Delivering low carbon energy service demands: A UK case study

An examination of Local Authority level energy consumption and the potential for a disaggregated approach to energy demand reduction

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The candidate confirms that the submission of this work is his own, except for where appropriate credit has been indicated on included figures and tables. Indication is given below as to the figures and tables included in the thesis which are not the candidates own work.

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[1] I missed my BSc graduation ceremony while travelling in the US, and my MSc graduation ceremony while travelling in New Zealand.

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Abstract

Alongside decarbonising energy supply and greenhouse gas removal, energy demand reduction is expected to contribute significantly towards the achievement of the UK's long-term climate goals. Many emission scenarios include ambitious improvements in energy efficiency, however, relying largely upon energy efficiency to deliver the level of energy demand reduction required for a 1.5°C future is considered a high risk strategy for demand-side mitigation.

The thesis has highlighted the role that local authorities can assume in the demand-side transition, through subsidiarity, and framed analysis around the concept of energy service demands. Using this broader framing of energy demand reduction, the current direct and embodied energy demand associated with delivering Great Britain's household energy service demands was modelled. Four universal energy demand reduction strategies which considered consumption-based policy options for energy demand reduction were also modelled, and capacity index scores for each local authority were calculated to assess whether universal energy demand reduction strategies would be equitable, and effective at reducing Great Britain's level of energy consumption in line with the levels required for a 1.5°C future.

This project found that energy service demands vary across Great Britain, driven primarily by heating and personal transport energy service demands, with households in London having the lowest energy service demands per capita across the majority of energy service categories. The energy demand reduction strategies demonstrate that energy consumption associated with household energy service demands can be significantly reduced while maintaining service levels and therefore not compromising wellbeing, however reduced service levels, and their associated energy demand reduction, need to be considered if Great Britain's energy consumption is to be reduced to levels which align with estimates of the energy demand reduction required for a 1.5°C future. Finally, assessing the energy service demand and energy demand reduction results in the context of the capacity index scores showed that universal approaches to energy demand reduction which do not consider local context would not lead to an equitable demand-side transition, and that subsidiarity must play a larger role in energy demand reduction going forward.

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List of Abbreviations

ASI	Avoid-shift-improve
BECCS	Bio-energy carbon capture and storage
BEIS	Department for Business, Energy and Industrial Strategy
BEV	Battery-electric vehicle
CBS	Centraal Bureau voor de Statistiek (Central Agency for Statistics)
CCC	Committee on Climate Change
CF	Carbon footprint
CG	Consumer goods
CI	Capacity Index
CO_2	Carbon dioxide
COICOP	Classification of Individual Consumption by Purpose
CREDS	Centre for Research on Energy Demand Solutions
DAC	Direct air capture
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DUKES	Digest of UK Energy Statistics
ECCC	Environment and Climate Change Canada
ECUK	Energy Consumption UK
EDR	Energy demand reduction
EE-MRIO	Environmentally extended multi-regional input-output
EPC	Energy performance certificate
ESD	Energy service demand
FC	Full consideration
GB	Great Britain
GHG	Greenhouse gas
Gtoe	Gigatonnes of oil equivalent
GWh	Gigawatt-hour
HMRC	His Majesty Revenue and Customs
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IO	Input-output
IRENA	International Renewable Energy Agency
J	Joules
LA	Local Authority
LGA	Local Government Association
Ktoe	Kilotonnes of oil equivalent
KWh	Kilowatt-hour
LCFS	Living Costs and Food survey

LSOA	Lower Layer Super Output Area
MRIO	Multi-regional input-output
MSL	Maintained service levels
$MtCO_2e$	Megatonnes of carbon dioxide equivalent
Mtoe	Megatonnes of oil equivalent
NECP	Nation energy and climate plans
OAC	Output area classification
ONS	Office for National Statistics
RC	Recreation & communication
RSL	Reduced service levels
SEDC	Service-driven energy demand chain
SR15	Special Report: Global Warming of 1.5ºC
SUT	Supply and Use tables
tCO_2	Tonnes of carbon dioxide
toe	Tonnes of oil equivalent
UK	United Kingdom
UN	United Nations
US	United States

1 Introduction

Human-induced climate change will affect every person on the planet throughout the 21st century with differing degrees of severity (Masson-Delmotte *et al.*, 2021). Reducing the impacts and mitigating the extent of human-induced climate change in order to transition towards a net-zero emission society, whereby greenhouse gas (GHG) emissions are balanced by GHG atmospheric removals, by the mid-21st century has therefore become one of the most significant global challenges of our time (Fankhauser *et al.*, 2022).

Addressing the climate crisis is a significant challenge as reducing GHG emissions will require technological change and improvement, as well as significant shifts in social practices, cultural norms and behaviours. There have been positive shifts away from fossil fuels towards renewable energy sources in the electricity sector of developed countries – which accounted for an average of 22.5% of GHG emissions in the UK between 2000 and 2019 – and improvements in the efficiency of conversion and end use (Eyre, 2021; BEIS, 2022b).

However, the transition towards a net-zero society is still in its early stages as countries are yet to address the transformative change required across different sectors, institutions, infrastructure, technologies and social practices to deliver net-zero (Grubler *et al.*, 2018; Barrett *et al.*, 2022). There are also concerns, particularly on the demand-side of the energy system, that the net-zero transition is not advancing at the pace necessary to avoid significant climate breakdown by meeting the global long-term temperature goal of limiting global temperature rise to 1.5°C above pre-industrial levels by 2100, as set out in the Paris Agreement (Grubler *et al.*, 2018; Barrett *et al.*, 2022).

The demand-side transition needs to be accelerated as energy demand reduction (EDR) allows future energy-related emissions to be avoided, while also reducing the burden of the energy system to meet high levels of household energy demand and reducing the reliance upon negative emission technologies to meet long-term climate targets (Anderson and Peters, 2016; Grubler *et al.*, 2018; Kriegler *et al.*, 2018). EDR is therefore essential to successful emission reduction, climate change mitigation and the realisation of the global long-term temperature goal for the 21st century in the Paris Agreement (Masson-Delmotte *et al.*, 2018; BEIS, 2021c).

This thesis will explore the demand-side energy transition, focusing upon energy services – i.e. the benefits provided to households by energy consumption (Fouquet, 2010). Focus will be placed upon framing energy demand from a services perspective at a Local Authority (LA) level in the UK as the energy service demands (ESDs) of households vary across space, driven by differences in socioeconomic indicators. The UK was chosen for this study because of its multi-level governance structure and due to its position as the first major global economy to pass a net-zero emission target into legislation. The LA-level is examined to consider household ESDs across space, the effect of nationally-led EDR strategies upon different areas of the UK, and to establish whether LAs where households have the capacity to reduce their energy demand without compromising their wellbeing align with the areas of high ESDs and EDR.

Section 1.1 will set out the underlying rationale of the PhD project, before the project aims and research questions are set out in Section 1.2. Finally, Section 1.3 will outline the thesis structure.

1.1 Project Rationale

1.1.1 Status of Mitigation: A Global Perspective

Broadly speaking, when considering a shift towards a net-zero society, policymakers have three main strategies available to them (Fawzy *et al.*, 2020). The three strategies are: decarbonisation of energy supply through fuel switching and electrification, EDR through energy efficiency improvements and changes in social practices, and GHG removal through bio-energy carbon capture and storage (BECCS) and direct air capture (DAC) (Fawzy *et al.*, 2020; Barrett *et al.*, 2022).

First, the primary method adopted thus far by governments around the world is decarbonisation (Scott *et al.*, 2022). One mechanism of decarbonisation involves fuel switching the present energy generation mix to lower carbon alternatives sources of energy – i.e. switching to lower carbon fossil fuels (e.g. coal to gas) or renewable energy sources (e.g. wind and solar power) (Figure 1.1) (Hache, 2015).

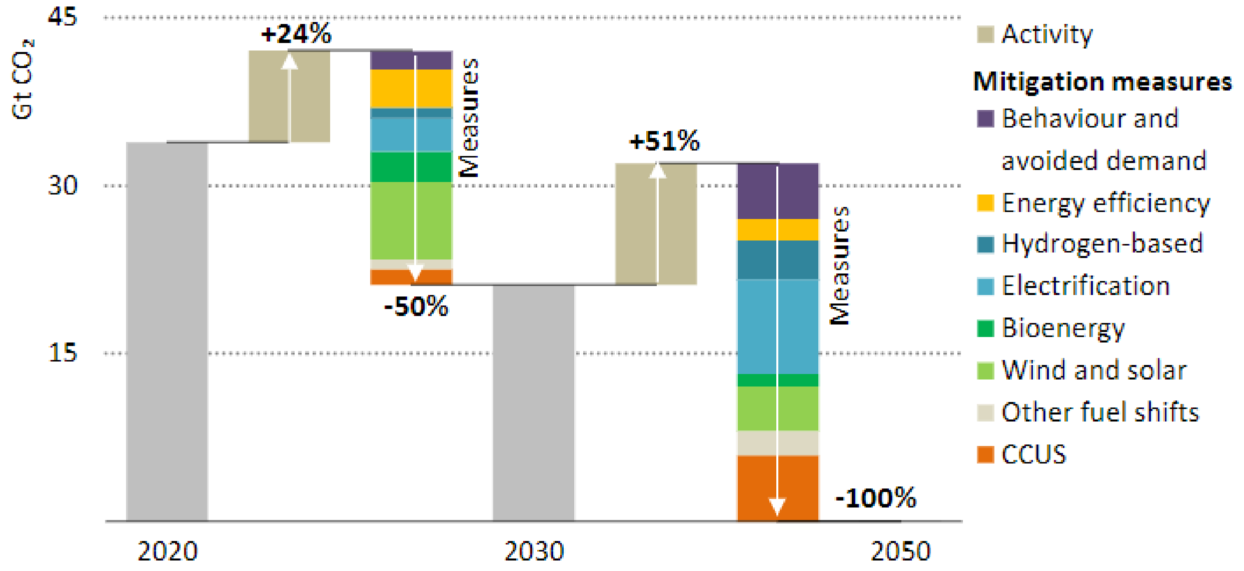

Figure 1.1 CO_2 reductions by time period in the IEA Net-Zero Energy Roadmap report. The key down the side of the figure shows the three main strategies for the transition to net-zero energy in a sector and fuel specific format. (Source: IEA, 2021).

