882,894	1,857,906	1,504,378	12,061,840
2019	3,090,779	3,762,400	1,889,760	1,866,978	1,508,482	12,118,399
2020	3,104,105	3,782,897	1,896,329	1,875,278	1,511,937	12,170,546
2021	3,116,040	3,801,962	1,902,413	1,882,859	1,514,768	12,218,041
2022	3,127,282	3,819,722	1,908,286	1,890,149	1,517,350	12,262,788
2023	3,138,237	3,836,219	1,914,106	1,897,289	1,519,939	12,305,790
2024	3,149,206	3,852,267	1,920,125	1,904,457	1,522,726	12,348,781
2025	3,160,145	3,867,793	1,926,243	1,911,770	1,525,711	12,391,662
2026	3,171,026	3,882,944	1,932,308	1,919,107	1,528,790	12,434,175
2027	3,181,463	3,897,245	1,938,227	1,926,250	1,531,742	12,474,927
2028	3,191,350	3,911,089	1,943,941	1,933,025	1,534,453	12,513,857
2029	3,200,866	3,924,505	1,949,459	1,939,623	1,537,034	12,551,489
2030	3,210,126	3,937,513	1,954,836	1,946,130	1,539,478	12,588,083
2031	3,219,064	3,950,269	1,959,900	1,952,531	1,541,808	12,623,572
2032	3,227,067	3,962,324	1,964,525	1,958,392	1,543,637	12,655,946
2033	3,234,514	3,974,034	1,968,839	1,963,930	1,545,109	12,686,425
2034	3,241,624	3,985,620	1,972,944	1,969,237	1,546,355	12,715,780
2035	3,248,620	3,997,018	1,976,966	1,974,472	1,547,509	12,744,585
2036	3,255,387	4,008,381	1,980,769	1,979,590	1,548,496	12,772,623
2037	3,261,780	4,019,207	1,984,296	1,984,573	1,549,264	12,799,119
2038	3,268,354	4,030,170	1,987,880	1,989,615	1,550,059	12,826,079
2039	3,275,099	4,041,264	1,991,513	1,994,701	1,550,895	12,853,472
2040	3,281,997	4,052,465	1,995,203	1,999,813	1,551,743	12,881,221
2041	3,288,927	4,063,723	1,998,868	2,004,874	1,552,576	12,908,967
2042	3,295,913	4,075,068	2,002,765	2,010,109	1,553,652	12,925,152
2043	3,302,899	4,086,414	2,006,662	2,015,343	1,554,729	12,941,388
2044	3,309,885	4,097,759	2,010,558	2,020,577	1,555,806	12,957,675
2045	3,316,872	4,109,104	2,014,455	2,025,812	1,556,883	12,974,012
2046	3,323,858	4,120,450	2,018,352	2,031,046	1,557,959	12,990,400
2047	3,330,844	4,131,795	2,022,249	2,036,280	1,559,036	13,006,836
2048	3,337,830	4,143,141	2,026,145	2,041,515	1,560,113	13,023,322
2049	3,344,817	4,154,486	2,030,042	2,046,749	1,561,190	13,039,855
2050	3,351,803	4,165,831	2,033,939	2,051,983	1,562,266	13,056,436

*2042-2050 data estimated using regression trendline data

Appendix table 24. Total biomethane generation potential data using medium fixed FW collection data (40kg/person/year) and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	1,904,410	1,100,201	1,157,479	1,361,021	703,250	6,226,362
2002	1,906,454	1,114,166	1,162,760	1,363,913	705,191	6,252,485
2003	1,909,788	1,137,189	1,166,022	1,367,045	704,808	6,284,852
2004	1,924,538	1,159,369	1,174,465	1,378,704	704,867	6,341,944
2005	1,956,768	1,188,602	1,185,689	1,395,104	712,155	6,438,317
2006	1,959,722	1,210,272	1,187,719	1,400,150	713,885	6,471,749
2007	1,966,059	1,228,700	1,189,072	1,406,222	717,422	6,507,475
2008	1,974,599	1,247,432	1,191,467	1,417,414	717,655	6,548,567
2009	1,980,542	1,264,748	1,199,570	1,429,083	722,447	6,596,389
2010	1,990,302	1,288,586	1,209,902	1,445,804	731,211	6,665,806
2011	1,972,542	1,298,174	1,213,180	1,452,929	729,343	6,666,168
2012	1,990,867	1,318,534	1,225,203	1,467,628	736,787	6,739,019
2013	1,999,855	1,327,231	1,229,966	1,475,515	747,341	6,779,908
2014	2,012,002	1,341,117	1,236,948	1,484,182	754,064	6,828,314
2015	2,032,895	1,370,909	1,254,118	1,499,596	760,685	6,918,202
2016	2,054,025	1,402,059	1,272,594	1,512,683	768,604	7,009,964
2017	2,067,728	1,419,333	1,283,272	1,523,494	773,774	7,067,601
2018	2,081,066	1,435,104	1,293,233	1,533,740	778,588	7,121,731
2019	2,093,175	1,449,063	1,302,210	1,542,672	782,487	7,169,607
2020	2,103,867	1,461,073	1,310,172	1,550,332	785,298	7,210,742
2021	2,113,128	1,471,481	1,317,225	1,556,969	787,274	7,246,076
2022	2,122,295	1,481,271	1,324,118	1,563,624	789,226	7,280,534
2023	2,131,955	1,490,662	1,331,108	1,570,620	791,481	7,315,826
2024	2,142,202	1,500,379	1,338,628	1,578,155	794,240	7,353,604
2025	2,153,050	1,510,475	1,346,598	1,586,374	797,572	7,394,069
2026	2,164,131	1,520,654	1,354,766	1,594,898	801,182	7,435,630
2027	2,175,244	1,530,857	1,363,055	1,603,562	804,908	7,477,626
2028	2,185,658	1,540,652	1,371,098	1,611,762	808,364	7,517,534
2029	2,195,667	1,550,192	1,378,912	1,619,752	811,666	7,556,188
2030	2,205,500	1,559,747	1,386,644	1,627,771	814,857	7,594,520
2031	2,215,058	1,569,275	1,394,177	1,635,765	817,908	7,632,185
2032	2,223,318	1,578,118	1,401,089	1,642,907	820,276	7,665,708
2033	2,230,562	1,586,274	1,407,383	1,649,379	822,026	7,695,624
2034	2,237,198	1,594,013	1,413,188	1,655,454	823,454	7,723,307
2035	2,243,614	1,601,586	1,418,837	1,661,515	824,807	7,750,358
2036	2,249,451	1,608,725	1,424,110	1,667,199	825,898	7,775,382
2037	2,255,108	1,615,715	1,429,188	1,672,874	826,924	7,799,809
2038	2,260,942	1,622,673	1,434,281	1,678,636	828,012	7,824,543
2039	2,266,912	1,629,550	1,439,357	1,684,457	829,124	7,849,400
2040	2,272,987	1,636,297	1,444,387	1,690,262	830,218	7,874,150
2041	2,279,027	1,642,831	1,449,311	1,695,986	831,265	7,898,421
2042	2,292,999	1,650,187	1,454,825	1,702,008	832,601	7,925,044
2043	2,306,972	1,657,542	1,460,338	1,708,030	833,937	7,951,668
2044	2,320,944	1,664,898	1,465,852	1,714,052	835,272	7,978,292
2045	2,334,917	1,672,254	1,471,365	1,720,074	836,608	8,004,915
2046	2,348,889	1,679,609	1,476,878	1,726,097	837,944	8,031,539
2047	2,362,862	1,686,965	1,482,392	1,732,119	839,279	8,058,162
2048	2,376,834	1,694,320	1,487,905	1,738,141	840,615	8,084,786
2049	2,390,807	1,701,676	1,493,419	1,744,163	841,951	8,111,410
2050	2,404,779	1,709,032	1,498,932	1,750,185	843,286	8,138,033

*2042-2050 data estimated using regression trendline data

Appendix table 25. Total biomethane generation potential data using medium fixed FW collection data (40kg/person/year) and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	5,545,846	6,690,419	3,626,942	3,372,154	2,888,287	22,123,649
2002	5,572,789	6,709,106	3,623,154	3,384,804	2,887,215	22,177,068
2003	5,598,401	6,750,707	3,622,001	3,398,709	2,882,201	22,252,020
2004	5,640,268	6,780,899	3,624,523	3,417,382	2,876,699	22,339,770
2005	5,704,317	6,819,001	3,627,817	3,443,396	2,883,295	22,477,827
2006	5,736,226	6,867,758	3,626,802	3,460,479	2,885,938	22,577,203
2007	5,775,427	6,911,798	3,624,391	3,478,037	2,893,496	22,683,148
2008	5,819,421	6,969,788	3,627,898	3,502,661	2,897,937	22,817,705
2009	5,852,974	7,023,038	3,635,345	3,525,039	2,907,120	22,943,515
2010	5,892,510	7,081,733	3,645,716	3,548,842	2,921,219	23,090,019
2011	5,911,599	7,134,907	3,657,677	3,567,621	2,932,224	23,204,027
2012	5,945,897	7,177,191	3,672,127	3,589,321	2,941,259	23,325,794
2013	5,973,383	7,210,148	3,677,041	3,605,693	2,954,186	23,420,451
2014	6,002,791	7,253,736	3,690,746	3,625,493	2,966,763	23,539,529
2015	6,045,921	7,317,886	3,712,219	3,650,789	2,975,368	23,702,182
2016	6,091,970	7,389,752	3,738,131	3,677,216	2,991,063	23,888,131
2017	6,121,972	7,434,804	3,751,634	3,696,392	2,999,681	24,004,482
2018	6,152,660	7,480,663	3,765,787	3,715,813	3,008,756	24,123,679
2019	6,181,558	7,524,800	3,779,519	3,733,957	3,016,964	24,236,798
2020	6,208,210	7,565,794	3,792,658	3,750,557	3,023,873	24,341,091
2021	6,232,081	7,603,924	3,804,827	3,765,717	3,029,535	24,436,083
2022	6,254,564	7,639,445	3,816,572	3,780,297	3,034,700	24,525,577
2023	6,276,474	7,672,439	3,828,211	3,794,577	3,039,879	24,611,580
2024	6,298,412	7,704,534	3,840,251	3,808,914	3,045,452	24,697,562
2025	6,320,290	7,735,586	3,852,487	3,823,540	3,051,421	24,783,324
2026	6,342,052	7,765,889	3,864,615	3,838,215	3,057,580	24,868,350
2027	6,362,925	7,794,490	3,876,455	3,852,500	3,063,485	24,949,855
2028	6,382,700	7,822,178	3,887,881	3,866,049	3,068,906	25,027,715
2029	6,401,732	7,849,011	3,898,919	3,879,247	3,074,069	25,102,977
2030	6,420,252	7,875,025	3,909,673	3,892,261	3,078,956	25,176,166
2031	6,438,128	7,900,538	3,919,801	3,905,061	3,083,616	25,247,144
2032	6,454,134	7,924,649	3,929,051	3,916,785	3,087,275	25,311,893
2033	6,469,027	7,948,068	3,937,677	3,927,860	3,090,218	25,372,850
2034	6,483,248	7,971,240	3,945,888	3,938,474	3,092,710	25,431,559
2035	6,497,240	7,994,036	3,953,931	3,948,944	3,095,018	25,489,169
2036	6,510,775	8,016,762	3,961,537	3,959,180	3,096,992	25,545,245
2037	6,523,559	8,038,413	3,968,592	3,969,146	3,098,528	25,598,238
2038	6,536,708	8,060,340	3,975,761	3,979,230	3,100,118	25,652,157
2039	6,550,197	8,082,528	3,983,027	3,989,401	3,101,790	25,706,943
2040	6,563,994	8,104,930	3,990,406	3,999,626	3,103,485	25,762,442
2041	6,577,853	8,127,446	3,997,736	4,009,748	3,105,151	25,817,935
2042	6,591,826	8,150,136	4,005,530	4,020,217	3,107,305	25,850,303
2043	6,605,798	8,172,827	4,013,323	4,030,686	3,109,458	25,882,775
2044	6,619,771	8,195,518	4,021,117	4,041,155	3,111,612	25,915,349
2045	6,633,743	8,218,209	4,028,910	4,051,623	3,113,765	25,948,025
2046	6,647,716	8,240,900	4,036,704	4,062,092	3,115,919	25,980,799
2047	6,661,688	8,263,590	4,044,497	4,072,561	3,118,072	26,013,673
2048	6,675,661	8,286,281	4,052,291	4,083,029	3,120,226	26,046,643
2049	6,689,633	8,308,972	4,060,085	4,093,498	3,122,379	26,079,710
2050	6,703,606	8,331,663	4,067,878	4,103,967	3,124,533	26,112,871

*2042-2050 data estimated using regression trendline data

Appendix table 26. Total biomethane generation potential data using high fixed FW collection data (100kg/person/year) and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	4,761,025	2,750,504	2,893,698	3,402,554	1,758,125	15,565,905
2002	4,766,135	2,785,415	2,906,901	3,409,783	1,762,979	15,631,211
2003	4,774,471	2,842,972	2,915,055	3,417,613	1,762,020	15,712,130
2004	4,811,346	2,898,423	2,936,162	3,446,759	1,762,169	15,854,859
2005	4,891,921	2,971,505	2,964,222	3,487,759	1,780,387	16,095,794
2006	4,899,305	3,025,681	2,969,298	3,500,375	1,784,714	16,179,372
2007	4,915,148	3,071,750	2,972,680	3,515,555	1,793,556	16,268,688
2008	4,936,498	3,118,581	2,978,667	3,543,534	1,794,137	16,371,416
2009	4,951,355	3,161,869	2,998,924	3,572,708	1,806,118	16,490,972
2010	4,975,756	3,221,465	3,024,756	3,614,510	1,828,028	16,664,515
2011	4,931,354	3,245,434	3,032,951	3,632,324	1,823,357	16,665,419
2012	4,977,167	3,296,336	3,063,008	3,669,071	1,841,967	16,847,548
2013	4,999,637	3,318,077	3,074,915	3,688,787	1,868,353	16,949,770
2014	5,030,006	3,352,793	3,092,371	3,710,455	1,885,160	17,070,784
2015	5,082,237	3,427,272	3,135,294	3,748,991	1,901,711	17,295,505
2016	5,135,063	3,505,147	3,181,484	3,781,708	1,921,509	17,524,910
2017	5,169,319	3,548,333	3,208,181	3,808,735	1,934,435	17,669,003
2018	5,202,664	3,587,760	3,233,081	3,834,351	1,946,471	17,804,327
2019	5,232,938	3,622,658	3,255,525	3,856,680	1,956,218	17,924,018
2020	5,259,668	3,652,682	3,275,431	3,875,830	1,963,244	18,026,854
2021	5,282,820	3,678,703	3,293,062	3,892,421	1,968,185	18,115,191
2022	5,305,736	3,703,178	3,310,295	3,909,060	1,973,066	18,201,335
2023	5,329,888	3,726,655	3,327,770	3,926,549	1,978,702	18,289,564
2024	5,355,504	3,750,948	3,346,569	3,945,389	1,985,600	18,384,010
2025	5,382,626	3,776,186	3,366,495	3,965,936	1,993,930	18,485,172
2026	5,410,328	3,801,634	3,386,914	3,987,245	2,002,955	18,589,075
2027	5,438,111	3,827,142	3,407,636	4,008,906	2,012,270	18,694,064
2028	5,464,145	3,851,631	3,427,745	4,029,406	2,020,910	18,793,836
2029	5,489,168	3,875,479	3,447,279	4,049,379	2,029,165	18,890,469
2030	5,513,751	3,899,367	3,466,611	4,069,427	2,037,143	18,986,299
2031	5,537,646	3,923,188	3,485,444	4,089,413	2,044,771	19,080,461
2032	5,558,294	3,945,294	3,502,724	4,107,267	2,050,691	19,164,269
2033	5,576,405	3,965,686	3,518,458	4,123,447	2,055,065	19,239,059
2034	5,592,996	3,985,031	3,532,970	4,138,634	2,058,635	19,308,267
2035	5,609,034	4,003,965	3,547,091	4,153,788	2,062,017	19,375,895
2036	5,623,628	4,021,812	3,560,274	4,167,997	2,064,744	19,438,454
2037	5,637,769	4,039,288	3,572,971	4,182,185	2,067,309	19,499,522
2038	5,652,356	4,056,683	3,585,701	4,196,590	2,070,029	19,561,358
2039	5,667,280	4,073,875	3,598,391	4,211,143	2,072,810	19,623,499
2040	5,682,467	4,090,743	3,610,967	4,225,655	2,075,544	19,685,376
2041	5,697,567	4,107,078	3,623,279	4,239,965	2,078,163	19,746,052
2042	5,732,498	4,125,467	3,637,062	4,255,020	2,081,502	19,812,611
2043	5,767,430	4,143,856	3,650,846	4,270,076	2,084,841	19,879,170
2044	5,802,361	4,162,245	3,664,629	4,285,131	2,088,181	19,945,729
2045	5,837,292	4,180,634	3,678,413	4,300,186	2,091,520	20,012,288
2046	5,872,223	4,199,023	3,692,196	4,315,241	2,094,859	20,078,847
2047	5,907,155	4,217,412	3,705,980	4,330,296	2,098,198	20,145,406
2048	5,942,086	4,235,801	3,719,763	4,345,352	2,101,538	20,211,965
2049	5,977,017	4,254,190	3,733,547	4,360,407	2,104,877	20,278,524
2050	6,011,948	4,272,579	3,747,330	4,375,462	2,108,216	20,345,083

*2042-2050 data estimated using regression trendline data

Appendix table 27. Total biomethane generation potential data using high fixed FW collection data (100kg/person/year) and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	13,864,615	16,726,048	9,067,356	8,430,386	7,220,718	55,309,122
2002	13,931,973	16,772,765	9,057,886	8,462,009	7,218,038	55,442,671
2003	13,996,004	16,876,769	9,055,004	8,496,772	7,205,504	55,630,051
2004	14,100,669	16,952,247	9,061,308	8,543,455	7,191,747	55,849,426
2005	14,260,793	17,047,503	9,069,543	8,608,491	7,208,237	56,194,567
2006	14,340,564	17,169,395	9,067,005	8,651,198	7,214,846	56,443,007
2007	14,438,567	17,279,494	9,060,977	8,695,094	7,233,739	56,707,871
2008	14,548,552	17,424,470	9,069,746	8,756,654	7,244,843	57,044,264
2009	14,632,434	17,557,594	9,088,362	8,812,598	7,267,799	57,358,787
2010	14,731,274	17,704,332	9,114,289	8,872,106	7,303,048	57,725,048
2011	14,778,997	17,837,267	9,144,191	8,919,052	7,330,561	58,010,067
2012	14,864,742	17,942,978	9,180,317	8,973,302	7,353,146	58,314,485
2013	14,933,457	18,025,369	9,192,602	9,014,234	7,385,465	58,551,127
2014	15,006,978	18,134,341	9,226,865	9,063,731	7,416,907	58,848,822
2015	15,114,803	18,294,714	9,280,548	9,126,972	7,438,419	59,255,456
2016	15,229,924	18,474,379	9,345,328	9,193,041	7,477,657	59,720,328
2017	15,304,930	18,587,009	9,379,085	9,240,980	7,499,203	60,011,206
2018	15,381,650	18,701,658	9,414,468	9,289,532	7,521,890	60,309,198
2019	15,453,896	18,812,000	9,448,799	9,334,892	7,542,410	60,591,996
2020	15,520,525	18,914,486	9,481,644	9,376,391	7,559,683	60,852,728
2021	15,580,202	19,009,809	9,512,066	9,414,293	7,573,838	61,090,207
2022	15,636,409	19,098,612	9,541,429	9,450,743	7,586,750	61,313,942
2023	15,691,185	19,181,097	9,570,528	9,486,443	7,599,697	61,528,950
2024	15,746,029	19,261,334	9,600,626	9,522,286	7,613,629	61,743,904
2025	15,800,724	19,338,966	9,631,217	9,558,851	7,628,553	61,958,311
2026	15,855,129	19,414,721	9,661,538	9,595,537	7,643,950	62,170,875
2027	15,907,313	19,486,224	9,691,137	9,631,251	7,658,712	62,374,637
2028	15,956,750	19,555,445	9,719,703	9,665,123	7,672,266	62,569,287
2029	16,004,331	19,622,527	9,747,297	9,698,117	7,685,172	62,757,443
2030	16,050,629	19,687,563	9,774,182	9,730,652	7,697,390	62,940,416
2031	16,095,321	19,751,344	9,799,502	9,762,653	7,709,040	63,117,860
2032	16,135,335	19,811,621	9,822,627	9,791,962	7,718,186	63,279,731
2033	16,172,568	19,870,171	9,844,193	9,819,650	7,725,544	63,432,126
2034	16,208,120	19,928,099	9,864,720	9,846,185	7,731,774	63,578,898
2035	16,243,099	19,985,090	9,884,828	9,872,361	7,737,545	63,722,923
2036	16,276,937	20,041,904	9,903,843	9,897,950	7,742,480	63,863,114
2037	16,308,898	20,096,033	9,921,481	9,922,865	7,746,320	63,995,596
2038	16,341,770	20,150,849	9,939,402	9,948,076	7,750,296	64,130,393
2039	16,375,493	20,206,321	9,957,566	9,973,503	7,754,474	64,267,358
2040	16,409,986	20,262,326	9,976,014	9,999,065	7,758,713	64,406,104
2041	16,444,634	20,318,614	9,994,340	10,024,371	7,762,878	64,544,837
2042	16,479,565	20,375,341	10,013,824	10,050,543	7,768,262	64,625,758
2043	16,514,496	20,432,068	10,033,308	10,076,715	7,773,646	64,706,938
2044	16,549,427	20,488,795	10,052,792	10,102,886	7,779,029	64,788,373
2045	16,584,359	20,545,522	10,072,276	10,129,058	7,784,413	64,870,061
2046	16,619,290	20,602,249	10,091,760	10,155,230	7,789,797	64,951,999
2047	16,654,221	20,658,976	10,111,244	10,181,402	7,795,181	65,034,182
2048	16,689,152	20,715,703	10,130,727	10,207,573	7,800,565	65,116,608
2049	16,724,084	20,772,430	10,150,211	10,233,745	7,805,948	65,199,275
2050	16,759,015	20,829,157	10,169,695	10,259,917	7,811,332	65,282,178

*2042-2050 data estimated using regression trendline data

Appendix table 28. Total biomethane generation potential data using low fixed FW collection data (20kg/person/year) and high FW to biomethane conversion yield (90m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	1,269,607	733,468	771,653	907,348	468,833	1,269,607
2002	1,270,969	742,777	775,174	909,275	470,128	1,270,969
2003	1,273,192	758,126	777,348	911,363	469,872	1,273,192
2004	1,283,026	772,913	782,977	919,136	469,912	1,283,026
2005	1,304,512	792,401	790,459	930,069	474,770	1,304,512
2006	1,306,481	806,848	791,813	933,433	475,924	1,306,481
2007	1,310,706	819,133	792,715	937,481	478,282	1,310,706
2008	1,316,399	831,622	794,311	944,942	478,436	1,316,399
2009	1,320,361	843,165	799,713	952,722	481,631	1,320,361
2010	1,326,868	859,057	806,602	963,869	487,474	1,326,868
2011	1,315,028	865,449	808,787	968,620	486,229	1,315,028
2012	1,327,244	879,023	816,802	978,419	491,191	1,327,244
2013	1,333,237	884,821	819,977	983,677	498,227	1,333,237
2014	1,341,335	894,078	824,632	989,455	502,709	1,341,335
2015	1,355,263	913,939	836,078	999,731	507,123	1,355,263
2016	1,369,350	934,706	848,396	1,008,455	512,402	1,369,350
2017	1,378,485	946,222	855,515	1,015,663	515,849	1,378,485
2018	1,387,377	956,736	862,155	1,022,494	519,059	1,387,377
2019	1,395,450	966,042	868,140	1,028,448	521,658	1,395,450
2020	1,402,578	974,048	873,448	1,033,555	523,532	1,402,578
2021	1,408,752	980,987	878,150	1,037,979	524,849	1,408,752
2022	1,414,863	987,514	882,745	1,042,416	526,151	1,414,863
2023	1,421,303	993,775	887,405	1,047,080	527,654	1,421,303
2024	1,428,134	1,000,253	892,418	1,052,104	529,493	1,428,134
2025	1,435,367	1,006,983	897,732	1,057,583	531,715	1,435,367
2026	1,442,754	1,013,769	903,177	1,063,265	534,121	1,442,754
2027	1,450,163	1,020,571	908,703	1,069,042	536,605	1,450,163
2028	1,457,105	1,027,102	914,065	1,074,508	538,909	1,457,105
2029	1,463,778	1,033,461	919,274	1,079,834	541,111	1,463,778
2030	1,470,334	1,039,831	924,430	1,085,180	543,238	1,470,334
2031	1,476,706	1,046,183	929,452	1,090,510	545,272	1,476,706
2032	1,482,212	1,052,078	934,060	1,095,271	546,851	1,482,212
2033	1,487,041	1,057,516	938,255	1,099,586	548,017	1,487,041
2034	1,491,466	1,062,675	942,125	1,103,636	548,969	1,491,466
2035	1,495,742	1,067,724	945,891	1,107,677	549,871	1,495,742
2036	1,499,634	1,072,483	949,406	1,111,466	550,598	1,499,634
2037	1,503,405	1,077,143	952,792	1,115,249	551,282	1,503,405
2038	1,507,295	1,081,782	956,187	1,119,091	552,008	1,507,295
2039	1,511,275	1,086,367	959,571	1,122,971	552,749	1,511,275
2040	1,515,325	1,090,865	962,924	1,126,841	553,478	1,515,325
2041	1,519,351	1,095,221	966,208	1,130,657	554,177	1,519,351
2042	1,528,666	1,100,125	969,883	1,134,672	555,067	1,528,666
2043	1,537,981	1,105,028	973,559	1,138,687	555,958	1,537,981
2044	1,547,296	1,109,932	977,234	1,142,702	556,848	1,547,296
2045	1,556,611	1,114,836	980,910	1,146,716	557,739	1,556,611
2046	1,565,926	1,119,740	984,586	1,150,731	558,629	1,565,926
2047	1,575,241	1,124,643	988,261	1,154,746	559,520	1,575,241
2048	1,584,556	1,129,547	991,937	1,158,760	560,410	1,584,556
2049	1,593,871	1,134,451	995,612	1,162,775	561,300	1,593,871
2050	1,603,186	1,139,354	999,288	1,166,790	562,191	1,603,186

*2042-2050 data estimated using regression trendline data

Appendix table 29. Total biomethane generation potential data using low fixed FW collection data (20kg/person/year) and high FW to biomethane conversion yield (90^3/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	3,697,231	4,460,279	2,417,962	2,248,103	1,925,525	14,749,099
2002	3,715,193	4,472,737	2,415,436	2,256,536	1,924,810	14,784,712
2003	3,732,268	4,500,472	2,414,668	2,265,806	1,921,468	14,834,680
2004	3,760,178	4,520,599	2,416,349	2,278,255	1,917,799	14,893,180
2005	3,802,878	4,546,001	2,418,545	2,295,598	1,922,197	14,985,218
2006	3,824,150	4,578,505	2,417,868	2,306,986	1,923,959	15,051,469
2007	3,850,285	4,607,865	2,416,261	2,318,692	1,928,997	15,122,099
2008	3,879,614	4,646,525	2,418,599	2,335,108	1,931,958	15,211,804
2009	3,901,982	4,682,025	2,423,563	2,350,026	1,938,080	15,295,676
2010	3,928,340	4,721,155	2,430,477	2,365,895	1,947,479	15,393,346
2011	3,941,066	4,756,604	2,438,451	2,378,414	1,954,816	15,469,351
2012	3,963,931	4,784,794	2,448,085	2,392,880	1,960,839	15,550,529
2013	3,982,255	4,806,765	2,451,361	2,403,796	1,969,457	15,613,634
2014	4,001,861	4,835,824	2,460,497	2,416,995	1,977,842	15,693,019
2015	4,030,614	4,878,590	2,474,813	2,433,859	1,983,578	15,801,455
2016	4,061,313	4,926,501	2,492,087	2,451,478	1,994,042	15,925,421
2017	4,081,315	4,956,536	2,501,089	2,464,261	1,999,787	16,002,988
2018	4,101,773	4,987,109	2,510,525	2,477,209	2,005,837	16,082,453
2019	4,121,039	5,016,533	2,519,680	2,489,305	2,011,309	16,157,866
2020	4,138,807	5,043,863	2,528,438	2,500,371	2,015,915	16,227,394
2021	4,154,720	5,069,282	2,536,551	2,510,478	2,019,690	16,290,722
2022	4,169,709	5,092,963	2,544,381	2,520,198	2,023,133	16,350,385
2023	4,184,316	5,114,959	2,552,141	2,529,718	2,026,586	16,407,720
2024	4,198,941	5,136,356	2,560,167	2,539,276	2,030,301	16,465,041
2025	4,213,526	5,157,058	2,568,325	2,549,027	2,034,281	16,522,216
2026	4,228,034	5,177,259	2,576,410	2,558,810	2,038,387	16,578,900
2027	4,241,950	5,196,326	2,584,303	2,568,334	2,042,323	16,633,237
2028	4,255,133	5,214,785	2,591,921	2,577,366	2,045,938	16,685,143
2029	4,267,822	5,232,674	2,599,279	2,586,164	2,049,379	16,735,318
2030	4,280,168	5,250,017	2,606,449	2,594,840	2,052,637	16,784,111
2031	4,292,086	5,267,025	2,613,200	2,603,374	2,055,744	16,831,429
2032	4,302,756	5,283,099	2,619,367	2,611,190	2,058,183	16,874,595
2033	4,312,685	5,298,712	2,625,118	2,618,573	2,060,145	16,915,234
2034	4,322,165	5,314,160	2,630,592	2,625,649	2,061,806	16,954,373
2035	4,331,493	5,329,357	2,635,954	2,632,630	2,063,345	16,992,779
2036	4,340,516	5,344,508	2,641,025	2,639,453	2,064,661	17,030,164
2037	4,349,039	5,358,942	2,645,728	2,646,097	2,065,685	17,065,492
2038	4,357,805	5,373,560	2,650,507	2,652,820	2,066,746	17,101,438
2039	4,366,798	5,388,352	2,655,351	2,659,601	2,067,860	17,137,962
2040	4,375,996	5,403,287	2,660,270	2,666,417	2,068,990	17,174,961
2041	4,385,236	5,418,297	2,665,157	2,673,166	2,070,101	17,211,956
2042	4,394,551	5,433,424	2,670,353	2,680,145	2,071,536	17,233,535
2043	4,403,866	5,448,551	2,675,549	2,687,124	2,072,972	17,255,183
2044	4,413,181	5,463,679	2,680,745	2,694,103	2,074,408	17,276,900
2045	4,422,496	5,478,806	2,685,940	2,701,082	2,075,844	17,298,683
2046	4,431,811	5,493,933	2,691,136	2,708,061	2,077,279	17,320,533
2047	4,441,126	5,509,060	2,696,332	2,715,040	2,078,715	17,342,449
2048	4,450,441	5,524,187	2,701,527	2,722,020	2,080,151	17,364,429
2049	4,459,756	5,539,315	2,706,723	2,728,999	2,081,586	17,386,473
2050	4,469,071	5,554,442	2,711,919	2,735,978	2,083,022	17,408,581