The other main mechanism of decarbonisation involves the electrification of different systems, sectors and technologies. Electrification is another form of fuel switching, whereby carbon intensive power sources are replaced by electricity – e.g. transport electrification by switching from internal combustion powered vehicles to battery electric vehicles, or heating electrification by switching from gas-powered central heating to heat pumps (Jing *et al*., 2022). Shifting to electrified technologies and systems removes emissions from the energy system, meaning that electricity has the potential to provide low carbon energy to households, especially when generated by low carbon energy sources, such as renewable energy.

Decarbonisation of the energy system is an important aspect of the transition to a net-zero society as energy system emissions make-up ~80% of the total global anthropogenic GHG emissions (Hooker-Stroud *et al.*, 2014; IEA, 2022a). Decarbonisation has proved popular thus far as the technology to generate lower carbon energy is readily available and has become much cheaper in recent years – particularly for wind and solar energy costs which dropped by 45% and 56% between 2015 and 2020 respectively (Clarke *et al.*, 2021; IRENA, 2022).

However, focusing heavily on decarbonisation, and less on energy efficiency and GHG removal, leads to a significant issue for governments. Renewable energy sources of energy are less reliable than fossil-fuel power plants due to the intermittency of supply – for example, poor weather leads to reduced output from solar sources of energy (Gowrisankaran *et al.*, 2016; Mlilo *et al*., 2021). The intermittency of supply means that energy storage solutions need to be integrated into the energy system, and the energy system stresses caused by peaks of energy demand must be solved (Chen *et al.*, 2018; Rahman *et al.*, 2020). Therefore, the shift towards a net-zero society will be expensive, require significant land use change and would leave a significant amount of stranded infrastructure assets if a decarbonisation-only strategy is adopted (Bos and Gupta, 2019).

Additionally, energy is not presently consumed at a sustainable level, as global final energy consumption is rising faster than global renewable energy supply (Figure 1.2) (IEA, 2022b). Global final energy consumption increased by 3.8 gigatonnes of oil equivalent (Gtoe) between 1990 and 2019, and global renewable energy supply increasing by 0.5Gtoe over the same time period (Figure 1.2) (IEA, 2022b). Therefore a renewables-led mitigation strategy is unlikely to be enough to transition to a net-zero society alone (Hirschnitz-Garbers *et al.*, 2016).

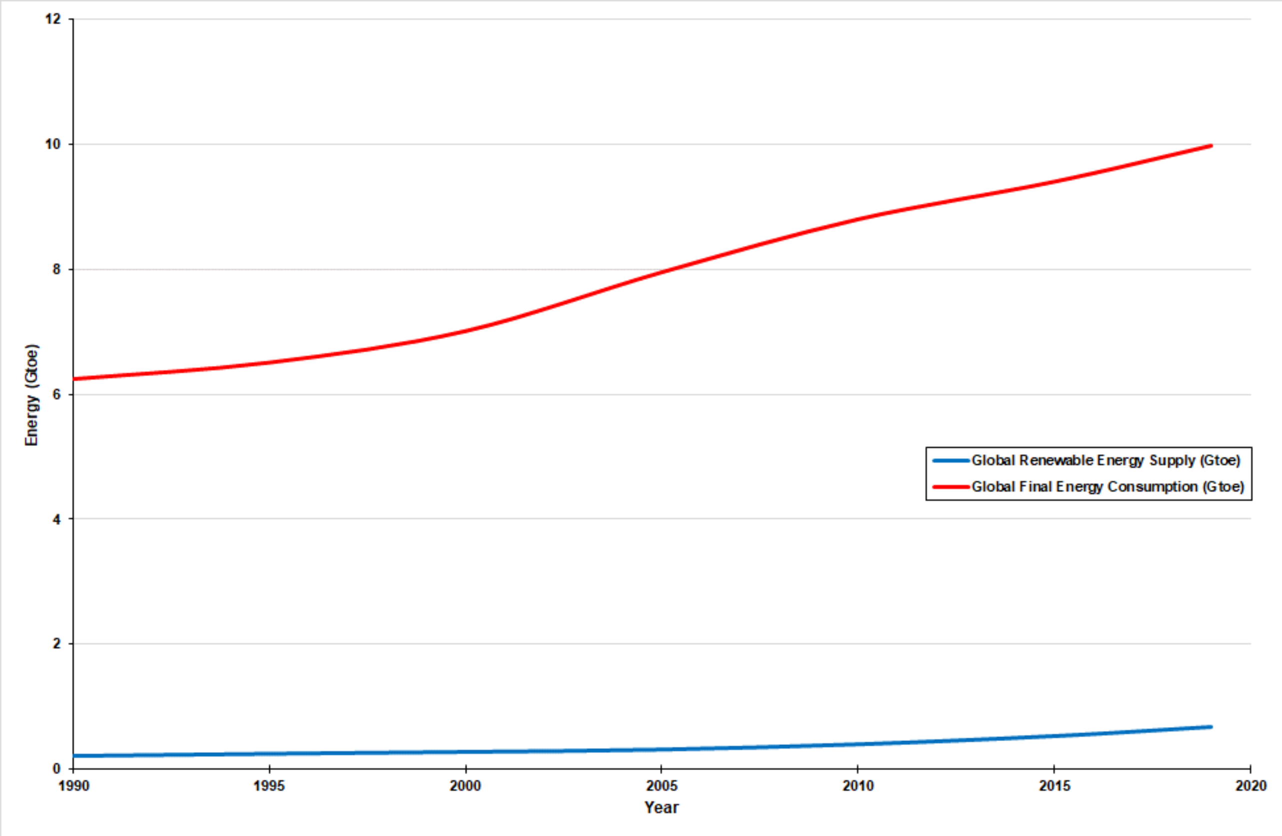

Figure 1.2 Global renewable energy supply and global final energy consumption from 1990 to 2019. Graph produced from data found in IEA (2022).

Second, alongside decarbonising energy supply, emission scenarios within the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) 'Special Report: Global Warming of 1.5ºC' (SR15) place an emphasis upon the potential of global EDR to contribute significantly towards the achievement of the Paris Agreement's 1.5°C long-term climate goal (Grubler *et al.*, 2018; Masson-Delmotte *et al.*, 2018; Brockway *et al.*, 2021; Kikstra *et al.*, 2021; Knobloch, 2021; Nielsen *et al.*, 2021; Poblete-Cazenave *et al.*, 2021; Barrett *et al.*, 2022).

Energy efficiency is the form of EDR favoured by policymakers as it allows the same level of energy service to be delivered to households for less energy demand, and provides multiple benefits, such as energy security, increased productivity, cost reductions and health and wellbeing improvements (Figure 1.3) (Sorrell, 2007; IEA, 2014; Shove, 2018). Energy efficiency measures aim to improve the thermodynamic efficiency of the technical energy system and technologies which deliver energy to households – e.g. reducing transformation losses when converting primary energy to final energy, or shifting to less energy intensive, electrified, technologies, such as battery-electric vehicles, rather than internal combustion engines (Sorrell, 2007; Creutzig *et al.*, 2018). Other forms of EDR include changes in social and behavioural practices, such as shifting to a plant-based diet or lowering heated room temperatures (Creutzig *et al.*, 2018; Shove, 2018).