*2042-2050 data estimated using regression trendline data

Appendix table 30. Total biomethane generation potential data using medium fixed FW collection data (40kg/person/year) and high FW to biomethane conversion yield (90m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	2,539,213	1,466,935	1,543,306	1,814,695	937,667	8,301,816
2002	2,541,938	1,485,554	1,550,347	1,818,551	940,255	8,336,646
2003	2,546,384	1,516,252	1,554,696	1,822,727	939,744	8,379,803
2004	2,566,051	1,545,826	1,565,953	1,838,272	939,823	8,455,925
2005	2,609,024	1,584,803	1,580,918	1,860,138	949,540	8,584,423
2006	2,612,963	1,613,696	1,583,626	1,866,866	951,847	8,628,998
2007	2,621,412	1,638,266	1,585,429	1,874,963	956,563	8,676,634
2008	2,632,799	1,663,243	1,588,622	1,889,885	956,873	8,731,422
2009	2,640,722	1,686,330	1,599,426	1,905,444	963,263	8,795,185
2010	2,653,736	1,718,114	1,613,203	1,927,739	974,948	8,887,741
2011	2,630,056	1,730,898	1,617,574	1,937,239	972,457	8,888,224
2012	2,654,489	1,758,046	1,633,604	1,956,838	982,382	8,985,359
2013	2,666,473	1,769,641	1,639,955	1,967,353	996,455	9,039,877
2014	2,682,670	1,788,156	1,649,264	1,978,909	1,005,419	9,104,418
2015	2,710,526	1,827,878	1,672,157	1,999,462	1,014,246	9,224,269
2016	2,738,700	1,869,412	1,696,792	2,016,911	1,024,805	9,346,619
2017	2,756,970	1,892,444	1,711,030	2,031,325	1,031,699	9,423,468
2018	2,774,754	1,913,472	1,724,310	2,044,987	1,038,118	9,495,641
2019	2,790,900	1,932,084	1,736,280	2,056,896	1,043,316	9,559,476
2020	2,805,156	1,948,097	1,746,896	2,067,109	1,047,064	9,614,322
2021	2,817,504	1,961,975	1,756,300	2,075,958	1,049,699	9,661,435
2022	2,829,726	1,975,028	1,765,490	2,084,832	1,052,302	9,707,378
2023	2,842,607	1,987,549	1,774,811	2,094,160	1,055,308	9,754,434
2024	2,856,269	2,000,506	1,784,837	2,104,207	1,058,987	9,804,805
2025	2,870,734	2,013,966	1,795,464	2,115,166	1,063,429	9,858,758
2026	2,885,508	2,027,538	1,806,354	2,126,531	1,068,242	9,914,173
2027	2,900,326	2,041,142	1,817,406	2,138,083	1,073,210	9,970,168
2028	2,914,211	2,054,203	1,828,130	2,149,016	1,077,818	10,023,379
2029	2,927,556	2,066,922	1,838,549	2,159,669	1,082,221	10,074,917
2030	2,940,667	2,079,662	1,848,859	2,170,361	1,086,476	10,126,026
2031	2,953,411	2,092,367	1,858,903	2,181,020	1,090,544	10,176,246
2032	2,964,424	2,104,157	1,868,119	2,190,542	1,093,702	10,220,944
2033	2,974,082	2,115,032	1,876,511	2,199,172	1,096,034	10,260,832
2034	2,982,931	2,125,350	1,884,251	2,207,272	1,097,939	10,297,742
2035	2,991,485	2,135,448	1,891,782	2,215,354	1,099,742	10,333,811
2036	2,999,268	2,144,966	1,898,813	2,222,932	1,101,197	10,367,176
2037	3,006,810	2,154,287	1,905,584	2,230,499	1,102,565	10,399,745
2038	3,014,590	2,163,564	1,912,374	2,238,181	1,104,016	10,432,724
2039	3,022,549	2,172,733	1,919,142	2,245,943	1,105,499	10,465,866
2040	3,030,649	2,181,730	1,925,849	2,253,683	1,106,957	10,498,867
2041	3,038,702	2,190,442	1,932,415	2,261,315	1,108,354	10,531,228
2042	3,057,332	2,200,249	1,939,766	2,269,344	1,110,135	10,566,726
2043	3,075,962	2,210,057	1,947,118	2,277,374	1,111,915	10,602,224
2044	3,094,592	2,219,864	1,954,469	2,285,403	1,113,696	10,637,722
2045	3,113,222	2,229,672	1,961,820	2,293,433	1,115,477	10,673,220
2046	3,131,852	2,239,479	1,969,171	2,301,462	1,117,258	10,708,718
2047	3,150,482	2,249,286	1,976,522	2,309,491	1,119,039	10,744,217
2048	3,169,112	2,259,094	1,983,874	2,317,521	1,120,820	10,779,715
2049	3,187,742	2,268,901	1,991,225	2,325,550	1,122,601	10,815,213
2050	3,206,372	2,278,709	1,998,576	2,333,580	1,124,382	10,850,711

*2042-2050 data estimated using regression trendline data

Appendix table 31. Total biomethane generation potential data using medium fixed FW collection data (40kg/person/year) and high FW to biomethane conversion yield (90^3/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	7,394,461	8,920,559	4,835,923	4,496,206	3,851,050	29,498,198
2002	7,430,386	8,945,474	4,830,872	4,513,072	3,849,620	29,569,424
2003	7,464,535	9,000,943	4,829,335	4,531,612	3,842,935	29,669,360
2004	7,520,357	9,041,198	4,832,698	4,556,509	3,835,598	29,786,360
2005	7,605,756	9,092,002	4,837,090	4,591,195	3,844,393	29,970,436
2006	7,648,301	9,157,010	4,835,736	4,613,972	3,847,918	30,102,937
2007	7,700,569	9,215,730	4,832,521	4,637,383	3,857,994	30,244,198
2008	7,759,228	9,293,051	4,837,198	4,670,215	3,863,916	30,423,607
2009	7,803,965	9,364,050	4,847,126	4,700,052	3,876,160	30,591,353
2010	7,856,680	9,442,310	4,860,954	4,731,790	3,894,959	30,786,692
2011	7,882,132	9,513,209	4,876,902	4,756,828	3,909,632	30,938,702
2012	7,927,862	9,569,588	4,896,169	4,785,761	3,921,678	31,101,059
2013	7,964,510	9,613,530	4,902,721	4,807,591	3,938,915	31,227,268
2014	8,003,722	9,671,648	4,920,995	4,833,990	3,955,684	31,386,038
2015	8,061,228	9,757,181	4,949,626	4,867,718	3,967,157	31,602,910
2016	8,122,626	9,853,002	4,984,175	4,902,955	3,988,084	31,850,842
2017	8,162,629	9,913,072	5,002,178	4,928,522	3,999,575	32,005,976
2018	8,203,547	9,974,218	5,021,050	4,954,417	4,011,674	32,164,906
2019	8,242,078	10,033,067	5,039,359	4,978,609	4,022,618	32,315,731
2020	8,277,613	10,087,726	5,056,877	5,000,742	4,031,831	32,454,788
2021	8,309,441	10,138,565	5,073,102	5,020,956	4,039,380	32,581,444
2022	8,339,418	10,185,926	5,088,762	5,040,396	4,046,267	32,700,769
2023	8,368,632	10,229,918	5,104,282	5,059,436	4,053,172	32,815,440
2024	8,397,882	10,272,712	5,120,334	5,078,552	4,060,602	32,930,082
2025	8,427,053	10,314,115	5,136,649	5,098,054	4,068,562	33,044,432
2026	8,456,069	10,354,518	5,152,820	5,117,620	4,076,773	33,157,800
2027	8,483,900	10,392,653	5,168,606	5,136,667	4,084,646	33,266,473
2028	8,510,267	10,429,571	5,183,842	5,154,732	4,091,875	33,370,286
2029	8,535,643	10,465,348	5,198,558	5,172,329	4,098,758	33,470,636
2030	8,560,336	10,500,034	5,212,897	5,189,681	4,105,274	33,568,222
2031	8,584,171	10,534,050	5,226,401	5,206,748	4,111,488	33,662,858
2032	8,605,512	10,566,198	5,238,734	5,222,380	4,116,366	33,749,190
2033	8,625,370	10,597,424	5,250,236	5,237,147	4,120,290	33,830,467
2034	8,644,331	10,628,320	5,261,184	5,251,298	4,123,613	33,908,746
2035	8,662,986	10,658,714	5,271,908	5,265,259	4,126,691	33,985,559
2036	8,681,033	10,689,016	5,282,050	5,278,907	4,129,322	34,060,327
2037	8,698,079	10,717,884	5,291,456	5,292,194	4,131,371	34,130,984
2038	8,715,611	10,747,120	5,301,014	5,305,640	4,133,491	34,202,876
2039	8,733,596	10,776,704	5,310,702	5,319,202	4,135,720	34,275,924
2040	8,751,992	10,806,574	5,320,541	5,332,835	4,137,980	34,349,922
2041	8,770,471	10,836,594	5,330,315	5,346,331	4,140,202	34,423,913
2042	8,789,101	10,866,848	5,340,706	5,360,289	4,143,073	34,467,071
2043	8,807,731	10,897,103	5,351,098	5,374,248	4,145,944	34,510,367
2044	8,826,361	10,927,357	5,361,489	5,388,206	4,148,816	34,553,799
2045	8,844,991	10,957,612	5,371,880	5,402,164	4,151,687	34,597,366
2046	8,863,621	10,987,866	5,382,272	5,416,123	4,154,558	34,641,066
2047	8,882,251	11,018,120	5,392,663	5,430,081	4,157,430	34,684,897
2048	8,900,881	11,048,375	5,403,055	5,444,039	4,160,301	34,728,858
2049	8,919,511	11,078,629	5,413,446	5,457,997	4,163,172	34,772,946
2050	8,938,141	11,108,884	5,423,837	5,471,956	4,166,044	34,817,161

*2042-2050 data estimated using regression trendline data

Appendix table 32. Total biomethane generation potential data using high fixed FW collection data (100kg/person/year) and high FW to biomethane conversion yield (90m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	6,348,033	3,667,338	3,858,264	4,536,738	2,344,167	20,754,540
2002	6,354,846	3,713,886	3,875,868	4,546,377	2,350,638	20,841,615
2003	6,365,961	3,790,629	3,886,740	4,556,817	2,349,360	20,949,507
2004	6,415,128	3,864,564	3,914,883	4,595,679	2,349,558	21,139,812
2005	6,522,561	3,962,007	3,952,296	4,650,345	2,373,849	21,461,058
2006	6,532,407	4,034,241	3,959,064	4,667,166	2,379,618	21,572,496
2007	6,553,530	4,095,666	3,963,573	4,687,407	2,391,408	21,691,584
2008	6,581,997	4,158,108	3,971,556	4,724,712	2,392,182	21,828,555
2009	6,601,806	4,215,825	3,998,565	4,763,610	2,408,157	21,987,963
2010	6,634,341	4,295,286	4,033,008	4,819,347	2,437,371	22,219,353
2011	6,575,139	4,327,245	4,043,934	4,843,098	2,431,143	22,220,559
2012	6,636,222	4,395,114	4,084,011	4,892,094	2,455,956	22,463,397
2013	6,666,183	4,424,103	4,099,887	4,918,383	2,491,137	22,599,693
2014	6,706,674	4,470,390	4,123,161	4,947,273	2,513,547	22,761,045
2015	6,776,316	4,569,696	4,180,392	4,998,654	2,535,615	23,060,673
2016	6,846,750	4,673,529	4,241,979	5,042,277	2,562,012	23,366,547
2017	6,892,425	4,731,111	4,277,574	5,078,313	2,579,247	23,558,670
2018	6,936,885	4,783,680	4,310,775	5,112,468	2,595,294	23,739,102
2019	6,977,250	4,830,210	4,340,700	5,142,240	2,608,290	23,898,690
2020	7,012,890	4,870,242	4,367,241	5,167,773	2,617,659	24,035,805
2021	7,043,760	4,904,937	4,390,749	5,189,895	2,624,247	24,153,588
2022	7,074,315	4,937,571	4,413,726	5,212,080	2,630,754	24,268,446
2023	7,106,517	4,968,873	4,437,027	5,235,399	2,638,269	24,386,085
2024	7,140,672	5,001,264	4,462,092	5,260,518	2,647,467	24,512,013
2025	7,176,834	5,034,915	4,488,660	5,287,914	2,658,573	24,646,896
2026	7,213,770	5,068,845	4,515,885	5,316,327	2,670,606	24,785,433
2027	7,250,814	5,102,856	4,543,515	5,345,208	2,683,026	24,925,419
2028	7,285,527	5,135,508	4,570,326	5,372,541	2,694,546	25,058,448
2029	7,318,890	5,167,305	4,596,372	5,399,172	2,705,553	25,187,292
2030	7,351,668	5,199,156	4,622,148	5,425,902	2,716,191	25,315,065
2031	7,383,528	5,230,917	4,647,258	5,452,551	2,726,361	25,440,615
2032	7,411,059	5,260,392	4,670,298	5,476,356	2,734,254	25,552,359
2033	7,435,206	5,287,581	4,691,277	5,497,929	2,740,086	25,652,079
2034	7,457,328	5,313,375	4,710,627	5,518,179	2,744,847	25,744,356
2035	7,478,712	5,338,620	4,729,455	5,538,384	2,749,356	25,834,527
2036	7,498,170	5,362,416	4,747,032	5,557,329	2,752,992	25,917,939
2037	7,517,025	5,385,717	4,763,961	5,576,247	2,756,412	25,999,362
2038	7,536,474	5,408,910	4,780,935	5,595,453	2,760,039	26,081,811
2039	7,556,373	5,431,833	4,797,855	5,614,857	2,763,747	26,164,665
2040	7,576,623	5,454,324	4,814,622	5,634,207	2,767,392	26,247,168
2041	7,596,756	5,476,104	4,831,038	5,653,287	2,770,884	26,328,069
2042	7,643,331	5,500,623	4,849,416	5,673,361	2,775,336	26,416,814
2043	7,689,906	5,525,141	4,867,794	5,693,434	2,779,789	26,505,560
2044	7,736,481	5,549,660	4,886,172	5,713,508	2,784,241	26,594,305
2045	7,783,056	5,574,179	4,904,550	5,733,581	2,788,693	26,683,051
2046	7,829,631	5,598,698	4,922,928	5,753,655	2,793,146	26,771,796
2047	7,876,206	5,623,216	4,941,306	5,773,729	2,797,598	26,860,541
2048	7,922,781	5,647,735	4,959,684	5,793,802	2,802,050	26,949,287
2049	7,969,356	5,672,254	4,978,062	5,813,876	2,806,502	27,038,032
2050	8,015,931	5,696,772	4,996,440	5,833,949	2,810,955	27,126,778

*2042-2050 data estimated using regression trendline data

Appendix table 33. Total biomethane generation potential data using high fixed FW collection data (100kg/person/year) and high FW to biomethane conversion yield (90m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	18,486,153	22,301,397	12,089,808	11,240,514	9,627,624	73,745,496
2002	18,575,964	22,363,686	12,077,181	11,282,679	9,624,051	73,923,561
2003	18,661,338	22,502,358	12,073,338	11,329,029	9,607,338	74,173,401
2004	18,800,892	22,602,996	12,081,744	11,391,273	9,588,996	74,465,901
2005	19,014,390	22,730,004	12,092,724	11,477,988	9,610,983	74,926,089
2006	19,120,752	22,892,526	12,089,340	11,534,931	9,619,794	75,257,343
2007	19,251,423	23,039,325	12,081,303	11,593,458	9,644,985	75,610,494
2008	19,398,069	23,232,627	12,092,994	11,675,538	9,659,790	76,059,018
2009	19,509,912	23,410,125	12,117,816	11,750,130	9,690,399	76,478,382
2010	19,641,699	23,605,776	12,152,385	11,829,474	9,737,397	76,966,731
2011	19,705,329	23,783,022	12,192,255	11,892,069	9,774,081	77,346,756
2012	19,819,656	23,923,971	12,240,423	11,964,402	9,804,195	77,752,647
2013	19,911,276	24,033,825	12,256,803	12,018,978	9,847,287	78,068,169
2014	20,009,304	24,179,121	12,302,487	12,084,975	9,889,209	78,465,096
2015	20,153,070	24,392,952	12,374,064	12,169,296	9,917,892	79,007,274
2016	20,306,565	24,632,505	12,460,437	12,257,388	9,970,209	79,627,104
2017	20,406,573	24,782,679	12,505,446	12,321,306	9,998,937	80,014,941
2018	20,508,867	24,935,544	12,552,624	12,386,043	10,029,186	80,412,264
2019	20,605,194	25,082,667	12,598,398	12,446,523	10,056,546	80,789,328
2020	20,694,033	25,219,314	12,642,192	12,501,855	10,079,577	81,136,971
2021	20,773,602	25,346,412	12,682,755	12,552,390	10,098,450	81,453,609
2022	20,848,545	25,464,816	12,721,905	12,600,990	10,115,667	81,751,923
2023	20,921,580	25,574,796	12,760,704	12,648,591	10,132,929	82,038,600
2024	20,994,705	25,681,779	12,800,835	12,696,381	10,151,505	82,325,205
2025	21,067,632	25,785,288	12,841,623	12,745,134	10,171,404	82,611,081
2026	21,140,172	25,886,295	12,882,051	12,794,049	10,191,933	82,894,500
2027	21,209,751	25,981,632	12,921,516	12,841,668	10,211,616	83,166,183
2028	21,275,667	26,073,927	12,959,604	12,886,830	10,229,688	83,425,716
2029	21,339,108	26,163,369	12,996,396	12,930,822	10,246,896	83,676,591
2030	21,400,839	26,250,084	13,032,243	12,974,202	10,263,186	83,920,554
2031	21,460,428	26,335,125	13,066,002	13,016,871	10,278,720	84,157,146
2032	21,513,780	26,415,495	13,096,836	13,055,949	10,290,915	84,372,975
2033	21,563,424	26,493,561	13,125,591	13,092,867	10,300,725	84,576,168
2034	21,610,827	26,570,799	13,152,960	13,128,246	10,309,032	84,771,864
2035	21,657,465	26,646,786	13,179,771	13,163,148	10,316,727	84,963,897
2036	21,702,582	26,722,539	13,205,124	13,197,267	10,323,306	85,150,818
2037	21,745,197	26,794,710	13,228,641	13,230,486	10,328,427	85,327,461
2038	21,789,027	26,867,799	13,252,536	13,264,101	10,333,728	85,507,191
2039	21,833,991	26,941,761	13,276,755	13,298,004	10,339,299	85,689,810
2040	21,879,981	27,016,434	13,301,352	13,332,087	10,344,951	85,874,805
2041	21,926,178	27,091,485	13,325,787	13,365,828	10,350,504	86,059,782
2042	21,972,753	27,167,121	13,351,766	13,400,724	10,357,682	86,167,677
2043	22,019,328	27,242,757	13,377,744	13,435,619	10,364,861	86,275,917
2044	22,065,903	27,318,393	13,403,723	13,470,515	10,372,039	86,384,498
2045	22,112,478	27,394,029	13,429,701	13,505,411	10,379,218	86,493,415
2046	22,159,053	27,469,665	13,455,680	13,540,307	10,386,396	86,602,665
2047	22,205,628	27,545,301	13,481,658	13,575,202	10,393,574	86,712,243
2048	22,252,203	27,620,937	13,507,637	13,610,098	10,400,753	86,822,145
2049	22,298,778	27,696,573	13,533,615	13,644,994	10,407,931	86,932,366
2050	22,345,353	27,772,209	13,559,594	13,679,889	10,415,110	87,042,904

*2042-2050 data estimated using regression trendline data

Appendix table 34. Total Biomethane production potential data for 2020, 2030, 2040 and 2050 (as key timeline milestones) across all NPH city regions

Fixed FW to biomethane conversion yield					
			Low (45m ³ /t)	Medium (67.50m ³ /t)	High (90m ³ /t)
Fixed FW collection	2020	Low (20m ³ /t)	2,403,581	3,605,371	4,807,161
		Medium (40m ³ /t)	4,807,161	7,210,742	9,614,322
		High (100m ³ /t)	12,017,903	18,026,854	24,035,805
	2030	Low (20m ³ /t)	2,531,507	3,797,260	5,063,013
		Medium (40m ³ /t)	5,063,013	7,594,520	10,126,026
		High (100m ³ /t)	12,657,533	18,986,299	25,315,065
	2040	Low (20m ³ /t)	2,624,717	3,937,075	5,249,434
		Medium (40m ³ /t)	5,249,434	7,874,150	10,498,867
		High (100m ³ /t)	13,123,584	19,685,376	26,247,168

Appendix table 35. Total biomethane generation potential data using variable time-adjusted WRAP FW collection trial data and low FW to biomethane conversion yield (45³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2007	2,860,177	1,801,859	1,802,712	2,065,569	1,084,939	9,615,649
2010	2,333,751	1,511,462	1,473,515	1,705,503	882,083	7,900,292
2012	2,301,594	1,511,922	1,450,080	1,695,578	866,310	7,816,422
2014	2,415,419	1,595,740	1,505,671	1,775,644	912,120	8,196,439
2015	2,397,702	1,602,928	1,496,292	1,764,078	905,509	8,158,888
2017	2,379,369	1,623,147	1,490,934	1,752,250	901,345	8,141,376
2018	2,229,003	1,526,048	1,397,684	1,642,028	843,576	7,632,184
2020	1,763,020	1,214,035	1,104,971	1,298,817	667,737	6,043,517
2025	1,474,053	1,028,521	924,765	1,084,444	551,996	5,061,710
2030	1,262,127	890,154	794,513	929,200	470,161	4,345,918
2035	1,105,317	786,265	699,548	816,095	409,612	3,816,465
2040	935,428	670,544	595,114	693,508	344,723	3,238,758
2045	806,929	575,626	509,113	592,781	291,687	2,775,690
2050	712,412	504,331	444,510	517,019	251,940	2,429,845

*2020-2050 data estimated using regression trendline data

Appendix table 36. Total biomethane generation potential data using variable time-adjusted WRAP FW collection trial data and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2007	4,290,265	2,702,788	2,704,068	3,098,354	1,627,408	14,423,473
2010	3,500,627	2,267,193	2,210,272	2,558,254	1,323,124	11,850,438
2012	3,452,391	2,267,884	2,175,120	2,543,367	1,299,465	11,724,634
2014	3,623,129	2,393,610	2,258,506	2,663,466	1,368,180	12,294,659
2015	3,596,552	2,404,392	2,244,438	2,646,116	1,358,264	12,238,332
2017	3,569,053	2,434,721	2,236,401	2,628,376	1,352,018	12,212,064
2018	3,343,504	2,289,072	2,096,526	2,463,043	1,265,365	11,448,276
2020	2,644,530	1,821,052	1,657,457	1,948,226	1,001,606	9,065,275
2025	2,211,080	1,542,782	1,387,148	1,626,667	827,994	7,592,564

2030	1,893,190	1,335,231	1,191,770	1,393,800	705,241	6,518,878
2035	1,657,975	1,179,398	1,049,322	1,224,142	614,418	5,724,698
2040	1,403,141	1,005,817	892,670	1,040,262	517,084	4,858,136
2045	1,210,393	863,439	763,669	889,171	437,530	4,163,535
2050	1,068,617	756,497	666,766	775,529	377,910	3,644,767

*2020-2050 data estimated using regression trendline data

Appendix table 37. Total biomethane generation potential data using variable time-adjusted WRAP FW collection trial data and high FW to biomethane conversion yield (90m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2007	5,720,354	3,603,717	3,605,424	4,131,138	2,169,877	19,231,297
2010	4,667,502	3,022,923	2,947,030	3,411,005	1,764,165	15,800,585
2012	4,603,187	3,023,845	2,900,160	3,391,155	1,732,620	15,632,845
2014	4,830,839	3,191,479	3,011,342	3,551,288	1,824,240	16,392,878
2015	4,795,403	3,205,856	2,992,584	3,528,155	1,811,019	16,317,776
2017	4,758,737	3,246,295	2,981,868	3,504,501	1,802,690	16,282,753
2018	4,458,005	3,052,096	2,795,367	3,284,057	1,687,153	15,264,368
2020	3,526,040	2,428,070	2,209,943	2,597,635	1,335,475	12,087,034
2025	2,948,107	2,057,042	1,849,530	2,168,889	1,103,992	10,123,419
2030	2,524,253	1,780,309	1,589,026	1,858,400	940,322	8,691,837
2035	2,210,633	1,572,531	1,399,096	1,632,190	819,224	7,632,931
2040	1,870,855	1,341,089	1,190,227	1,387,016	689,446	6,477,515
2045	1,613,857	1,151,252	1,018,226	1,185,561	583,373	5,551,379
2050	1,424,823	1,008,663	889,021	1,034,039	503,879	4,859,690

*2020-2050 data estimated using regression trendline data

Appendix table 38. Total biomethane generation potential data using variable time-adjusted WRAP FW collection trial data and low FW to biomethane conversion yield (45m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2007	8,401,957	10,135,985	5,494,818	5,108,814	4,375,755	33,517,328
2010	6,909,328	8,306,601	4,440,041	4,186,293	3,523,956	27,366,219
2012	6,873,910	8,229,863	4,346,118	4,146,808	3,458,316	27,055,015
2014	7,206,383	8,630,921	4,492,547	4,337,462	3,588,612	28,255,925
2015	7,130,873	8,556,401	4,429,062	4,294,673	3,541,841	27,952,849
2017	7,044,655	8,502,430	4,358,731	4,251,415	3,494,234	27,651,465
2018	6,590,036	7,954,720	4,069,941	3,978,164	3,259,895	25,852,755
2020	5,202,419	6,286,571	3,198,647	3,142,094	2,571,194	20,400,925
2025	4,327,091	5,267,360	2,645,664	2,613,770	2,111,875	16,965,759
2030	3,674,073	4,494,311	2,240,146	2,221,867	1,776,513	14,406,911
2035	3,200,866	3,924,505	1,949,459	1,939,623	1,537,034	12,551,489
2040	2,701,353	3,321,350	1,644,120	1,641,031	1,288,629	10,596,483
2045	2,292,569	2,828,885	1,394,059	1,396,290	1,085,626	8,997,430
2050	1,985,931	2,458,655	1,206,335	1,212,346	933,484	7,796,752

*2020-2050 data estimated using regression trendline data

Appendix table 39. Total biomethane generation potential data using variable time-adjusted WRAP FW collection trial data and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2007	12,602,935	15,203,977	8,242,227	7,663,220	6,563,633	50,275,992
2010	10,363,992	12,459,902	6,660,061	6,279,439	5,285,934	41,049,328
2012	10,310,866	12,344,795	6,519,177	6,220,212	5,187,474	40,582,522
2014	10,809,574	12,946,381	6,738,821	6,506,194	5,382,918	42,383,888
2015	10,696,309	12,834,601	6,643,593	6,442,009	5,312,761	41,929,273
2017	10,566,983	12,753,646	6,538,097	6,377,122	5,241,351	41,477,198
2018	9,885,053	11,932,081	6,104,911	5,967,245	4,889,842	38,779,133
2020	7,803,629	9,429,857	4,797,970	4,713,140	3,856,792	30,601,387
2025	6,490,636	7,901,040	3,968,495	3,920,655	3,167,812	25,448,638
2030	5,511,110	6,741,467	3,360,219	3,332,800	2,664,770	21,610,366
2035	4,801,299	5,886,758	2,924,189	2,909,435	2,305,552	18,827,233
2040	4,052,030	4,982,025	2,466,180	2,461,546	1,932,944	15,894,725
2045	3,438,854	4,243,327	2,091,089	2,094,436	1,628,440	13,496,145
2050	2,978,897	3,687,983	1,809,503	1,818,520	1,400,225	11,695,127

*2020-2050 data estimated using regression trendline data

Appendix table 40. Total biomethane generation potential data using variable time-adjusted WRAP FW collection trial data and high FW to biomethane conversion yield (90m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2007	16,803,913	20,271,970	10,989,635	10,217,627	8,751,510	67,034,656
2010	13,818,656	16,613,202	8,880,082	8,372,586	7,047,912	54,732,437
2012	13,747,821	16,459,726	8,692,235	8,293,615	6,916,632	54,110,030
2014	14,412,765	17,261,842	8,985,095	8,674,925	7,177,224	56,511,850
2015	14,261,746	17,112,801	8,858,123	8,589,345	7,083,682	55,905,697
2017	14,089,310	17,004,861	8,717,462	8,502,829	6,988,468	55,302,931
2018	13,180,071	15,909,441	8,139,881	7,956,327	6,519,790	51,705,510
2020	10,404,838	12,573,143	6,397,293	6,284,187	5,142,389	40,801,850
2025	8,654,181	10,534,720	5,291,327	5,227,540	4,223,749	33,931,518
2030	7,348,147	8,988,623	4,480,292	4,443,733	3,553,027	28,813,822
2035	6,401,732	7,849,011	3,898,919	3,879,247	3,074,069	25,102,977
2040	5,402,707	6,642,700	3,288,240	3,282,062	2,577,258	21,192,966
2045	4,585,138	5,657,770	2,788,119	2,792,581	2,171,253	17,994,860
2050	3,971,863	4,917,311	2,412,670	2,424,693	1,866,967	15,593,503

*2020-2050 data estimated using regression trendline data

Appendix table 41. Total biomethane generation potential data using variable time-adjusted Waste Data Flow (WDF) FW collection trial data and low FW to biomethane conversion yield (45m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	1,611,927	1,043,614	979,889	1,170,943	592,201	5,398,575
2011	1,486,833	978,518	914,453	1,095,167	549,753	5,024,724
2012	1,319,418	873,839	811,986	972,649	488,295	4,466,188
2013	1,459,588	968,676	897,687	1,076,900	545,445	4,948,297
2014	1,338,397	892,120	822,826	987,288	501,608	4,542,239
2015	1,460,959	985,217	901,283	1,077,699	546,673	4,971,831
2016	1,637,796	1,117,944	1,014,714	1,206,152	612,853	5,589,459
2017	1,305,514	896,133	810,227	961,898	488,542	4,462,314
2018	1,326,153	914,516	824,109	977,372	496,153	4,538,303
2020	1,227,256	852,292	764,267	904,360	458,090	4,206,266
2025	1,148,293	805,586	718,186	846,066	425,372	3,943,503
2030	1,029,234	727,882	647,101	759,626	380,267	3,544,109
2035	934,839	667,328	591,182	692,298	343,670	3,229,316
2040	833,429	599,976	529,608	619,763	304,413	2,887,188
2045	758,848	543,482	478,194	559,024	271,898	2,611,446
2050	681,354	484,226	424,697	495,886	238,931	2,325,094

*2020-2050 data estimated using regression trendline data

Appendix table 42. Total biomethane generation potential data using variable time-adjusted Waste Data Flow (WDF) FW collection trial data and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2007	2,417,891	1,565,421	1,469,833	1,756,415	888,302	8,097,862
2010	2,230,249	1,467,777	1,371,679	1,642,751	824,630	7,537,086
2012	1,979,127	1,310,759	1,217,979	1,458,974	732,442	6,699,281
2014	2,189,383	1,453,014	1,346,531	1,615,351	818,167	7,422,445
2015	2,007,596	1,338,180	1,234,239	1,480,931	752,413	6,813,358
2017	2,191,439	1,477,825	1,351,925	1,616,548	820,010	7,457,747
2018	2,456,694	1,676,917	1,522,071	1,809,228	919,280	8,384,189
2020	1,958,270	1,344,199	1,215,341	1,442,846	732,814	6,693,471
2025	1,989,230	1,371,774	1,236,163	1,466,058	744,230	6,807,454
2030	1,840,884	1,278,439	1,146,401	1,356,540	687,135	6,309,399
2035	1,722,440	1,208,380	1,077,278	1,269,099	638,058	5,915,255
2040	1,543,850	1,091,823	970,651	1,139,439	570,400	5,316,164
2045	1,402,259	1,000,991	886,773	1,038,447	515,504	4,843,974
2050	1,250,143	899,963	794,413	929,644	456,620	4,330,783