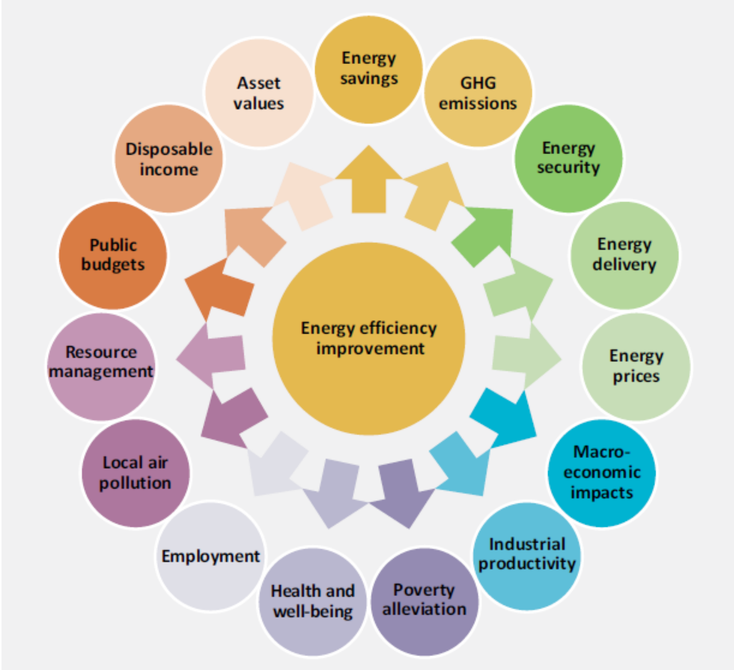

Figure 1.3 Multiple benefits of energy efficiency improvements across society. Image reproduced from IEA (2014).

Large-scale, near-term EDR allows future energy-related emissions to be avoided, which has a large impact upon maintaining global cumulative emissions below the estimated 1.5°C carbon budget (Kriegler *et al.*, 2018; Barrett *et al.*, 2022; Scott *et al.*, 2022). Declining trends in energy demand could also reduce the pressure placed upon the supply-side of the energy system therefore allowing energy supply to be decarbonised at a faster rate (Grubler *et al.*, 2018). Additionally, 1.5°C emission scenarios which include stabilised energy demand also suggest that our reliance upon negative emission technologies, which are untested at a large-scale, to deliver a 1.5°C future, will be reduced, as shown by Figure 1.4 (Anderson and Peters, 2016; Masson-Delmotte *et al.*, 2018).

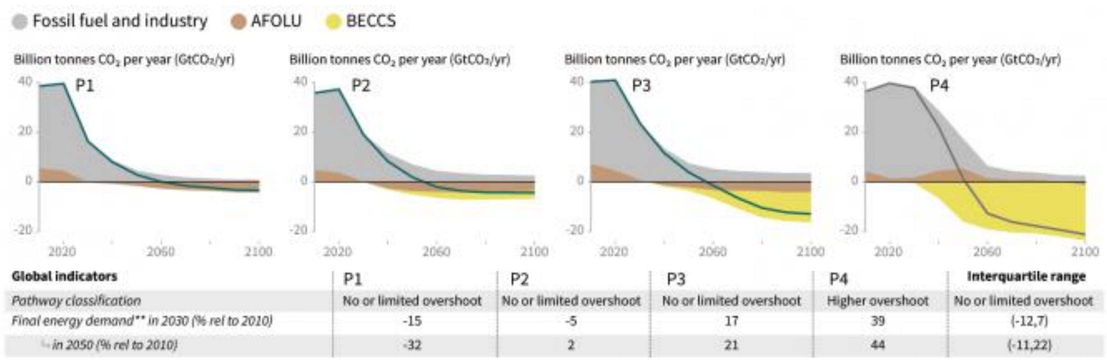

Figure 1.4 1.5°C emission scenarios within the IPCC's SR15. Scenarios P1 and P2 contain reduced and stabilised global final energy demand respectively. Whereas within scenarios P3 and P4 global final energy demand continues to rise which increases the need for negative emissions[2] to achieve the 1.5°C climate target (Source: (Masson-Delmotte *et al.*, 2018).

[2] In the IPCC SR15 1.5°C scenarios, negative emissions are achieved through changes in Agriculture, Forestry and Other Land Use (AFOLU) and the deployment of negative emission technologies, such as Bio-energy with carbon capture and storage (BECCS).

However, despite the contribution that EDR could make towards achieving the 1.5°C climate target, global final energy demand continues to increase (IEA, 2022b). Global final energy consumption grew from 6.2 Gtoe in 1990 to 10.0 Gtoe in 2019 at an average rate of 1.3% per annum (Ayres *et al*., 2019; IEA, 2022b).

The third lever for GHG emission reductions focuses upon removing already emitted GHG emissions from the atmosphere to reduce anthropogenic-induced warming. GHG removal can be a natural option, using techniques such as afforestation or a technological option, using DAC or BECCS (Royal Society, 2009; Cox *et al.*, 2018). GHG removals often play a large role in future emission scenario, with GHG removal allowing for delayed climate action through removing any GHG emissions in the long-term which cause carbon budgets to be exceeded in the short-term (Waller *et al.*, 2020).

However, relying upon GHG removal alone to transition to a net-zero society would be a flawed decision by policymakers. GHG removal is expected to balance remaining CO_2 emissions in future scenarios, rather than solve the climate crisis alone (Anderson and Peters, 2016; McLaren, 2020). A large number of natural and technological GHG removal techniques, produced at a large-scale, would be required to significantly reduce GHG levels in the atmosphere to safe levels before a threshold for dangerous climate change is crossed (Anderson and Peters, 2016). Additionally, the technological GHG removal strategies modelled in mitigation and emission pathways do not yet remove GHG emissions at the scale required to avert dangerous climate change (Cox *et al.*, 2018). Therefore, while GHG removal may have a role to play in ensuring that goals are met closer to 2050, it is likely to provide small-scale contributions to reducing the impact of the climate crisis at best (Anderson and Peters, 2016; Cox *et al.*, 2018).

In reality, all three of the main mitigation strategies will contribute to the transition towards a net-zero society (Masson-Delmotte *et al.*, 2018; Fawzy *et al.*, 2020). At present, decarbonisation is utilised most effectively by governments, while EDR focusing upon energy efficiency is yet to implement the transformative societal changes required for net-zero across different sectors, institutions, infrastructure, technologies and social practices, and GHG removal technology is relatively undeveloped, and yet to be effective at a large-scale (Grubler *et al.*, 2018; Barrett *et al.*, 2022).

As the methods and mechanisms underlying decarbonisation are already well-utilised by governments, and GHG removal technology unlikely to be deployed at scale before 2050, it is EDR that both offers significant opportunities to exploit untapped potential to reduce GHG emissions to meet the 1.5°C target (Creutzig *et al.*, 2018; Grubler *et al.*, 2018; Barrett *et al.*, 2022).

As stated previously, however energy demand continues to rise globally despite the implementation of energy efficiency measures designed to reduce energy demand, which is concerning for GHG emission reduction efforts (IEA, 2022b). However, the trend in final energy consumption at different spatial scales does not reflect the global trend (IEA, 2022b).

1.1.2 Energy consumption and demand reduction at different spatial scales

The IEA (2022b) reported statistics which show an increase of 37.6% in global final energy consumption between 1990 and 2019, which suggests that EDR through energy efficiency has been unsuccessful at reducing energy consumption. However, at a smaller-scale, final energy consumption and the effect of EDR efforts are more nuanced, with Figure 1.5 demonstrating that final energy consumption has not risen at the same rate across the world as it has in the global figures (IEA, 2022b).

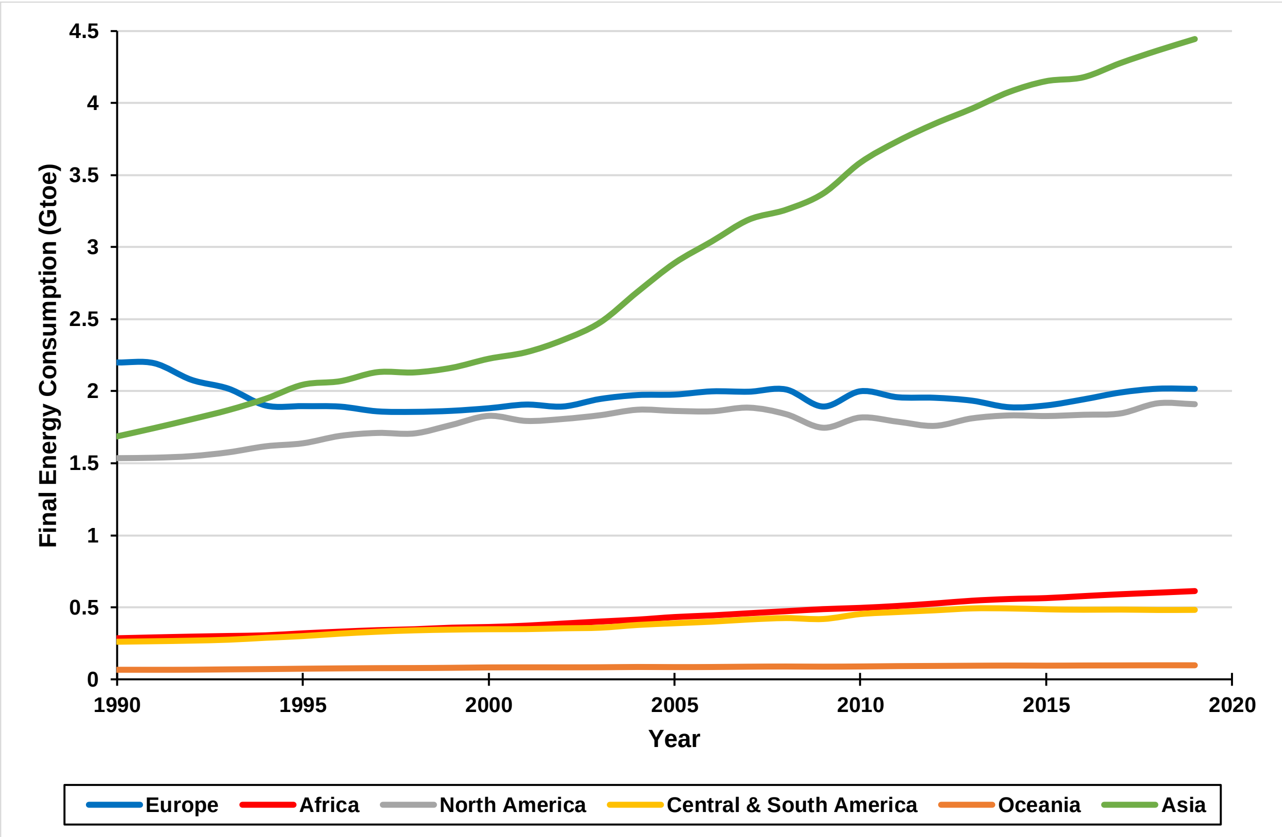

Figure 1.5 Final energy consumption at a continental-level from 1990 to 2019. Graph produced from data in IEA (2022).

As well as the IEA, individual countries also maintain national accounts of GHG emissions and energy consumption (Figure 1.6), with some countries, such as the UK, keeping sub-national accounts of direct energy consumption at a regional and LA-level (BEIS, 2021d). Figure 1.6 shows that energy consumption at a national-level in the UK has remained relatively stable before 2008 and since 2011, despite large reduction in GHG emissions, primarily due to the effect of offshoring of high energy sectors, such as manufacturing, and energy efficiency (Hardt *et al.*, 2017).

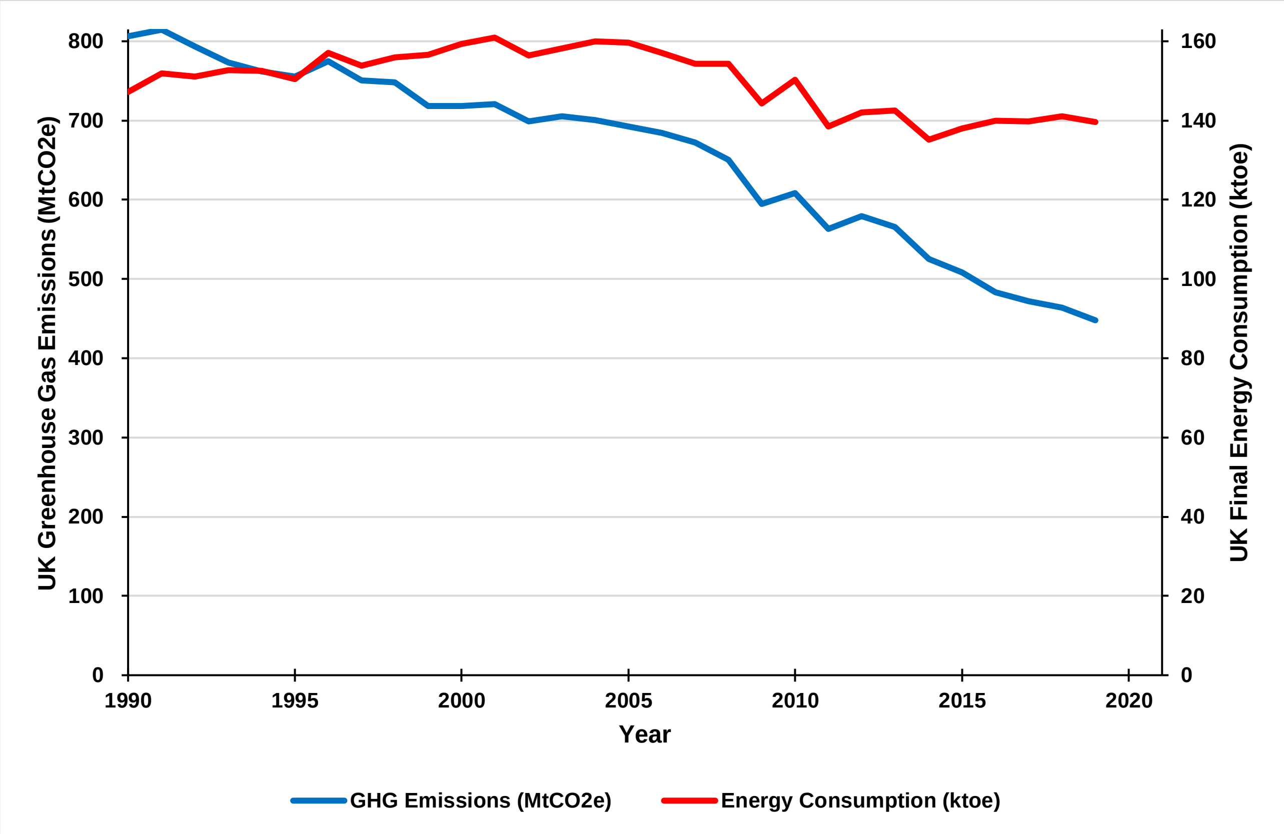

Figure 1.6 UK GHG emissions and UK final energy consumption from 1990 to 2019 (Data sources: BEIS, 2022b; DUKES, 2022a).

Figure 1.5 and Figure 1.6 demonstrate that energy consumption varies at different levels and across space (BEIS, 2022b; DUKES, 2022a; IEA, 2022b). Each individual nation is responsible for the energy consumed within its territorial boundaries, meaning that the responsibility of reducing energy demand falls upon national-level governments.

Currently, national-level policies designed to stabilise or reduce energy demand focus upon the concept of energy efficiency, which has become synonymous with all types of demand-side action (Shove, 2018). For example, within the UK's recent draft National Energy and Climate Plan (NECP), improving energy efficiency is one of the five key objectives that will allow the UK to achieve its climate targets (BEIS, 2019). Energy efficiency improvements utilise technological measures, such as improving thermodynamic conversion efficiencies, and shifting energy consumption to more efficient technologies, such as battery-electric vehicles (BEVs), to deliver EDR (Creutzig *et al.*, 2018). Energy efficiency measures are considered to be an EDR measure as they allow a reduced level of energy input to meet the same level of household energy demand, therefore reducing energy use without significantly affecting current lifestyle practices or requiring behavioural change (Mallaburn and Eyre, 2014; Shove, 2018).

However, energy efficiency policy alone cannot deliver the transformative change required across social practices, behaviours and lifestyles for a 1.5°C future, such as the digitalisation of the energy sector, the elimination of single occupancy car trips or an increase in the number of households adopting plant-based diets (Barrett *et al.*, 2022). Additionally, there is evidence to suggest that improved energy efficiency drives the energy rebound effect, whereby "energy-saving innovations induce an increase in energy consumption that offsets the technology-derived saving" (Stern, 2011, p40). The rebound effect hinders the effectiveness of energy efficiency measures meaning that the expected level of EDR delivered by energy efficiency policy is often not realised (Sorrell, 2007; Stern, 2011; Sorrell, 2015; Brockway *et al.*, 2017, 2021). There is also evidence which suggests that the rate of energy efficiency increases is slowing in developed countries, such as the UK and the US, meaning that the uptake of energy efficiency improvements has not occurred at the rate projected in 1.5°C emission scenarios (Brockway *et al.*, 2014).

An energy efficiency approach also encourages a focus upon technological solutions to rising energy demand (Shove, 2018). This limits the scope of demand-side intervention strategies by neglecting EDR options that exist beyond the boundaries of the technical energy system, such as improved spatial planning for urban areas, and also misrepresents the underlying dynamics of energy demand (Shove and Walker, 2014; Creutzig *et al.*, 2016). National-level governments therefore need to go beyond energy efficiency demand reduction measures to implement an effective transition to a low energy demand society (Creutzig *et al.*, 2018).

EDR however is not solely the responsibility of national-level governments. For example, regional governments in France and Germany set out EDR policy (IEA, 2016, 2020b), while the devolved UK governments of Wales and Scotland have the ability to set out their own energy efficiency policies (Bridge *et al.*, 2013). Additionally, countries such as Austria, Ireland, The Netherlands and Spain, involve local-level government in their implementation of EDR policy (IEA, 2019b, 2020d, 2020a, 2021).

A more localised approach to EDR, through subsidiarity, is considered to be vital in achieving the transition to a net-zero society, and the international-level climate targets set out in the Paris Agreement (Bale *et al.*, 2012; Wanzenböck and Frenken, 2018; LGA, 2019). Subsidiarity states that all tasks of government should be undertaken at the most localised-level possible, with the central government only performing tasks which cannot be performed at a lower level (Lenaerts, 1993; Gagnon and Keil, 2017). Local government can draw together local partners and advocates for climate action to decide the best direction for EDR in their respective localities (Wanzenböck and Frenken, 2018; LGA, 2019). This is important when considering the variation of household energy consumption across space, and the need for EDR to be just as well as effective (Wanzenböck and Frenken, 2018).