*2020-2050 data estimated using regression trendline data

Appendix table 43. Total biomethane generation potential data using variable time-adjusted Waste Data Flow (WDF) FW collection trial data and high FW to biomethane conversion yield (90m³/t FW) data across NPH city regions (ONS population projection data) for 2010-2050

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
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2010	3,223,855	2,087,227	1,959,778	2,341,887	1,184,403	10,797,149
2011	2,973,666	1,957,035	1,828,905	2,190,335	1,099,506	10,049,447
2012	2,638,836	1,747,679	1,623,972	1,945,299	976,590	8,932,375
2013	2,919,177	1,937,351	1,795,375	2,153,801	1,090,890	9,896,593
2014	2,676,794	1,784,240	1,645,652	1,974,575	1,003,217	9,084,478
2015	2,921,918	1,970,433	1,802,567	2,155,398	1,093,346	9,943,662
2016	3,275,591	2,235,889	2,029,429	2,412,303	1,225,706	11,178,918
2017	2,611,027	1,792,266	1,620,455	1,923,795	977,085	8,924,627
2018	2,652,306	1,829,032	1,648,218	1,954,744	992,306	9,076,606
2020	2,454,512	1,704,585	1,528,534	1,808,721	916,181	8,412,532
2025	2,296,587	1,611,173	1,436,371	1,692,132	850,743	7,887,007
2030	2,058,467	1,455,764	1,294,201	1,519,253	760,533	7,088,218
2035	1,869,678	1,334,655	1,182,364	1,384,596	687,339	6,458,632
2040	1,666,857	1,199,951	1,059,217	1,239,526	608,826	5,774,377
2045	1,517,696	1,086,965	956,387	1,118,048	543,795	5,222,892
2050	1,362,708	968,451	849,395	991,771	477,862	4,650,188

*2020-2050 data estimated using regression trendline data

Appendix table 44. Total biomethane generation potential data using variable time-adjusted Waste Data Flow (WDF) FW collection trial data and low FW to biomethane conversion yield (45m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2010	4,772,289	5,735,430	2,952,631	2,874,175	2,365,868	18,700,394
2011	4,455,956	5,378,043	2,757,028	2,689,148	2,210,208	17,490,383
2012	3,940,557	4,756,580	2,433,649	2,378,770	1,949,277	15,458,833
2013	4,359,657	5,262,306	2,683,678	2,631,605	2,156,104	17,093,350
2014	3,993,096	4,825,233	2,455,109	2,411,701	1,973,510	15,658,649
2015	4,344,958	5,259,068	2,667,821	2,623,674	2,138,276	17,033,797
2016	4,857,488	5,892,286	2,980,633	2,932,062	2,384,951	19,047,420
2017	3,865,266	4,694,157	2,368,692	2,333,813	1,893,927	15,155,854
2018	3,920,765	4,767,032	2,399,737	2,367,891	1,917,321	15,372,747
2020	3,621,456	4,413,380	2,212,384	2,187,825	1,763,926	14,198,970
2025	3,370,821	4,125,646	2,054,660	2,039,221	1,627,425	13,217,773
2030	2,996,117	3,675,012	1,824,514	1,816,388	1,436,846	11,748,878
2035	2,707,183	3,330,848	1,647,471	1,645,394	1,289,591	10,620,487
2040	2,406,798	2,971,808	1,463,149	1,466,530	1,137,945	9,446,229
2045	2,155,967	2,670,918	1,309,396	1,316,778	1,011,974	8,465,032
2050	1,899,355	2,360,638	1,152,565	1,162,791	885,284	7,460,633

Appendix table 45. Total biomethane generation potential data using variable time-adjusted Waste Data Flow (WDF) FW collection trial data and medium FW to biomethane conversion yield (67.50m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2010	7,158,434	8,603,145	4,428,947	4,311,262	3,548,803	28,050,590
2011	6,683,934	8,067,064	4,135,543	4,033,721	3,315,312	26,235,574
2012	5,910,836	7,134,870	3,650,474	3,568,156	2,923,915	23,188,249
2013	6,539,485	7,893,459	4,025,517	3,947,408	3,234,157	25,640,025
2014	5,989,644	7,237,849	3,682,663	3,617,552	2,960,265	23,487,973
2015	6,517,437	7,888,602	4,001,732	3,935,511	3,207,414	25,550,696
2016	7,286,232	8,838,429	4,470,950	4,398,093	3,577,427	28,571,131
2017	5,797,899	7,041,235	3,553,037	3,500,720	2,840,890	22,733,781
2018	5,881,148	7,150,548	3,599,606	3,551,837	2,875,982	23,059,121
2020	5,432,184	6,620,070	3,318,575	3,281,737	2,645,889	21,298,455
2025	5,056,232	6,188,469	3,081,990	3,058,832	2,441,137	19,826,659
2030	4,494,176	5,512,518	2,736,771	2,724,582	2,155,269	17,623,316
2035	4,060,775	4,996,272	2,471,207	2,468,090	1,934,386	15,930,731
2040	3,610,197	4,457,712	2,194,723	2,199,794	1,706,917	14,169,343
2045	3,233,950	4,006,377	1,964,094	1,975,166	1,517,961	12,697,547
2050	2,849,033	3,540,957	1,728,848	1,744,186	1,327,926	11,190,950

Appendix table 46. Total biomethane generation potential data using variable time-adjusted Waste Data Flow (WDF) FW collection trial data and high FW to biomethane conversion yield (90m³/t FW) data across NPH metropolitan county regions (ONS population projection data) for 2010-2050

	West Yorkshire	Greater Manchester	Merseyside	South Yorkshire	Tyne and Wear	NPH 5-metropolitan county region Total
2010	9,544,578	11,470,860	5,905,263	5,748,349	4,731,737	37,400,787
2011	8,911,912	10,756,085	5,514,057	5,378,295	4,420,416	34,980,765
2012	7,881,114	9,513,160	4,867,298	4,757,541	3,898,553	30,917,666
2013	8,719,313	10,524,612	5,367,356	5,263,210	4,312,209	34,186,700
2014	7,986,192	9,650,466	4,910,217	4,823,403	3,947,020	31,317,298
2015	8,689,917	10,518,135	5,335,643	5,247,348	4,276,552	34,067,595
2016	9,714,975	11,784,572	5,961,266	5,864,124	4,769,903	38,094,841
2017	7,730,532	9,388,313	4,737,383	4,667,626	3,787,853	30,311,709
2018	7,841,531	9,534,064	4,799,475	4,735,783	3,834,642	30,745,495
2020	7,242,912	8,826,760	4,424,767	4,375,649	3,527,852	28,397,940
2025	6,741,642	8,251,292	4,109,319	4,078,443	3,254,849	26,435,546
2030	5,992,235	7,350,024	3,649,028	3,632,777	2,873,692	23,497,755
2035	5,414,366	6,661,697	3,294,943	3,290,787	2,579,182	21,240,974
2040	4,813,596	5,943,615	2,926,297	2,933,059	2,275,889	18,892,457
2045	4,311,933	5,341,836	2,618,792	2,633,555	2,023,947	16,930,063
2050	3,798,710	4,721,276	2,305,131	2,325,581	1,770,569	14,921,266

Appendix table 47. Table of data for % population 'saturation' for NPH Leeds city region with regard to type of waste collected vs. AD plant waste capacity for 2010-2050 using fixed FW collection scenario data of 20, 40 and 100 kg/person/year

NPH Leeds city region						
	All AD capacity - Low: 20kg/person/year	All AD capacity - Medium: 40kg/person/year	All AD capacity - High: 100kg/person/year	FW only AD capacity - Low: 20kg/person/year	FW only AD - capacity - Medium: 40kg/person/year	FW only AD capacity - High: 100kg/person/year
2001	1393.84%	696.92%	278.77%	865.72%	432.86%	173.14%
2002	1392.34%	696.17%	278.47%	864.79%	432.40%	172.96%
2003	1389.91%	694.96%	277.98%	863.28%	431.64%	172.66%
2004	1379.26%	689.63%	275.85%	856.67%	428.33%	171.33%
2005	1356.54%	678.27%	271.31%	842.56%	421.28%	168.51%
2006	1354.50%	677.25%	270.90%	841.29%	420.64%	168.26%
2007	1350.13%	675.07%	270.03%	838.57%	419.29%	167.71%
2008	1344.29%	672.15%	268.86%	834.95%	417.47%	166.99%
2009	1340.26%	670.13%	268.05%	832.44%	416.22%	166.49%
2010	1333.69%	666.84%	266.74%	828.36%	414.18%	165.67%
2011	1345.69%	672.85%	269.14%	835.82%	417.91%	167.16%
2012	1333.31%	666.65%	266.66%	828.13%	414.06%	165.63%
2013	1327.32%	663.66%	265.46%	824.40%	412.20%	164.88%
2014	1319.30%	659.65%	263.86%	819.43%	409.71%	163.89%
2015	1305.74%	652.87%	261.15%	811.00%	405.50%	162.20%
2016	1292.31%	646.16%	258.46%	802.66%	401.33%	160.53%
2017	1283.75%	641.87%	256.75%	797.34%	398.67%	159.47%
2018	1275.52%	637.76%	255.10%	792.23%	396.12%	158.45%
2019	1268.14%	634.07%	253.63%	787.65%	393.82%	157.53%
2020	1261.69%	630.85%	252.34%	783.65%	391.82%	156.73%
2021	1256.17%	628.08%	251.23%	780.21%	390.11%	156.04%
2022	1250.74%	625.37%	250.15%	776.84%	388.42%	155.37%
2023	1245.07%	622.54%	249.01%	773.32%	386.66%	154.66%
2024	1239.12%	619.56%	247.82%	769.62%	384.81%	153.92%
2025	1232.87%	616.44%	246.57%	765.75%	382.87%	153.15%
2026	1226.56%	613.28%	245.31%	761.82%	380.91%	152.36%
2027	1220.29%	610.15%	244.06%	757.93%	378.97%	151.59%
2028	1214.48%	607.24%	242.90%	754.32%	377.16%	150.86%
2029	1208.94%	604.47%	241.79%	750.88%	375.44%	150.18%
2030	1203.55%	601.78%	240.71%	747.53%	373.77%	149.51%
2031	1198.36%	599.18%	239.67%	744.31%	372.15%	148.86%
2032	1193.91%	596.95%	238.78%	741.54%	370.77%	148.31%
2033	1190.03%	595.02%	238.01%	739.14%	369.57%	147.83%
2034	1186.50%	593.25%	237.30%	736.94%	368.47%	147.39%
2035	1183.11%	591.55%	236.62%	734.84%	367.42%	146.97%
2036	1180.04%	590.02%	236.01%	732.93%	366.46%	146.59%
2037	1177.08%	588.54%	235.42%	731.09%	365.55%	146.22%
2038	1174.04%	587.02%	234.81%	729.20%	364.60%	145.84%
2039	1170.95%	585.47%	234.19%	727.28%	363.64%	145.46%
2040	1167.82%	583.91%	233.56%	725.34%	362.67%	145.07%
2041	1164.72%	582.36%	232.94%	723.42%	361.71%	144.68%
2042	1157.63%	578.81%	231.53%	719.01%	359.50%	143.80%
2043	1150.62%	575.31%	230.12%	714.65%	357.33%	142.93%

2044	1143.69%	571.84%	228.74%	710.35%	355.18%	142.07%
2045	1136.84%	568.42%	227.37%	706.10%	353.05%	141.22%
2046	1130.08%	565.04%	226.02%	701.90%	350.95%	140.38%
2047	1123.40%	561.70%	224.68%	697.75%	348.88%	139.55%
2048	1116.80%	558.40%	223.36%	693.65%	346.82%	138.73%
2049	1110.27%	555.13%	222.05%	689.59%	344.80%	137.92%
2050	1103.82%	551.91%	220.76%	685.59%	342.79%	137.12%

Appendix table 48. Table of data for % population 'saturation' for NPH West Yorkshire metropolitan county region with regard to type of waste collected vs. AD plant waste capacity for 2010-2050 using fixed FW collection scenario data of 20, 40 and 100 kg/person/year

West Yorkshire metropolitan county region						
	All AD capacity - Low: 20kg/person/year	All AD capacity - Medium: 40kg/person/year	All AD capacity - High: 100kg/person/year	FW only AD capacity - Low: 20kg/person/year	FW only AD - capacity - Medium: 40kg/person/year	FW only AD capacity - High: 100kg/person/year
2001	478.64%	239.32%	95.73%	297.28%	148.64%	59.46%
2002	476.32%	238.16%	95.26%	295.85%	147.92%	59.17%
2003	474.14%	237.07%	94.83%	294.49%	147.25%	58.90%
2004	470.62%	235.31%	94.12%	292.31%	146.15%	58.46%
2005	465.34%	232.67%	93.07%	289.02%	144.51%	57.80%
2006	462.75%	231.37%	92.55%	287.42%	143.71%	57.48%
2007	459.61%	229.80%	91.92%	285.47%	142.73%	57.09%
2008	456.13%	228.07%	91.23%	283.31%	141.65%	56.66%
2009	453.52%	226.76%	90.70%	281.68%	140.84%	56.34%
2010	450.48%	225.24%	90.10%	279.79%	139.90%	55.96%
2011	449.02%	224.51%	89.80%	278.89%	139.45%	55.78%
2012	446.43%	223.22%	89.29%	277.28%	138.64%	55.46%
2013	444.38%	222.19%	88.88%	276.01%	138.00%	55.20%
2014	442.20%	221.10%	88.44%	274.65%	137.33%	54.93%
2015	439.05%	219.52%	87.81%	272.69%	136.35%	54.54%
2016	435.73%	217.86%	87.15%	270.63%	135.32%	54.13%
2017	433.59%	216.80%	86.72%	269.31%	134.65%	53.86%
2018	431.43%	215.71%	86.29%	267.96%	133.98%	53.59%
2019	429.41%	214.71%	85.88%	266.71%	133.36%	53.34%
2020	427.57%	213.78%	85.51%	265.57%	132.78%	53.11%
2021	425.93%	212.97%	85.19%	264.55%	132.27%	52.91%
2022	424.40%	212.20%	84.88%	263.60%	131.80%	52.72%
2023	422.92%	211.46%	84.58%	262.68%	131.34%	52.54%
2024	421.45%	210.72%	84.29%	261.76%	130.88%	52.35%
2025	419.99%	209.99%	84.00%	260.86%	130.43%	52.17%
2026	418.55%	209.27%	83.71%	259.96%	129.98%	51.99%
2027	417.17%	208.59%	83.43%	259.11%	129.55%	51.82%
2028	415.88%	207.94%	83.18%	258.31%	129.15%	51.66%
2029	414.64%	207.32%	82.93%	257.54%	128.77%	51.51%
2030	413.45%	206.72%	82.69%	256.79%	128.40%	51.36%
2031	412.30%	206.15%	82.46%	256.08%	128.04%	51.22%
2032	411.28%	205.64%	82.26%	255.45%	127.72%	51.09%
2033	410.33%	205.17%	82.07%	254.86%	127.43%	50.97%