Variation in household energy consumption is driven by differences in socioeconomic factors such as income, household size, population density and household age (Sorrell, 2015). Socioeconomic factors vary across continents, countries, regions and localities, thereby affecting the level of household energy consumption at different scales, which must be taken into account when considering EDR to avoid compromising the wellbeing of households that EDR measures are being implemented upon (Bhattacharjee and Reichard, 2011; Wiedenhofer *et al.*, 2013; Azam *et al.*, 2016; Mrówczyńska *et al.*, 2020; Owen and Barrett, 2020; Ghofrani, Zaidan and Abulibdeh, 2022). For example, a national-level policy banning petrol-powered vehicles to encourage households to shift to BEVs, and therefore reduce their energy demand, would significantly compromise the ability of less affluent households, who cannot afford to purchase a BEV, to achieve their transport needs. Whereas, a locally led approach to increase the density of public transportation by buses in a LA, and therefore encourage households to shift their transport needs to a low carbon option, would not compromise the wellbeing of less affluent households.

LAs are therefore well-placed to ensure EDR is conducted in an effective, just manner, while implementing EDR measures at a local-level could also improve levels of social acceptance as local politicians are more familiar with the needs of households (Wanzenböck and Frenken, 2018). However, at present, EDR policy across many countries is set out at a national-level, including the UK, (IEA, 2018, 2019b, 2020c), thereby ignoring the potential benefits of implementing EDR at a local-level, or in partnership with local-level government (Bale *et al.*, 2012).

The UK is one such country that sets EDR policy at a national-level – e.g. the Green Homes Grant – despite its multi-level governance structure (Bale *et al.*, 2012; International Energy Agency, 2019c; Paun *et al*., 2019). The UK will be considered as a case study for local-level EDR due to UK LAs having significant control over various areas of policy, including housing and transport – two important areas for EDR – and its position as the first major global economy to legislate a net-zero emission target (Paun *et al*., 2019; BEIS, 2021b).

1.1.3 Status of energy demand reduction: UK

Figure 1.6 shows that despite a large reduction in GHG emissions, energy consumption has remained relatively stable across the time periods 1990-2008 and 2011-2019. The drop in energy consumption between 2008 and 2011 is due to the 2008 global financial crisis, and the effect of reduced economic growth from this, rather than being an effect of policy (Sakai *et al.*, 2018; Ayres *et al*., 2019; Brockway *et al.*, 2019; BEIS, 2022a; Defra, 2022).

An effective and just transition towards a low energy demand society is necessary if the UK is to reach its long-term climate targets (Barrett *et al.*, 2022; Scott *et al.*, 2022). More effective demand-side policy would reduce the burden of a decarbonised supply-side of the energy system to cope with current demand levels and also avoid emissions from energy use altogether (Creutzig *et al.*, 2018).

In the UK, energy policies are defined at a national level, with limited direct powers for LAs to set energy policy (Smith, 2007; Ellis *et al.*, 2013; Cowell *et al.*, 2015, 2017). Despite Wales and Scotland having the ability to set out their own energy efficiency policies, energy and climate governance is broadly considered to be a national issue, while LAs control policy areas which could be utilised to reduce energy demand – e.g. transport planning (Bridge *et al.*, 2013; Paun *et al.*, 2019).

At present, the primary focus of the Department of Business, Energy and Industrial Strategy (BEIS) is to consider the energy trilemma of security, affordability and decarbonisation with a primary focus on decarbonising energy supply through policies such as "advancing offshore wind" and "driving the growth of low carbon hydrogen" or "Jet Zero" (BEIS, 2020a; BEIS, 2020b). Much of the language in policy documents, such as the Clean Growth Strategy and the Green Industrial Revolution, is focused on fuel switching and increasing the capacity of renewables, as opposed to EDR (BEIS, 2020a, 2020b).

The most recent national-level flagship policy centred on EDR for households was the Green Homes Grant, which aimed to encourage homeowners and landlords to improve the energy efficiency of their homes using grants of up to £5000 (BEIS 2021c). The Green Homes Grant scheme can be considered a failure due to a low uptake and a short policy lifetime[3] (Kenyon, 2021). Another similar national-level demand-side policy failure in the UK is the Green Deal which ran from 2012 to 2015 (Rosenow and Eyre, 2016). The Green Deal was an energy efficiency policy also focused upon improving household efficiency, but only managed to retrofit 14,000 out of a projected 14 million households, mainly due to the high rate of interest on the loans given to households, making them an unattractive prospect (Rosenow and Eyre, 2016).

National-level EDR policies and strategies in the UK, often consider EDR using an efficiency framing. For example, in the Clean Growth Strategy, "Improving business and industry efficiency" and "improving efficiency of homes" are both mentioned as policy aims (Sorrell, 2007; BEIS, 2017). However, in the Green Industrial Revolution, EDR is not specifically mentioned, but instead pledges to introduce "green public transport, cycling and walking" (BEIS, 2020b). The wording in the Green Industrial Revolution implies the strategy will aim to shift transport ESDs to less energy intensive options, however this is not stated outright (BEIS, 2020b).

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[3] The policy was launched during the latter half of 2020 (30th September 2020 to March 31st 2021) after the beginning of the Coronavirus pandemic and was unsuccessful due to the backlog of work from early 2020, and the November 2020 and early 2021 national lockdowns which prevented work being undertaken.

The Green Industrial Revolution therefore shows that the UK government is seeking to reduce energy demand through measures which shift energy demand to less energy intensive practices. 'Shift' measured can be considered alongside energy efficiency measures using the avoid-shift-improve (ASI) framework (Table 1.1) (Creutzig *et al.*, 2018; BEIS, 2020b). The ASI framework was set out by Creutzig *et al.*, (2018) and is used to consider the different measures associated with EDR. Under the ASI framework, 'avoid' measures negate the need for energy demand altogether, whereas 'shift' measures focus upon shifting energy demand to less energy intensive practices without compromising service level, and 'improve' measures aim to reduce energy demand without changing consumer behaviour or societal practices through energy efficiency (Table 1.1) (Creutzig *et al.*, 2018). 'Avoid' and 'shift' measures designed to reduce household ESDs, and the energy associated with ESDs can be implemented alongside 'improve' options (Creutzig *et al.*, 2018).

Table 1.1 Example of the Avoid-Shift-Improve framework (Source: Creutzig *et al.*, 2018)

Table 1 | Illustrative 'avoid–shift–improve' options in different sectors and services

	Service	Avoid	Shift	Improve
Transport	Accessibility Mobility	Integrate transport and land-use planning Smart logistics Teleworking Compact cities	Mode shift from car to cycling, walking, or public transit	Electric two-, three- and four-wheelers Eco-driving Electric vehicles Smaller, light weight vehicles
Buildings	Shelter	Passive house or retrofit (avoiding demand for heating/cooling) Change temperature set-points	Heat pumps, district heating and cooling Combined heat and power Invertor air conditioning	Condensing boilers Incremental insulation options Energy-efficient appliances
Manufactured products and services	Clothing Appliances	Long-lasting fabric, appliances, sharing economy Eco-industrial parks, circular economy	Shift to recycled materials, low-carbon materials for buildings and infrastructure	Use of low-carbon fabrics New manufacturing processes and equipment use
Food	Nutrition	Calories in line with daily needs Food waste reduction	Shift from ruminant meat to other protein sources where appropriate	Reuse food waste Smaller, efficient fridges Healthy fresh food to replace processed food

Many options, such as urban form and infrastructures, are systemic and influence several sectors simultaneously.

The UK's national transport and heating strategies show evidence of 'shift' options being considered too, through the planned phase-out of fossil fuel powered vehicles for BEVs, and the increase of heat pumps to deliver heating ESDs to households. However, measures from the 'avoid' column of the ASI framework are generally neglected, with the exception of reducing personal transport and undertaking shorter journeys by foot (Creutzig *et al.*, 2018; BEIS, 2020b).

At a national-level, UK energy demand policy has thus far offered a narrow perspective for EDR, favouring technical efficiency improvements in the past, and more through technological shifts. Different levels of government in the UK do not possess powers to enact energy policy. There is no funding for set aside for UK sub-national governments to devise and implement energy policies, therefore ensuring large-scale, well-funded energy policies remain in control of the UK's national-level government (Muinzer and Ellis, 2017; LGA, 2019; Kenyon, 2021).

However, LAs have significant control of policy areas which can be used to reduce energy demand in their local area – e.g. transport planning and landlord regulation (Figure 2.5) (Paun *et al*., 2019). For example, local councils run and maintain public car parks in their locality (Paun *et al*., 2019). By closing the car parks, and converting them into green space, they are discouraging car use in the town centre and therefore encouraging EDR through an attempt to shift household habits to lower carbon options such as walking or cycling (Creutzig *et al.*, 2018).

The climate plans set out by LAs in the UK are often more ambitious in their climate goals than national governments (Figure 1.7) (Climate Emergency UK, 2022; mySociety, 2022). For example, Leeds City Council is aiming to reach net-zero emissions by 2030, 20 years sooner than the national target of net-zero by 2050 (Figure 1.7) (Leeds Climate Commission, 2021a).

A disparity therefore exists between the levels of mitigation ambition at different levels of the UK multi-level governance structure (BEIS, 2021c; Climate Emergency UK, 2022; mySociety, 2022). High ambition, coupled with the ability of LAs to work alongside residents, local business leaders and other stakeholders to implement a just, effective and accepted EDR strategy offers a space which could be exploited to accelerate EDR, and therefore GHG emission reduction in the UK (Wanzenböck and Frenken, 2018; Climate Emergency UK, 2022; mySociety, 2022).

However, at present, LAs in the UK lack the finances to effectively implement EDR and their climate plans (Sugar *et al.*, 2022). Additionally, the energy consumption data published at a LA-level in the UK focuses upon the quantity of fuels used to provide energy demand, rather than the underlying reasons energy is demanded by households in each LA (BEIS, 2021d). Focusing upon fuel consumption in each LA perpetuates the current framing of EDR through an efficiency lens – e.g. through fuel switching, electrification or thermodynamic conversion efficiency improvements – rather than allowing LAs to address high energy consumption and bring about the transformative change in societal practices and household behaviour required for a low energy demand future and net-zero (Morley, 2018). An alternative approach to considering LA energy consumption must be adopted to unlock the full potential of EDR at a local-level.

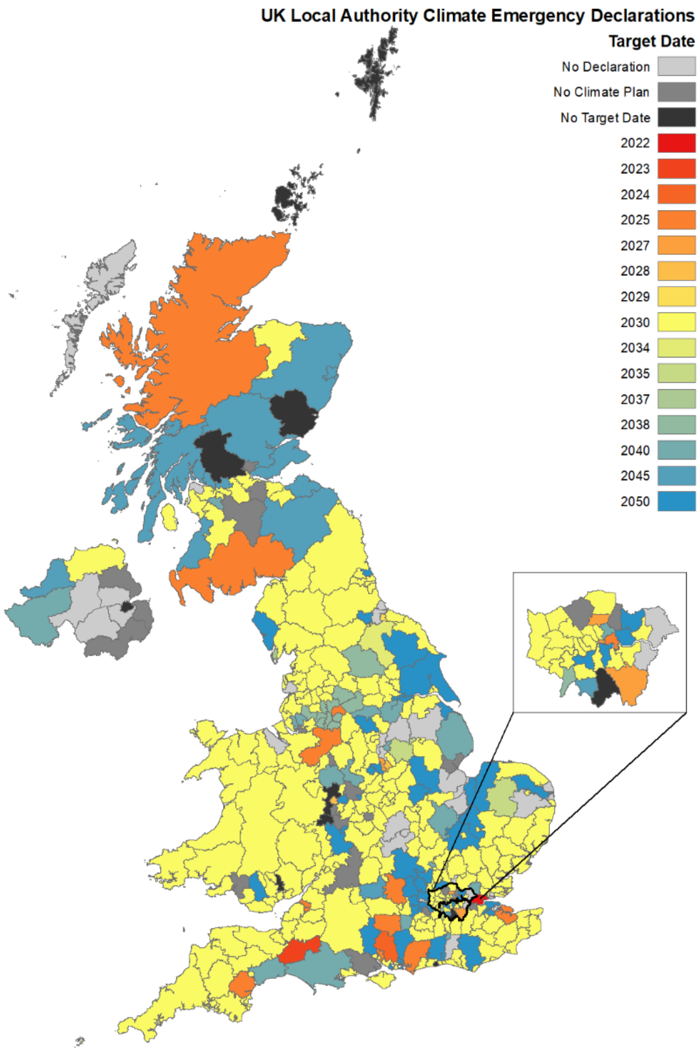

Figure 1.7 Map showing the UK local authorities which have declared climate emergency as of October 2020, and the year which each LA's earliest target is set for (Data source: Climate Emergency UK (2022); mySociety (2022).

1.1.4 Energy Service Demands

"Energy is not consumed for itself, but as a means to supply a demand of useful services" (Le Gallic *et al*., 2017, p2619) to households. These 'useful services' are known as 'energy services' and include examples such as space heating, transport and illumination (Haas *et al.*, 2008; Fouquet, 2014; Geels *et al.*, 2018). Energy services are used by all households on a day-to-day basis and are important for meeting human needs to achieve wellbeing (Modi *et al.*, 2005; Brand-Correa *et al.*, 2018). Therefore, energy services are often considered from a top-down perspective, as the end goal for the energy system (Kalt *et al.*, 2019).

Energy service demands (ESDs) can also be considered from a bottom-up perspective, by relating them to human wants and needs (Brand-Correa *et al*., 2018). From this perspective, ESDs are key component of achieving wellbeing throughout a population and have been previously referred to as the "golden thread" linking human needs and energy consumption (Brand-Correa *et al*., 2018). There is therefore an implication that reducing ESDs has the potential to compromise the ability of households to meet their needs, however, this argument ignores issues of overconsumption and less energy intensive alternatives which maintain service levels to households (Rockström *et al.*, 2009; Raworth, 2012; Steffen *et al.*, 2015; Creutzig *et al.*, 2018; Hickel, 2019; Rockström *et al.*, 2021). Studies have previously identified that energy consumption rises with income (Oswald *et al*., 2020; Owen and Barrett, 2020), while other studies have also identified that wellbeing directly increases with energy consumption, only up to a certain point, at which point, energy consumption continues to rise, but wellbeing increases stagnate, and can even decrease (Steinberger and Roberts, 2010; Brand-Correa and Steinberger, 2017; Rao *et al.*, 2017; Grubler *et al.*, 2018; Rao *et al*., 2019; Vita *et al.*, 2019; Millward-Hopkins *et al.*, 2020).

Understanding that excessive consumption does not continue to bring about continuous wellbeing increases for both essential and non-essential services, and that household ESD levels can be reduced without reducing wellbeing, offers greater opportunities for EDR in countries, such as the UK, in which demand for energy services continues to rise, but wellbeing is no longer increasing (Raworth, 2012; Brand-Correa *et al*., 2018; Morley, 2018). ESDs can therefore be reduced, without compromising wellbeing, by using methods from the 'avoid' and 'shift' pillars of the ASI framework, set out by Creutzig *et al.*, (2018), as well as 'improve' measures such as energy efficiency (Table 1.1).

For example, switching an individual's primary mode of transportation for commuting from their own privately owned motor vehicle to public transport, shifts a household's ESD for mobility to a low carbon alternative (Creutzig *et al.*, 2018). Alternatively, altering a company's work practices to permit an employee to work from home if they desire, can lead to the ESD for mobility being avoided altogether (Creutzig *et al.*, 2018). At this point, the same 'end' is achieved – i.e. The individual was able to attend work – however, the energy associated with mobility ESDs is less energy intensive or avoided completely. Despite no energy demand for mobility occurring, avoided energy use can still lead to a rebound effect through higher energy use at home (Brockway *et al.*, 2021). Improve measures, such as stricter internal combustion engine standards to improve the energy efficiency of the public transport mode's engine can be implemented alongside avoid and shift measures to further reduce the energy associated with this ESD (Creutzig *et al.*, 2018).

Considering the ESDs, rather than energy demand, of households is important when examining energy consumption in LAs. ESDs are directly related to consumption – being the service demanded by households from the energy system (Le Gallic *et al*., 2017) – which is the stage of the energy chain that takes place in LAs. LAs can therefore directly address the ESDs of households – i.e. consumption – rather than the systems delivering demanded from the energy system to households

– i.e. production – which is important when considering subsidiarity (Wanzenböck and Frenken, 2018).

The concept of ESDs allows energy system analyses of energy demand to go beyond calculating the amount of energy supplied to meet household demand, towards examining the actual services ('ends') delivered to households by the energy system and allows the full range of options for EDR to be considered (Creutzig *et al.*, 2018; Morley, 2018). For demand-side studies to fully exploit the services concept, a consistent framing of energy services at a LA-level, which recognises the true dynamics of ESDs and energy demand, needs to be applied.
However, at present, the energy service categories, accounting methods and framings of energy services are inconsistent across different papers (Modi *et al.*, 2005; Sorrell, 2007; Fouquet, 2014; Fell, 2017; Rao and Min, 2018; Hardt *et al.*, 2019; Owen and Barrett, 2020). Additionally, the UK government produces data on the end-use proportions of each fuel on different energy services such as space heating, cooking and lighting, but, as stated in Section 1.1.3, the UK government only maintains LA-level data on final energy consumption by sector and fuel type, not household ESDs (BEIS, 2021d; ECUK, 2022).

1.1.5 Energy Service Accounting

As stated in Section 1.1.4, the UK government keeps detailed records of energy consumption throughout the UK at different levels, for different sectors and for different fuels, but only produces data on the end use proportions of each fuel on different energy services such as space heating, cooking and lighting at a national-level (BEIS, 2021d; ECUK, 2022). National-level records of ESDs miss the nuance of variations in ESDs across space and do not show whether energy consumption is disproportionate in different areas of the country (Minx *et al.*, 2013).