2034	409.43%	204.72%	81.89%	254.30%	127.15%	50.86%
2035	408.55%	204.27%	81.71%	253.75%	126.88%	50.75%
2036	407.70%	203.85%	81.54%	253.22%	126.61%	50.64%
2037	406.90%	203.45%	81.38%	252.73%	126.36%	50.55%
2038	406.08%	203.04%	81.22%	252.22%	126.11%	50.44%
2039	405.25%	202.62%	81.05%	251.70%	125.85%	50.34%
2040	404.39%	202.20%	80.88%	251.17%	125.59%	50.23%
2041	403.54%	201.77%	80.71%	250.64%	125.32%	50.13%
2042	402.69%	201.34%	80.54%	250.11%	125.06%	50.02%
2043	401.83%	200.92%	80.37%	249.58%	124.79%	49.92%
2044	400.99%	200.49%	80.20%	249.06%	124.53%	49.81%
2045	400.14%	200.07%	80.03%	248.53%	124.27%	49.71%
2046	399.30%	199.65%	79.86%	248.01%	124.00%	49.60%
2047	398.46%	199.23%	79.69%	247.49%	123.74%	49.50%
2048	397.63%	198.81%	79.53%	246.97%	123.48%	49.39%
2049	396.80%	198.40%	79.36%	246.45%	123.23%	49.29%
2050	395.97%	197.99%	79.19%	245.94%	122.97%	49.19%

Appendix table 49. Table of data for % population 'saturation' for NPH Leeds city region with regard to type of waste collected vs. AD plant waste capacity for 2010-2050 using variable WRAP and Waste Data Flow (WDF) based FW collection scenario data

NPH Leeds city region				
	WDF, All AD waste, Leeds city	WDF, AD FW only, Leeds city	WRAP, All AD waste, Leeds city	WRAP, AD FW only, Leeds city
2010	548.92%	340.94%	362.91%	225.40%
2015	605.64%	376.17%	357.25%	221.89%
2020	720.97%	447.80%	485.27%	301.40%
2025	770.55%	478.59%	587.08%	364.64%
2030	859.68%	533.95%	687.74%	427.16%
2035	946.49%	587.87%	788.74%	489.89%
2040	1061.65%	659.40%	934.26%	580.27%
2045	1177.06%	731.08%	1092.98%	678.86%
2050	1327.22%	824.34%	1253.48%	778.55%

Appendix table 50. Table of data for % population 'saturation' for NPH West Yorkshire metropolitan county region with regard to type of waste collected vs. AD plant waste capacity for 2010-2050 using variable WRAP and Waste Data Flow (WDF) based FW collection scenario data

NPH West Yorkshire metropolitan county region				
	WDF, All AD waste, Leeds city	WDF, AD FW only, Leeds city	WRAP, All AD waste, Leeds city	WRAP, AD FW only, Leeds city
2010	185.41%	115.16%	122.58%	76.13%
2015	203.64%	126.48%	120.12%	74.61%
2020	244.33%	151.75%	164.45%	102.14%
2025	262.49%	163.04%	199.99%	124.22%
2030	295.32%	183.42%	236.26%	146.74%
2035	326.84%	203.00%	272.37%	169.17%
2040	367.63%	228.34%	323.51%	200.94%
2045	409.69%	254.46%	380.43%	236.29%
2050	464.27%	288.36%	438.47%	272.34%

Appendix table 51. Table of data for biomethane production potential for all Leeds and West Yorkshire based AD plants based on waste feedstock - using Low FW to biomethane yield of 45m³/t

Number of Individuals that can be accommodated by respective AD plants based on FW collection scenario and specific waste capacity utilized (no unit)							
FW collection scenario			South Kirby Business Park	Maltings Organic Treatment Facility	Greencore Grocery	Allerton Waste Recovery Park	
	Low (20kg/pp/year)	Food waste	87,750,000	112,500,000	20,531,250	54,000,000	274,781,250
		Other waste	58,500,000	73,125,000	0	36,000,000	167,625,000
		Total feedstock	146,250,000	185,625,000	20,531,250	90,000,000	442,406,250
	Medium (40kg/pp/year)	Food waste	43,875,000	56,250,000	10,265,625	27,000,000	137,390,625
		Other waste	29,250,000	36,562,500	0	18,000,000	83,812,500
		Total feedstock	73,125,000	92,812,500	10,265,625	45,000,000	221,203,125
	High (100kg/pp/year)	Food waste	17,550,000	22,500,000	4,106,250	10,800,000	54,956,250
		Other waste	11,700,000	14,625,000	0	7,200,000	33,525,000
		Total feedstock	29,250,000	37,125,000	4,106,250	18,000,000	88,481,250

Appendix table 52. Table of data for biomethane production potential for all Leeds and West Yorkshire based AD plants based on waste feedstock - using Medium FW to biomethane yield of 67.5m³/t (with all AD plant values shown individually)

Number of Individuals that can be accommodated by respective AD plants based on FW collection scenario and specific waste capacity utilized (no unit)							
FW collection scenario			South Kirby Business Park	Maltings Organic Treatment Facility	Greencore Grocery	Allerton Waste Recovery Park	Total
	Low (20kg/pp/year)	Food waste	131,625,000	168,750,000	30,796,875	81,000,000	412,171,875
		Other waste	87,750,000	109,687,500	0	54,000,000	251,437,500
		Total feedstock	219,375,000	278,437,500	30,796,875	135,000,000	663,609,375
	Medium (40kg/pp/year)	Food waste	65,812,500	84,375,000	15,398,438	40,500,000	206,085,938
		Other waste	43,875,000	54,843,750	0	27,000,000	125,718,750
		Total feedstock	109,687,500	139,218,750	15,398,438	67,500,000	331,804,688
	High (100kg/pp/year)	Food waste	26,325,000	33,750,000	6,159,375	16,200,000	82,434,375
		Other waste	17,550,000	21,937,500	0	10,800,000	50,287,500
		Total feedstock	43,875,000	55,687,500	6,159,375	27,000,000	132,721,875

Appendix table 53. Table of data for biomethane production potential for all Leeds and West Yorkshire based AD plants based on waste feedstock - using high FW to biomethane yield of 90m³/t

Number of Individuals that can be accommodated by respective AD plants based on FW collection scenario and specific waste capacity utilized (no unit)							
FW collection scenario			South Kirby Business Park	Maltings Organic Treatment Facility	Greencore Grocery	Allerton Waste Recovery Park	
	Low (20kg/pp/year)	Food waste	175,500,000	225,000,000	41,062,500	108,000,000	549,562,500
		Other waste	117,000,000	146,250,000	0	72,000,000	335,250,000
		Total feedstock	292,500,000	371,250,000	41,062,500	180,000,000	884,812,500
		Food waste	87,750,000	112,500,000	20,531,250	54,000,000	274,781,250

	Medium (40kg/pp/year)	Other waste	58,500,000	73,125,000	0	36,000,000	167,625,000
		Total feedstock	146,250,000	185,625,000	20,531,250	90,000,000	442,406,250
	High (100kg/pp/year)	Food waste	35,100,000	45,000,000	8,212,500	21,600,000	109,912,500
		Other waste	23,400,000	29,250,000	0	14,400,000	67,050,000
		Total feedstock	58,500,000	74,250,000	8,212,500	36,000,000	176,962,500

Appendix table 54. Table of data for aggregate total for all combined Leeds city and West Yorkshire county based AD plant capacity based on low, medium and high FW to biomethane conversion scenarios

Biomethane conversion scenarios				
		Low FW to biomethane conversion scenario - 45m ³ /t	Medium FW to biomethane conversion scenario - 67.50m ³ /t	High FW to biomethane conversion scenario - 90m ³ /t
Low (20kg/pp/year)	Food waste	274,781,250	412,171,875	549,562,500
	Other waste	167,625,000	251,437,500	335,250,000
	Total feedstock	442,406,250	663,609,375	884,812,500
Medium (40kg/pp/year)	Food waste	137,390,625	206,085,938	274,781,250
	Other waste	83,812,500	125,718,750	167,625,000
	Total feedstock	221,203,125	331,804,688	442,406,250
High (100kg/pp/year)	Food waste	54,956,250	82,434,375	109,912,500
	Other waste	33,525,000	50,287,500	67,050,000
	Total feedstock	88,481,250	132,721,875	176,962,500
Combined FW (Low + Medium + High scenario)	Food waste	467,128,125	700,692,188	934,256,250
Combined Other waste (Low + Medium + High scenario)	Other waste	284,962,500	427,443,750	569,925,000
Combined FW+ Other wastes (Low + Medium + High scenario)	Total feedstock	752,090,625	1,128,135,938	1,504,181,250

Appendix table 55. Table of data for % population 'saturation' for Manchester NPH city region with regard to type of waste collected vs. AD plant waste capacity for 2010-2050

Manchester city region						
	All AD capacity - Low: 20kg/person/year	All AD capacity - Medium: 40kg/person/year	All AD capacity - High: 100kg/person/year	FW only AD capacity - Low: 20kg/person/year	FW only AD - capacity - Medium: 40kg/person/year	FW only AD capacity - High: 100kg/person/year
2001	1797.63%	898.81%	359.53%	1282.27%	641.13%	256.45%
2002	1775.09%	887.55%	355.02%	1266.19%	633.10%	253.24%
2003	1739.16%	869.58%	347.83%	1240.56%	620.28%	248.11%
2004	1705.88%	852.94%	341.18%	1216.83%	608.41%	243.37%
2005	1663.93%	831.96%	332.79%	1186.90%	593.45%	237.38%
2006	1634.14%	817.07%	326.83%	1165.65%	582.82%	233.13%
2007	1609.63%	804.81%	321.93%	1148.16%	574.08%	229.63%
2008	1585.46%	792.73%	317.09%	1130.92%	565.46%	226.18%
2009	1563.75%	781.88%	312.75%	1115.44%	557.72%	223.09%
2010	1534.82%	767.41%	306.96%	1094.80%	547.40%	218.96%
2011	1523.49%	761.74%	304.70%	1086.72%	543.36%	217.34%
2012	1499.96%	749.98%	299.99%	1069.94%	534.97%	213.99%
2013	1490.13%	745.07%	298.03%	1062.93%	531.46%	212.59%
2014	1474.70%	737.35%	294.94%	1051.92%	525.96%	210.38%
2015	1442.66%	721.33%	288.53%	1029.06%	514.53%	205.81%

2016	1410.60%	705.30%	282.12%	1006.20%	503.10%	201.24%
2017	1393.44%	696.72%	278.69%	993.95%	496.98%	198.79%
2018	1378.12%	689.06%	275.62%	983.03%	491.51%	196.61%
2019	1364.85%	682.42%	272.97%	973.56%	486.78%	194.71%
2020	1353.63%	676.81%	270.73%	965.56%	482.78%	193.11%
2021	1344.05%	672.03%	268.81%	958.73%	479.36%	191.75%
2022	1335.17%	667.59%	267.03%	952.39%	476.20%	190.48%
2023	1326.76%	663.38%	265.35%	946.39%	473.20%	189.28%
2024	1318.17%	659.08%	263.63%	940.26%	470.13%	188.05%
2025	1309.36%	654.68%	261.87%	933.98%	466.99%	186.80%
2026	1300.59%	650.30%	260.12%	927.73%	463.86%	185.55%
2027	1291.92%	645.96%	258.38%	921.54%	460.77%	184.31%
2028	1283.71%	641.85%	256.74%	915.68%	457.84%	183.14%
2029	1275.81%	637.91%	255.16%	910.05%	455.02%	182.01%
2030	1267.99%	634.00%	253.60%	904.47%	452.24%	180.89%
2031	1260.30%	630.15%	252.06%	898.98%	449.49%	179.80%
2032	1253.23%	626.62%	250.65%	893.94%	446.97%	178.79%
2033	1246.79%	623.39%	249.36%	889.35%	444.67%	177.87%
2034	1240.74%	620.37%	248.15%	885.03%	442.52%	177.01%
2035	1234.87%	617.43%	246.97%	880.85%	440.42%	176.17%
2036	1229.39%	614.69%	245.88%	876.94%	438.47%	175.39%
2037	1224.07%	612.04%	244.81%	873.14%	436.57%	174.63%
2038	1218.82%	609.41%	243.76%	869.40%	434.70%	173.88%
2039	1213.68%	606.84%	242.74%	865.73%	432.86%	173.15%
2040	1208.67%	604.34%	241.73%	862.16%	431.08%	172.43%
2041	1203.87%	601.93%	240.77%	858.73%	429.37%	171.75%
2042	1198.50%	599.25%	239.70%	854.90%	427.45%	170.98%
2043	1193.18%	596.59%	238.64%	851.11%	425.55%	170.22%
2044	1187.91%	593.96%	237.58%	847.35%	423.67%	169.47%
2045	1182.69%	591.34%	236.54%	843.62%	421.81%	168.72%
2046	1177.51%	588.75%	235.50%	839.93%	419.96%	167.99%
2047	1172.37%	586.19%	234.47%	836.27%	418.13%	167.25%
2048	1167.28%	583.64%	233.46%	832.63%	416.32%	166.53%
2049	1162.24%	581.12%	232.45%	829.04%	414.52%	165.81%
2050	1157.23%	578.62%	231.45%	825.47%	412.73%	165.09%

Appendix table 56. Table of data for % population 'saturation' for Manchester NPH metropolitan county region with regard to type of waste collected vs. AD plant waste capacity for 2010-2050

Greater Manchester metropolitan county region						
	All AD capacity - Low: 20kg/person/year	All AD capacity - Medium: 40kg/person/year	All AD capacity - High: 100kg/person/year	FW only AD capacity - Low: 20kg/person/year	FW only AD - capacity - Medium: 40kg/person/year	FW only AD capacity - High: 100kg/person/year
2001	295.61%	147.80%	59.12%	210.86%	105.43%	42.17%
2002	294.79%	147.39%	58.96%	210.27%	105.14%	42.05%
2003	292.97%	146.48%	58.59%	208.98%	104.49%	41.80%
2004	291.66%	145.83%	58.33%	208.05%	104.02%	41.61%
2005	290.04%	145.02%	58.01%	206.89%	103.44%	41.38%

2006	287.98%	143.99%	57.60%	205.42%	102.71%	41.08%
2007	286.14%	143.07%	57.23%	204.11%	102.05%	40.82%
2008	283.76%	141.88%	56.75%	202.41%	101.20%	40.48%
2009	281.61%	140.80%	56.32%	200.87%	100.44%	40.17%
2010	279.27%	139.64%	55.85%	199.21%	99.60%	39.84%
2011	277.19%	138.60%	55.44%	197.73%	98.86%	39.55%
2012	275.56%	137.78%	55.11%	196.56%	98.28%	39.31%
2013	274.30%	137.15%	54.86%	195.66%	97.83%	39.13%
2014	272.65%	136.33%	54.53%	194.49%	97.24%	38.90%
2015	270.26%	135.13%	54.05%	192.78%	96.39%	38.56%
2016	267.63%	133.82%	53.53%	190.91%	95.45%	38.18%
2017	266.01%	133.01%	53.20%	189.75%	94.87%	37.95%
2018	264.38%	132.19%	52.88%	188.59%	94.29%	37.72%
2019	262.83%	131.42%	52.57%	187.48%	93.74%	37.50%
2020	261.41%	130.70%	52.28%	186.46%	93.23%	37.29%
2021	260.10%	130.05%	52.02%	185.53%	92.76%	37.11%
2022	258.89%	129.44%	51.78%	184.67%	92.33%	36.93%
2023	257.77%	128.89%	51.55%	183.87%	91.94%	36.77%
2024	256.70%	128.35%	51.34%	183.11%	91.55%	36.62%
2025	255.67%	127.83%	51.13%	182.37%	91.19%	36.47%
2026	254.67%	127.34%	50.93%	181.66%	90.83%	36.33%
2027	253.74%	126.87%	50.75%	180.99%	90.50%	36.20%
2028	252.84%	126.42%	50.57%	180.35%	90.18%	36.07%
2029	251.97%	125.99%	50.39%	179.74%	89.87%	35.95%
2030	251.14%	125.57%	50.23%	179.14%	89.57%	35.83%
2031	250.33%	125.17%	50.07%	178.56%	89.28%	35.71%
2032	249.57%	124.78%	49.91%	178.02%	89.01%	35.60%
2033	248.83%	124.42%	49.77%	177.50%	88.75%	35.50%
2034	248.11%	124.06%	49.62%	176.98%	88.49%	35.40%
2035	247.40%	123.70%	49.48%	176.48%	88.24%	35.30%
2036	246.70%	123.35%	49.34%	175.98%	87.99%	35.20%
2037	246.04%	123.02%	49.21%	175.50%	87.75%	35.10%
2038	245.37%	122.68%	49.07%	175.02%	87.51%	35.00%
2039	244.69%	122.35%	48.94%	174.54%	87.27%	34.91%
2040	244.02%	122.01%	48.80%	174.06%	87.03%	34.81%
2041	243.34%	121.67%	48.67%	173.58%	86.79%	34.72%
2042	242.66%	121.33%	48.53%	173.10%	86.55%	34.62%
2043	241.99%	121.00%	48.40%	172.61%	86.31%	34.52%
2044	241.32%	120.66%	48.26%	172.14%	86.07%	34.43%
2045	240.65%	120.33%	48.13%	171.66%	85.83%	34.33%
2046	239.99%	120.00%	48.00%	171.19%	85.59%	34.24%
2047	239.33%	119.67%	47.87%	170.72%	85.36%	34.14%
2048	238.68%	119.34%	47.74%	170.25%	85.13%	34.05%
2049	238.03%	119.01%	47.61%	169.79%	84.89%	33.96%
2050	237.38%	118.69%	47.48%	169.32%	84.66%	33.86%