Additionally, the data only considers services related to direct energy consumption – direct energy – thus neglecting the energy embodied within goods and services bought by households – indirect energy (Vringer and Blok, 1995; Haas *et al.*, 2008; Barrett *et al.*, 2013). Therefore a significant proportion of energy consumption is absent from the UK's national-level energy consumption figures (BEIS, 2022a; ECUK, 2022).

The energy requirements of households across LAs, throughout the UK, are more nuanced than the direct energy demanded from the energy system (Vringer and Blok, 1995; Haas *et al.*, 2008). Indirect energy, generated in the supply chain, in the production and transport of goods to households, as well as direct energy, demanded from the energy system itself by households, is required to provide the services households require to meet their needs and achieve wellbeing (Vringer and Blok, 1995; Haas *et al.*, 2008). Modelling the indirect energy associated with LA-level household ESD footprints ties together the consumption and production aspects of the energy system, thus allowing EDR measures, implemented within LAs to affect the globalised energy system and also broadens the scope of potential interventions for EDR available to LAs, which may not be taken into account when only considering EDR of direct energy (Miller and Blair, 2009; Wood *et al.*, 2018).

Current UK energy consumption accounts therefore neglect a significant proportion of energy demanded by households to achieve wellbeing, which means that EDR opportunities may be missed by both the national-level government and LAs, while only providing direct energy consumption data may misappropriate the onus to reduce energy demand elsewhere in the world (Barrett *et al.*, 2013; BEIS, 2022a). Without a LA-level database of ESDs, which includes household's direct and indirect energy requirements for different ESDs, the full ESD footprints of LA-level household ESD footprints, and the full scope of options for EDR from the ASI framework cannot be utilised by LAs (Barrett *et al.*, 2013; Creutzig *et al.*, 2018). However, the focus on international climate targets and national EDR strategies in the past has led to subsidiarity, and local-level ESD variation, being given less attention by researchers and policymakers (Morris *et al.*, 2017).

1.1.6 The need for further research

Further research is needed as EDR needs to be fully exploited for the UK to reach its climate targets, and subsidiarity may be the key to unlocking the potential of EDR in the UK (Creutzig *et al.*, 2018; Wanzenböck and Frenken, 2018; BEIS, 2021c). However, energy policy remains the prerogative of the UK national-level government, while household energy demand in the UK is yet to be significantly reduced despite the implementation of energy efficiency improvements (Figure 1.6).

Household energy consumption is driven by demand for energy services to achieve human needs, wants and wellbeing (Brand-Correa *et al*., 2018). EDR, must therefore be delivered in such a way that does not compromise the ability of households to meet these ends.

Energy consumption, and therefore wellbeing, is affected by socioeconomic factors, such as income, household size and population density (Sorrell, 2015). Therefore, household ESDs, and the level of household capacity to adopt EDR strategies, is likely to vary significantly across different LAs as socioeconomic factors vary (Minx *et al.*, 2013; Naumann and Rudolph, 2020). Variation in consumption, and environmental footprints, across different population segments is well researched across nations, including the UK (Minx *et al.*, 2013) and Spain (Arce *et al*., 2017); between cities all over the world (Moran, *et al.*, 2018), across the rural-urban divide in Germany (Gill & Moeller, 2018) and between social groups in the UK (Druckman and Jackson, 2009; Abdallah *et al.*, 2011; Büchs and Schnepf, 2013; Owen and Barrett, 2020). Beyond footprint studies across space, other studies which focus on energy consumption in specific local areas of developed countries tend to focus on instances of fuel poverty and energy justice (Love and Garwood, 2011; Mccauley *et al*., 2013; Jenkins *et al.*, 2016; Bailey and Darkal, 2018).

However, the quantification of a consumption-based account of household ESDs at a LA-level in the UK would allow a deeper insight into how energy is used in different areas of the country, allowing the identification of areas of overconsumption and low consumption (Minx *et al.*, 2013). Framing EDR through an energy service lens at a LA-level will also offer a method of linking household consumption at a LA-level to the globalised energy system, and allow an examination of whether universal EDR strategies have the same effect upon different segments of the UK population without compromising the wellbeing of households. Analysing ESD data and EDR data in the context of capacity index (CI) scores of households would also offer an insight into whether universal EDR strategies could compromise the wellbeing of households.

Combining the ESD, EDR and CI elements of LAs into an overarching analysis of universal EDR strategies would allow an insight into whether universal EDR strategies reduce energy consumption in LAs exhibiting higher levels of ESDs, and also reduce energy consumption to a greater extent in LAs where households have a greater capacity to adopt EDR strategies. If these elements do not align, then the concept of subsidiarity, and localised demand-side action, needs to be utilised more in the demand-side transition in the UK.

Embodied energy must be included in ESD calculations to ensure the full scope of energy required to fulfil household wellbeing is considered in an EDR modelling study. Actively considering embodied energy would broaden the scope of EDR to energy services which are not demanded directly from the energy system, and offer a greater number of opportunities for households to reduce energy demand associated directly with UK energy consumption, and indirectly, with the supply chain providing households with products and services (Ivanova *et al.*, 2020).

The aims and research questions in Section 1.2 will address these research gaps to establish whether adopting an energy services approach to EDR would be beneficial towards the UK's mitigation goals. The aim and research questions of the thesis will be set out in the next section.

1.2 Aims and Research Questions

Based upon the scale of the task facing the UK government to implement large-scale reductions in energy demand to meet its net-zero obligations towards the Paris Agreement's 1.5°C temperature goal, **this thesis aims to assess the variation in energy service demands of households at a local authority level across Great Britain, and the potential of a nationally-led approach to energy demand reduction to establish whether a disaggregated approach to energy demand reduction could benefit demand-side action for different energy service demands in Great Britain**. The thesis will achieve this aim by examining the following research questions.

1.2.1 Research Question #1

How can the full energy system be framed from a local authority level using an energy services perspective?

The first research question addresses the framing of the energy system at a LA-level. Chapter 4 of the thesis sets out a framework designed to have both theoretical and practical application when considering EDR at a LA-level. Establishing an LA-level perspective is fundamentally important for the subsequent chapters of the thesis. If the energy system and EDR cannot be examined from a LA perspective, then undertaking further analyses using this approach would not be productive. Research question #1 is answered in Chapter 4 of thesis.

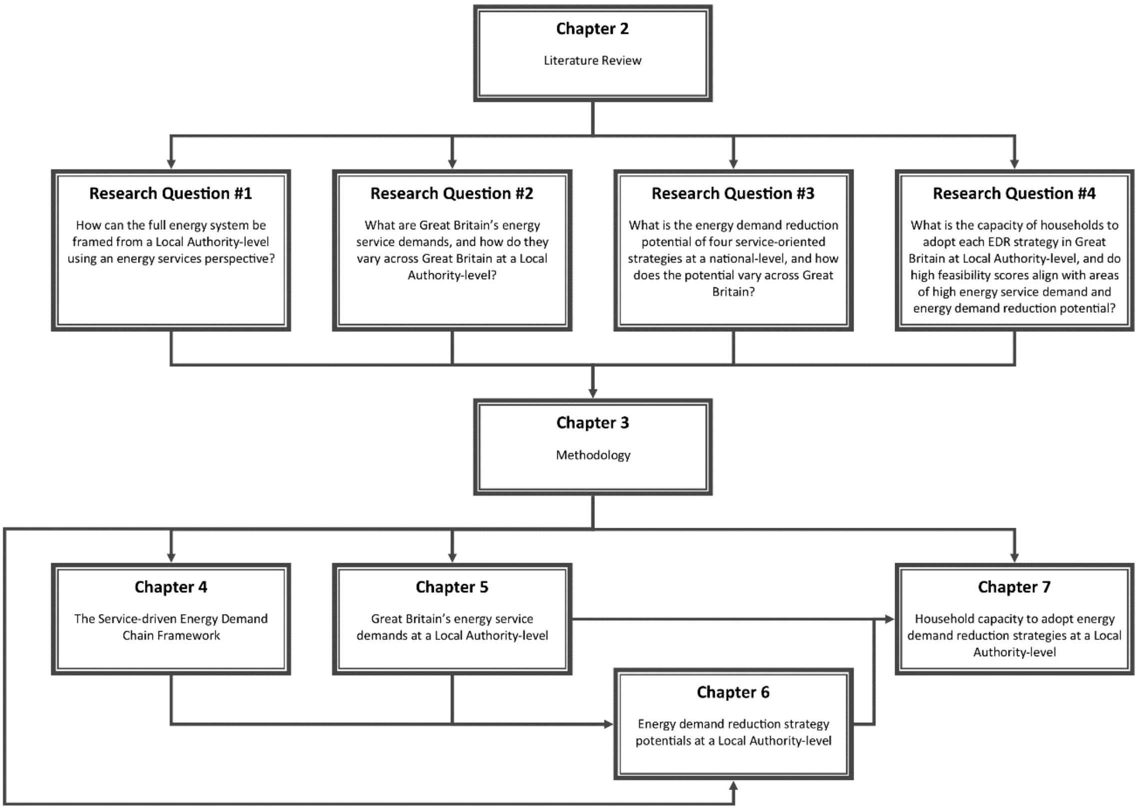

Figure 1.8 Diagram showing the linkages between the research questions set out in Section 1.2 and the different sections of the thesis.