Appendix table 57. Table of data for highest revenue generation potential for Compressed Biomethane (CBM) sales revenue potential scenario 1 – Using highest fixed FW collection data 100 kg/person/year) and highest biomethane conversion yield of 90m³ and highest unit sales value of CBM of 98.41p/kg

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	£437,309		£252,639	£265,792	£312,531	£1,429,757

2002	£437,778	£255,845	£267,004	£313,195	£161,933	£1,435,756
2003	£438,544	£261,132	£267,753	£313,914	£161,845	£1,443,188
2004	£441,931	£266,226	£269,692	£316,591	£161,858	£1,456,298
2005	£449,332	£272,938	£272,269	£320,357	£163,532	£1,478,428
2006	£450,010	£277,914	£272,736	£321,516	£163,929	£1,486,105
2007	£451,465	£282,146	£273,046	£322,910	£164,741	£1,494,309
2008	£453,426	£286,447	£273,596	£325,480	£164,795	£1,503,745
2009	£454,791	£290,424	£275,457	£328,160	£165,895	£1,514,726
2010	£457,032	£295,897	£277,829	£331,999	£167,908	£1,530,667
2011	£452,954	£298,099	£278,582	£333,636	£167,479	£1,530,750
2012	£457,162	£302,775	£281,343	£337,011	£169,188	£1,547,478
2013	£459,226	£304,772	£282,437	£338,822	£171,612	£1,556,868
2014	£462,015	£307,960	£284,040	£340,812	£173,155	£1,567,983
2015	£466,813	£314,801	£287,983	£344,352	£174,676	£1,588,624
2016	£471,665	£321,954	£292,225	£347,357	£176,494	£1,609,695
2017	£474,812	£325,921	£294,677	£349,839	£177,681	£1,622,931
2018	£477,874	£329,542	£296,965	£352,192	£178,787	£1,635,360
2019	£480,655	£332,748	£299,026	£354,243	£179,682	£1,646,354
2020	£483,110	£335,506	£300,854	£356,002	£180,328	£1,655,800
2021	£485,237	£337,896	£302,474	£357,526	£180,781	£1,663,914
2022	£487,342	£340,144	£304,057	£359,054	£181,230	£1,671,826
2023	£489,560	£342,300	£305,662	£360,661	£181,747	£1,679,930
2024	£491,913	£344,532	£307,389	£362,391	£182,381	£1,688,605
2025	£494,404	£346,850	£309,219	£364,279	£183,146	£1,697,897
2026	£496,949	£349,187	£311,094	£366,236	£183,975	£1,707,441
2027	£499,501	£351,530	£312,998	£368,225	£184,831	£1,717,084
2028	£501,892	£353,779	£314,845	£370,108	£185,624	£1,726,249
2029	£504,190	£355,970	£316,639	£371,943	£186,383	£1,735,125
2030	£506,448	£358,164	£318,415	£373,784	£187,115	£1,743,927
2031	£508,643	£360,352	£320,144	£375,620	£187,816	£1,752,576
2032	£510,540	£362,383	£321,732	£377,260	£188,360	£1,760,274
2033	£512,203	£364,256	£323,177	£378,746	£188,761	£1,767,143
2034	£513,727	£366,033	£324,510	£380,141	£189,089	£1,773,500
2035	£515,200	£367,772	£325,807	£381,533	£189,400	£1,779,712
2036	£516,541	£369,411	£327,018	£382,838	£189,651	£1,785,458
2037	£517,840	£371,016	£328,184	£384,141	£189,886	£1,791,067
2038	£519,179	£372,614	£329,353	£385,465	£190,136	£1,796,747
2039	£520,550	£374,193	£330,519	£386,801	£190,391	£1,802,455
2040	£521,945	£375,742	£331,674	£388,134	£190,643	£1,808,138
2041	£523,332	£377,243	£332,805	£389,449	£190,883	£1,813,711
2042	£526,541	£378,932	£334,071	£390,832	£191,190	£1,819,825
2043	£529,749	£380,621	£335,337	£392,214	£191,497	£1,825,939
2044	£532,958	£382,310	£336,603	£393,597	£191,803	£1,832,052
2045	£536,166	£383,999	£337,869	£394,980	£192,110	£1,838,166
2046	£539,375	£385,688	£339,135	£396,363	£192,417	£1,844,279
2047	£542,583	£387,377	£340,401	£397,746	£192,723	£1,850,393
2048	£545,792	£389,066	£341,667	£399,129	£193,030	£1,856,506
2049	£549,000	£390,755	£342,933	£400,511	£193,337	£1,862,620
2050	£552,209	£392,444	£344,199	£401,894	£193,644	£1,868,734

Appendix table 58. Table of data for lowest revenue generation potential for Compressed Biomethane (CBM) sales revenue potential scenario 1 – Using fixed FW collection data 20 kg/person/year) and low biomethane conversion yield of 45m³ and highest unit sales value of CBM of 61.13p/kg

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2001	£28,072	£16,218	£17,062	£20,062	£10,366	£91,781
2002	£28,103	£16,424	£17,140	£20,105	£10,395	£92,166

2003	£28,152	£16,763	£17,188	£20,151	£10,389	£92,643
2004	£28,369	£17,090	£17,312	£20,323	£10,390	£93,485
2005	£28,844	£17,521	£17,478	£20,565	£10,498	£94,906
2006	£28,888	£17,840	£17,508	£20,639	£10,523	£95,398
2007	£28,981	£18,112	£17,528	£20,729	£10,575	£95,925
2008	£29,107	£18,388	£17,563	£20,894	£10,579	£96,531
2009	£29,195	£18,643	£17,683	£21,066	£10,649	£97,236
2010	£29,339	£18,995	£17,835	£21,312	£10,779	£98,259
2011	£29,077	£19,136	£17,883	£21,417	£10,751	£98,264
2012	£29,347	£19,436	£18,060	£21,634	£10,861	£99,338
2013	£29,479	£19,564	£18,131	£21,750	£11,016	£99,941
2014	£29,658	£19,769	£18,234	£21,878	£11,115	£100,654
2015	£29,966	£20,208	£18,487	£22,105	£11,213	£101,979
2016	£30,278	£20,667	£18,759	£22,298	£11,330	£103,332
2017	£30,480	£20,922	£18,916	£22,457	£11,406	£104,182
2018	£30,676	£21,154	£19,063	£22,608	£11,477	£104,980
2019	£30,855	£21,360	£19,196	£22,740	£11,534	£105,685
2020	£31,013	£21,537	£19,313	£22,853	£11,576	£106,292
2021	£31,149	£21,691	£19,417	£22,951	£11,605	£106,813
2022	£31,284	£21,835	£19,518	£23,049	£11,634	£107,320
2023	£31,427	£21,973	£19,622	£23,152	£11,667	£107,841
2024	£31,578	£22,117	£19,732	£23,263	£11,708	£108,398
2025	£31,738	£22,266	£19,850	£23,384	£11,757	£108,994
2026	£31,901	£22,416	£19,970	£23,510	£11,810	£109,607
2027	£32,065	£22,566	£20,092	£23,638	£11,865	£110,226
2028	£32,218	£22,710	£20,211	£23,759	£11,916	£110,814
2029	£32,366	£22,851	£20,326	£23,876	£11,965	£111,384
2030	£32,511	£22,992	£20,440	£23,995	£12,012	£111,949
2031	£32,652	£23,132	£20,551	£24,112	£12,057	£112,504
2032	£32,773	£23,263	£20,653	£24,218	£12,091	£112,998
2033	£32,880	£23,383	£20,746	£24,313	£12,117	£113,439
2034	£32,978	£23,497	£20,831	£24,403	£12,138	£113,847
2035	£33,073	£23,609	£20,915	£24,492	£12,158	£114,246
2036	£33,159	£23,714	£20,992	£24,576	£12,174	£114,615
2037	£33,242	£23,817	£21,067	£24,659	£12,189	£114,975
2038	£33,328	£23,919	£21,142	£24,744	£12,206	£115,340
2039	£33,416	£24,021	£21,217	£24,830	£12,222	£115,706
2040	£33,506	£24,120	£21,291	£24,916	£12,238	£116,071
2041	£33,595	£24,217	£21,364	£25,000	£12,253	£116,429
2042	£33,801	£24,325	£21,445	£25,089	£12,273	£116,821
2043	£34,006	£24,433	£21,526	£25,178	£12,293	£117,213
2044	£34,212	£24,542	£21,608	£25,266	£12,313	£117,606
2045	£34,418	£24,650	£21,689	£25,355	£12,332	£117,998
2046	£34,624	£24,759	£21,770	£25,444	£12,352	£118,391
2047	£34,830	£24,867	£21,852	£25,533	£12,372	£118,783
2048	£35,036	£24,976	£21,933	£25,621	£12,391	£119,176
2049	£35,242	£25,084	£22,014	£25,710	£12,411	£119,568
2050	£35,448	£25,192	£22,095	£25,799	£12,431	£119,961

Appendix table 59. Table of data for highest revenue generation potential for Compressed Biomethane (CBM) sales revenue potential scenario 2.1 – Using time-adjusted variable WRAP FW collection data with high biomethane conversion yield of 90m³ and high unit sales value of CBM of 98.41/kg

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	333,634	216,005	202,815	242,360	122,573	1,117,387
2015	280,088	188,881	172,790	206,611	104,805	953,174
2020	251,217	174,463	156,444	185,121	93,770	861,016

2025	207,650	145,677	129,872	152,997	76,921	713,117
2030	177,257	125,357	111,445	130,825	65,490	610,374
2035	154,560	110,331	97,742	114,460	56,820	533,914
2040	130,486	93,936	82,918	97,034	47,661	452,035
2045	112,595	80,640	70,952	82,946	40,343	387,476
2050	99,975	70,944	62,184	72,590	34,911	340,604

Appendix table 60. Table of data for lowest revenue generation potential for Compressed Biomethane (CBM) sales revenue potential scenario 2.1 – Using time-adjusted variable WRAP FW collection data with low biomethane conversion yield of 45m³ and low unit sales value of CBM of 61.13p/kg

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	107,086	69,331	65,097	77,790	39,342	358,645
2015	89,899	60,625	55,460	66,315	33,639	305,938
2020	80,633	55,997	50,214	59,418	30,097	276,358
2025	66,649	46,758	41,685	49,107	24,689	228,888
2030	56,894	40,236	35,770	41,990	21,020	195,910
2035	49,609	35,413	31,372	36,738	18,237	171,369
2040						
	41,882	30,150	26,614	31,145	15,298	145,089
2045	36,139	25,883	22,773	26,623	12,949	124,367
2050	32,089	22,771	19,959	23,299	11,205	109,323

Appendix table 61. Table of data for highest revenue generation potential for Compressed Biomethane (CBM) sales revenue potential scenario 2.2 – Using time-adjusted variable WDF FW collection data with high biomethane conversion yield of 90m³ and high unit sales value of CBM of 98.41/kg

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	210,235	136,113	127,802	152,720	77,238	704,107
2015	186,725	125,921	115,193	137,741	69,870	635,450
2020	169,089	117,427	105,299	124,601	63,115	579,530
2025	158,209	110,992	98,950	116,569	58,607	543,327
2030	141,806	100,286	89,156	104,660	52,392	488,299
2035	128,800	91,943	81,452	95,383	47,350	444,928
2040	114,828	82,663	72,968	85,390	41,941	397,790
2045	104,552	74,880	65,884	77,021	37,461	359,799
2050	94,421	67,003	58,729	68,557	32,972	321,681

Appendix table 62. Table of data for lowest revenue generation potential for Compressed Biomethane (CBM) sales revenue potential scenario 2.2 – Using time-adjusted variable WDF FW collection data with low biomethane conversion yield of 45m³ and low unit sales value of CBM of 61.13p/kg

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	67,479	43,688	41,020	49,018	24,791	225,996
2015	59,933	40,416	36,973	44,210	22,426	203,959
2020	54,272	37,690	33,798	39,993	20,258	186,010
2025	50,780	35,625	31,760	37,415	18,811	174,390
2030	45,515	32,189	28,616	33,592	16,816	156,728
2035	41,341	29,511	26,143	30,615	15,198	142,808
2040	36,856	26,532	23,420	27,407	13,462	127,678
2045	33,558	24,034	21,147	24,721	12,024	115,484
2050	30,306	21,506	18,850	22,005	10,583	103,249

Appendix table 63. RTFC weekly data for pence per certificate (p/cert), as obtained from Energy census RTFC data tracker (Census, 2020)

	Every Monday	Certificate issue date	Unit	RTFC Index
1	23/10/2017	Census Price Assessments: 23 Oct 2017	p/cert.	22
2	30/10/2017	Census Price Assessments: 30 Oct 2017	p/cert.	22.13
3	6/11/2017	Census Price Assessments: 6 Nov 2017	p/cert.	22.13
4	13/11/2017	Census Price Assessments: 13 Nov 2017	p/cert.	21.6
5	20/11/2017	Census Price Assessments: 20 Nov 2017	p/cert.	21.67
6	27/11/2017	Census Price Assessments: 27 Nov 2017	p/cert.	21.6
7	4/12/2017	Census Price Assessments: 4 Dec 2017	p/cert.	20.65
8	11/12/2017	Census Price Assessments: 11 Dec 2017	p/cert.	20.75
9	18/12/2017	Census Price Assessments: 18 Dec 2017	p/cert.	20.25
10	25/12/2017	Census Price Assessments: 25 Dec 2017	p/cert.	20.25
11	1/1/2018	Census Price Assessments: 1 Jan 2018	p/cert.	20.25
12	8/1/2018	Census Price Assessments: 8 Jan 2018	p/cert.	19.6
13	15/1/2018	Census Price Assessments: 15 Jan 2018	p/cert.	19.4
14	22/1/2018	Census Price Assessments: 22 Jan 2018	p/cert.	17.5
15	29/1/2018	Census Price Assessments: 29 Jan 2018	p/cert.	15.45
16	5/2/2018	Census Price Assessments: 5 Feb 2018	p/cert.	15.25
17	12/2/2018	Census Price Assessments: 12 Feb 2018	p/cert.	15.25
18	19/2/2018	Census Price Assessments: 19 Feb 2018	p/cert.	15.65
19	26/2/2018	Census Price Assessments: 26 Feb 2018	p/cert.	15.65
20	5/3/2018	Census Price Assessments: 5 Mar 2018	p/cert.	15.75
21	12/3/2018	Census Price Assessments: 12 Mar 2018	p/cert.	15.6
22	19/3/2018	Census Price Assessments: 19 Mar 2018	p/cert.	15.75
23	26/3/2018	Census Price Assessments: 26 Mar 2018	p/cert.	15.58
24	2/4/2018	Census Price Assessments: 2 Apr 2018	p/cert.	14.03
25	9/4/2018	Census Price Assessments: 9 Apr 2018	p/cert.	14.63
26	16/4/2018	Census Price Assessments: 16 Apr 2018	p/cert.	14.63
27	23/4/2018	Census Price Assessments: 23 Apr 2018	p/cert.	16.33
28	30/4/2018	Census Price Assessments: 30 Apr 2018	p/cert.	16.33
29	7/5/2018	Census Price Assessments: 7 May 2018	p/cert.	16.67
30	14/5/2018	Census Price Assessments: 14 May 2018	p/cert.	16.92
31	21/5/2018	Census Price Assessments: 21 May 2018	p/cert.	16.33
32	28/5/2018	Census Price Assessments: 28 May 2018	p/cert.	16.32
33	4/6/2018	Census Price Assessments: 4 Jun 2018	p/cert.	16.7
34	11/6/2018	Census Price Assessments: 11 Jun 2018	p/cert.	17.7
35	18/6/2018	Census Price Assessments: 18 Jun 2018	p/cert.	17.7
36	25/6/2018	Census Price Assessments: 25 Jun 2018	p/cert.	16.83
37	2/7/2018	Census Price Assessments: 2 Jul 2018	p/cert.	17.17
38	9/7/2018	Census Price Assessments: 9 Jul 2018	p/cert.	17.23
39	16/7/2018	Census Price Assessments: 16 Jul 2018	p/cert.	17.27
40	23/7/2018	Census Price Assessments: 23 Jul 2018	p/cert.	17.5
41	30/7/2018	Census Price Assessments: 30 Jul 2018	p/cert.	17.57
42	6/8/2018	Census Price Assessments: 6 Aug 2018	p/cert.	17.5
43	13/8/2018	Census Price Assessments: 13 Aug 2018	p/cert.	16.73
44	20/8/2018	Census Price Assessments: 20 Aug 2018	p/cert.	16.83
45	27/8/2018	Census Price Assessments: 27 Aug 2018	p/cert.	17.03
46	3/9/2018	Census Price Assessments: 3 Sep 2018	p/cert.	17
47	10/9/2018	Census Price Assessments: 10 Sep 2018	p/cert.	16.83
48	17/9/2018	Census Price Assessments: 17 Sep 2018	p/cert.	16.82
49	24/9/2018	Census Price Assessments: 24 Sep 2018	p/cert.	16.8
50	1/10/2018	Census Price Assessments: 1 Oct 2018	p/cert.	16.28
51	8/10/2018	Census Price Assessments: 8 Oct 2018	p/cert.	15.6
52	15/10/2018	Census Price Assessments: 15 Oct 2018	p/cert.	14.9
53	22/10/2018	Census Price Assessments: 22 Oct 2018	p/cert.	14.4
54	29/10/2018	Census Price Assessments: 29 Oct 2018	p/cert.	14.15
55	5/11/2018	Census Price Assessments: 5 Nov 2018	p/cert.	12.25
56	12/11/2018	Census Price Assessments: 12 Nov 2018	p/cert.	12.4
57	19/11/2018	Census Price Assessments: 19 Nov 2018	p/cert.	11.85
58	26/11/2018	Census Price Assessments: 26 Nov 2018	p/cert.	11.4
59	3/12/2018	Census Price Assessments: 3 Dec 2018	p/cert.	11.65
60	10/12/2018	Census Price Assessments: 10 Dec 2018	p/cert.	11.9
61	17/12/2018	Census Price Assessments: 17 Dec 2018	p/cert.	11.45
62	24/12/2018	Census Price Assessments: 24 Dec 2018	p/cert.	11.48
63	31/12/2018	Census Price Assessments: 31 Dec 2018	p/cert.	11.48
64	7/1/2019	Census Price Assessments: 7 Jan 2019	p/cert.	11.48
65	14/1/2019	Census Price Assessments: 14 Jan 2019	p/cert.	11.63
66	21/1/2019	Census Price Assessments: 21 Jan 2019	p/cert.	12.45
67	28/1/2019	Census Price Assessments: 28 Jan 2019	p/cert.	12.5
68	4/2/2019	Census Price Assessments: 4 Feb 2019	p/cert.	11.55
69	11/2/2019	Census Price Assessments: 11 Feb 2019	p/cert.	11.55
70	18/2/2019	Census Price Assessments: 18 Feb 2019	p/cert.	11.15
71	25/2/2019	Census Price Assessments: 25 Feb 2019	p/cert.	11.35
72	4/3/2019	Census Price Assessments: 4 Mar 2019	p/cert.	11.25
73	11/3/2019	Census Price Assessments: 11 Mar 2019	p/cert.	10.95
74	18/3/2019	Census Price Assessments: 18 Mar 2019	p/cert.	11.45
75	25/3/2019	Census Price Assessments: 25 Mar 2019	p/cert.	11.25
76	1/4/2019	Census Price Assessments: 1 Apr 2019	p/cert.	11.85
77	8/4/2019	Census Price Assessments: 8 Apr 2019	p/cert.	12.35
78	15/4/2019	Census Price Assessments: 15 Apr 2019	p/cert.	12.25
79	22/4/2019	Census Price Assessments: 22 Apr 2019	p/cert.	12.25

80	29/4/2019	Census Price Assessments: 29 Apr 2019	p/cert.	12.2
81	6/5/2019	Census Price Assessments: 6 May 2019	p/cert.	12.25
82	13/5/2019	Census Price Assessments: 13 May 2019	p/cert.	12.65
83	20/5/2019	Census Price Assessments: 20 May 2019	p/cert.	13.15
84	27/5/2019	Census Price Assessments: 27 May 2019	p/cert.	13.35
85	3/6/2019	Census Price Assessments: 3 Jun 2019	p/cert.	13.35
86	10/6/2019	Census Price Assessments: 10 Jun 2019	p/cert.	16.55
87	17/6/2019	Census Price Assessments: 17 Jun 2019	p/cert.	16.55
88	24/6/2019	Census Price Assessments: 24 Jun 2019	p/cert.	17.9
89	1/7/2019	Census Price Assessments: 1 Jul 2019	p/cert.	17.13
90	8/7/2019	Census Price Assessments: 8 Jul 2019	p/cert.	16.95
91	15/7/2019	Census Price Assessments: 15 Jul 2019	p/cert.	16.85
92	22/7/2019	Census Price Assessments: 22 Jul 2019	p/cert.	16.78
93	29/7/2019	Census Price Assessments: 29 Jul 2019	p/cert.	16.95
94	5/8/2019	Census Price Assessments: 5 Aug 2019	p/cert.	16.95
95	12/8/2019	Census Price Assessments: 12 Aug 2019	p/cert.	17.15
96	19/8/2019	Census Price Assessments: 19 Aug 2019	p/cert.	19.73
97	26/8/2019	Census Price Assessments: 26 Aug 2019	p/cert.	22.15
98	2/9/2019	Census Price Assessments: 2 Sep 2019	p/cert.	22.95
99	9/9/2019	Census Price Assessments: 9 Sep 2019	p/cert.	23.85
100	16/9/2019	Census Price Assessments: 16 Sep 2019	p/cert.	25.05
101	23/9/2019	Census Price Assessments: 23 Sep 2019	p/cert.	24.13
102	30/9/2019	Census Price Assessments: 30 Sep 2019	p/cert.	24.38
103	7/10/2019	Census Price Assessments: 7 Oct 2019	p/cert.	24.28
104	14/10/2019	Census Price Assessments: 14 Oct 2019	p/cert.	24.28
105	21/10/2019	Census Price Assessments: 21 Oct 2019	p/cert.	24.08
106	28/10/2019	Census Price Assessments: 28 Oct 2019	p/cert.	24.5
107	4/11/2019	Census Price Assessments: 4 Nov 2019	p/cert.	25
108	11/11/2019	Census Price Assessments: 11 Nov 2019	p/cert.	25
109	18/11/2019	Census Price Assessments: 18 Nov 2019	p/cert.	27.25
110	25/11/2019	Census Price Assessments: 25 Nov 2019	p/cert.	26.6
111	2/12/2019	Census Price Assessments: 2 Dec 2019	p/cert.	26.25
112	9/12/2019	Census Price Assessments: 9 Dec 2019	p/cert.	26.75
113	16/12/2019	Census Price Assessments: 16 Dec 2019	p/cert.	28
114	23/12/2019	Census Price Assessments: 23 Dec 2019	p/cert.	28.5
115	30/12/2019	Census Price Assessments: 30 Dec 2019	p/cert.	28.5
116	6/1/2020	Census Price Assessments: 6 Jan 2020	p/cert.	29.5
117	13/1/2020	Census Price Assessments: 13 Jan 2020	p/cert.	29.38
118	20/1/2020	Census Price Assessments: 20 Jan 2020	p/cert.	28.13
119	27/1/2020	Census Price Assessments: 27 Jan 2020	p/cert.	28.08
120	3/2/2020	Census Price Assessments: 3 Feb 2020	p/cert.	28.25
121	10/2/2020	Census Price Assessments: 10 Feb 2020	p/cert.	27.75
122	17/2/2020	Census Price Assessments: 17 Feb 2020	p/cert.	27.7
123	24/2/2020	Census Price Assessments: 24 Feb 2020	p/cert.	27.7
124	2/3/2020	Census Price Assessments: 2 Mar 2020	p/cert.	27.75
125	9/3/2020	Census Price Assessments: 9 Mar 2020	p/cert.	28
126	16/3/2020	Census Price Assessments: 16 Mar 2020	p/cert.	26.8
127	23/3/2020	Census Price Assessments: 23 Mar 2020	p/cert.	26.25
128	30/3/2020	Census Price Assessments: 30 Mar 2020	p/cert.	23.75
129	6/4/2020	Census Price Assessments: 6 Apr 2020	p/cert.	24.5
130	13/4/2020	Census Price Assessments: 13 Apr 2020	p/cert.	24.88
131	20/4/2020	Census Price Assessments: 20 Apr 2020	p/cert.	24.75
132	27/4/2020	Census Price Assessments: 27 Apr 2020	p/cert.	24.88
133	4/5/2020	Census Price Assessments: 4 May 2020	p/cert.	25.69
134	11/5/2020	Census Price Assessments: 11 May 2020	p/cert.	26.13
135	18/5/2020	Census Price Assessments: 18 May 2020	p/cert.	25.44
136	25/5/2020	Census Price Assessments: 25 May 2020	p/cert.	26.09
137	1/6/2020	Census Price Assessments: 1 Jun 2020	p/cert.	26.31
138	8/6/2020	Census Price Assessments: 8 Jun 2020	p/cert.	26.13
139	15/6/2020	Census Price Assessments: 15 Jun 2020	p/cert.	26.81
140	22/6/2020	Census Price Assessments: 22 Jun 2020	p/cert.	27.13
141	29/6/2020	Census Price Assessments: 29 Jun 2020	p/cert.	28.38

Appendix table 64. Table of data for landfill revenue savings arising from avoided FW landfill tax – based on time-adjusted variable WRAP FW collection data

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	£2,600,662	£1,683,752	£1,580,939	£1,889,184	£955,449	£8,709,986
2015	£4,546,200	£3,065,789	£2,804,606	£3,353,575	£1,701,133	£15,471,303
2020	£3,822,960	£2,654,931	£2,380,729	£2,817,125	£1,426,973	£13,102,718
2025	£3,503,252	£2,457,710	£2,191,065	£2,581,207	£1,297,738	£12,030,972
2030	£3,276,393	£2,317,091	£2,059,937	£2,418,144	£1,210,516	£11,282,081
2035	£3,106,158	£2,217,307	£1,964,300	£2,300,275	£1,141,899	£10,729,940
2040	£2,832,815	£2,039,311	£1,800,134	£2,106,567	£1,034,697	£9,813,524

2045	£2,601,316	£1,887,458	£1,661,113	£1,939,928	£945,957	£9,035,772
2050	£2,425,102	£1,772,931	£1,555,873	£1,813,479	£878,109	£8,445,494

Appendix table 65. Table of data for landfill revenue savings arising from avoided FW landfill tax – based on time-adjusted variable WDF FW collection data

	Leeds	Manchester	Liverpool	Sheffield	Newcastle	NPH 5-city region total
2010	£1,719,389	£1,113,188	£1,045,215	£1,249,006	£631,681	£5,758,480
2015	£2,681,672	£1,808,420	£1,654,356	£1,978,176	£1,003,449	£9,126,072
2020	£2,573,146	£1,786,973	£1,602,414	£1,896,142	£960,463	£8,819,137
2025	£2,669,144	£1,872,541	£1,669,383	£1,966,634	£988,753	£9,166,454
2030	£2,621,115	£1,853,672	£1,647,950	£1,934,515	£968,413	£9,025,665
2035	£2,588,465	£1,847,756	£1,636,917	£1,916,896	£951,583	£8,941,617
2040	£2,492,877	£1,794,594	£1,584,118	£1,853,779	£910,533	£8,635,902
2045	£2,415,507	£1,752,640	£1,542,462	£1,801,362	£878,388	£8,390,359
2050	£2,290,374	£1,674,435	£1,469,435	£1,712,730	£829,325	£7,976,300

Appendix table 66. Table of data for AD plant FW and other waste capacity and cost

Site name	Food Waste	2ndary waste	Total
AdnaMSBio Energy	10,000	2,500	12,500
Barkip AD	40,000	35,000	75,000
Bore Hill Farm	12,000	8,000	20,000
Bourne Park AD	37,000	6000	43,000
Brookfield Farm	27,750	2,250	30,000
Cassington AD	50,000		50,000
Coursers Farm	48,500		48,500
Deerdykes Composting and OrganiCSRecycling Facility	30,000		30,000
Westry Food AD	70,000		70,000
ReFood Widnes	150,000		150,000
Halstead Renewable Power Project	45,000		45,000
London Sustainable Industries	160,000		160,000
Language Farm	19,500	500	20,000
Llwyn Isaf AD Plant	11,500		11,500
Lochhead Landfill (Dry AD)	20,000	25,000	45,000
West London AD	48,000		48,000
Millerhill AD	30,000		30,000
Anglesey Ecoparc	10,000	15,000	25,000
Holsworthy Biogas Plant	80,000		80,000
Twinwoods	35,000	12,000	47,000
Walpole Landfill AD	30,000		30,000
Poplars Landfill AD	120,000		120,000
Newton Aycliffe Industrial	73,000		73,000
ReFood Doncaster AD	160,000		160,000
Rogerstone Park	5,850	14,950	20,800
South Shropshire Biowaste	5,000		5,000
Stormy Down AD	70,000		70,000
Bygrave Lodge Farm	45,000		45,000
Western Isles Integrated Waste Management Facility	20,000		20,000
Teeside Green Energy Plant	16,000	24,000	40,000
Cattlegate Farm	27,000		27,000
Parley Renewable Energy Park	25,000	20,000	45,000
Waen Biogas	22,500		22,500
Tomorrow's Valley	22,500		22,500
B9 Energy Group	75,000		75,000
Arla Foods (Food Waste)	50,000		50,000
Wingmoor Quarry (East)	34,000		34,000
Maltings Organic Treatment Facility	50,000	32,500	82,500
Downiehills Farm	10,000	45,000	55,000
Riverside AD	36,000		36,000