1.2.2 Research Question #2

What are Great Britain's energy service demands, and how do they vary across Great Britain at a local authority level?

Research question #2 addresses the scarcity of LA-level ESD data available for Great Britain (GB). The disaggregation of the national-level energy footprint to examine LA variation has been limited to GB, rather than the UK, as LAs in Northern Ireland are purely administrative, and do not possess any power to define and implement policies which could reduce household energy demand, therefore considering policy at a LA-level in Northern Ireland is redundant. The term GB rather than the UK will therefore be used to refer to results from across England, Scotland and Wales, as the term is synonymous with these countries. In reality, the region of GB also includes the crown dependencies of Guernsey, Jersey and the Isle of Man, however, as the crown dependencies are self-governing, and not located within the territorial boundaries of the England, Scotland or Wales, the term GB will not include these islands within this study[4].

At present, BEIS produces LA-level data on direct energy consumption by fuel at a LA-level, but does not set out how the energy from each fuel is utilised from different energy services across each LA (BEIS, 2021d). Without data on energy service consumption across GB, a LA-level approach to EDR focusing upon EDR for different ESDs cannot be considered. Additionally, neglecting indirect energy embodied in products and services at the LA-level reduces the potential number of EDR options that can be considered in this thesis.

Research Question #2 aims to generate and examine a LA-level, consumption-based energy service dataset for GB, using the Living Costs and Food survey (LCFS) from 2015/16, 2016/17 and 2017/18, to better understand GB's ESDs across space. Research question #2 is answered in Chapter 5 of thesis and is used as a baseline in Chapter 6 of the thesis.

1.2.3 Research Question #3

What is the energy demand reduction potential of four service-oriented strategies at a national-level, and how does the energy demand reduction potential vary across Great Britain?

Research question #3 assesses the potential of four different EDR strategies upon GB's ESDs[5]. The four EDR strategies are an energy efficiency strategy, a maintained service level (MSL) strategy, a reduced service level (RSL) strategy and a full consideration (FC) strategy. Considering the EDR potential of the energy services approach is important as effective EDR is necessary if the UK is to meet its net-zero targets for a 1.5°C future. The results from the energy efficiency, MSL, RSL and FC strategies will be compared at a national-level initially to establish the EDR potential of going beyond energy efficiency measures in GB.

The variation in EDR potential of each strategy at a LA-level across GB will subsequently be considered alongside the average EDR potential of the respective strategy being analysed. Considering the variation of the potential of each EDR strategy is important to understand whether

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[4] Despite referring to GB in the results chapters of the thesis (Chapters 4 to 7), the national-level policies discussed in Chapter 2 will still be discussed in the context of the UK and the UK government as the national-level energy policy, which applies to England, Scotland and Wales is set out by the UK Parliament in Westminster in London.

[5] As the results generated for Research Question #2 focus upon GB, the results used to answer Research Question #3 will also focus upon GB.

a disaggregated, localised approach would be beneficial for different ESDs and accelerating the transition to a low energy demand society.

Research question #3 will be answered in Chapter 6 using a modelling approach devised by Wood *et al.*, (2018). The ESD values generated and examined in Chapter 5 will be used as a present-day baseline from which the strategies will be modelled upon.

1.2.4 Research Question #4

What is the capacity of households to adopt each energy demand reduction strategy in Great Britain at local authority level, and do high capacity index scores align with local authorities exhibiting high levels of energy service demands and energy demand reduction potential?

Research question #4 will consider the capacity of each LA to adopt the four EDR strategies modelled in Chapter 6, and analyse whether LAs with high levels of capacity to adopt EDR measures align with areas of high ESDs and large EDR potential, modelled in Chapter 5 and Chapter 6 respectively[6]. Considering the capacity of households within LAs to adopt EDR strategies is important to ensure that the demand-side transition is just and does not compromise wellbeing of households.

EDR requires a broad range of actors to devise and deliver EDR strategies (Sorrell, 2015). Placing too much onus on a single actor or set of actors may lead to the EDR potential of different strategies not being realised (Geels *et al.*, 2018). The demand-side transition will therefore require actors beyond households to bring about significant levels of EDR in the future. However, the capacity of households is only considered in Chapter 7 to assess whether a single, national-level approach to EDR could compromise the wellbeing of households in different LAs throughout GB.

Research question #4 will be considered in Chapter 7 of the thesis. Research question #4 draws the final elements of the thesis together to provide final analyses of the potential of a disaggregated approach to EDR from a LA-level services perspective.

1.3 Thesis Structure

The remainder of the thesis comprises of Chapter 2 to 9, with appendices. Chapter 2 forms a literature review which examines EDR and its importance in climate change mitigation. Chapter 2 will also examine the framing of ESDs in frameworks, models and the categories utilised by these two areas. Following this, different footprinting methodologies will be set out and the best method identified before finally examining UK EDR policy and EDR at a LA-level.

[6] As with Research Question #2 and Research Question #3, Research Question #4 will focus upon GB.

Chapter 3 focuses on the data and methodological aspects of the thesis. The core method underpinning the generation of consumption-based ESD accounts for the UK, input-output (IO) modelling and multi-regional input-output modelling (MRIO), are set out in Chapter 3. In addition to IO and MRIO, Chapter 3 will also explore how a UK-based social survey, the LCFS, will be utilised to generate consumption-based ESD accounts for LAs throughout GB. Finally, the equations underlying the modelling methodology in Chapter 6 will be set out, as will the method underpinning the CI analysis in Chapter 7.

Chapters 4 to 7 focus upon the results of the project. Chapter 4 sets out a framework for examining EDR options at different stages of the energy system from an energy services perspective at a LA-level. Following this, Chapter 5 quantifies different ten different ESD categories using IO modelling. The first section of Chapter 5 examines the aggregated national-level ESD footprints for GB, before examining each energy service category across space at a LA-level for GB. Finally, the last section of Chapter 5 use correlation and regression analyses to examine whether the underlying socioeconomic factors identified as drivers of energy consumption by previous studies, also exhibit the same relationship with the aggregated LA-level ESD footprints.

In Chapter 6, four EDR strategies are modelled. Section 6.1 examines the EDR potential of each strategy at a national-level to assess whether each strategy is capable of delivering the level of EDR required to meet the global 1.5°C target. Following this, Section 6.2 examines the LA-level variation of each EDR strategy to understand the expected levels of EDR across different areas of GB under a nationally-led approach. Chapter 7 will subsequently examine the capacity of households within each LA to adopt the EDR strategies modelled in Chapter 6 (Section 7.1). Following this, the VI scores will be analysed alongside the ESD data generated in Chapter 5 and the EDR data modelled in Chapter 6 to establish whether areas scoring highly in household capacity are also modelled to have high, present-day, ESD levels and high levels of EDR potential.

Chapter 8 assesses the research undertaken in this thesis in the context of other studies, and identifies how the research in Chapters 4 to 7 differs from, and builds upon existing research. Chapter 9 draws the thesis together to assess whether the aim of this project has been achieved and identifies the contribution this work has made to the knowledge base in the ESD and EDR spheres through recommendations for further research. Additionally, Chapter 9 will highlight the limitations of the project.

1.4 Thesis Novelty

The thesis aim and research questions have been devised to address four research gaps, identified in Chapter 1 and Chapter 2, and contribute towards knowledge in the ESD and EDR space in the UK and beyond. Firstly, research question #1 addresses a theoretical research gap by setting out a services-oriented framework of the energy system from a LA perspective. Presently, energy system frameworks, models, EDR studies and energy policies recognise that energy services are the reason that energy is demanded from the energy system by households. However, a framework which places ESDs at the forefront of an energy system framework, and demonstrates the effect local-level actions could have upon the energy system has yet to be set out. Designing a service-oriented framework from a LA perspective will offer an alternative perspective of the energy system, and aim to reframe EDR away from energy efficiency by focusing less upon the stages of delivering direct energy to households.

Secondly, research question #2 addresses two research gaps: a knowledge gap, whereby the research findings did not previously exist, and a population gap, whereby the data generated in Chapter 5 is under-represented in prior research and statistics. At present, government-produced LA data for household ESDs is limited, and while previous studies have examined per capita environmental footprints across space (Minx *et al.*, 2013), and household ESDs for different income deciles (Owen and Barrett, 2020), a comprehensive dataset of household ESDs for each LA has yet to be modelled for GB. Modelling the ESDs of different LAs throughout GB provide greater information on household ESDs in GB, and will allow an examination of the variation in each LA's per capita ESDs to identify areas of high and low energy consumption throughout GB.

Thirdly, two research gaps are also addressed by research question #3, with a methodological gap and a knowledge gap addressed in Chapter 6. The methodological gap focuses upon the methodology set out by Wood *et al.*, (2018). The methodology is not new to this thesis, having previously been used in a demonstrative example by Wood *et al.*, (2018), however, to my knowledge, the IO methodology has not yet been used to model EDR at a local-level, or across space, thereby demonstrating the ability of the IO methodology to be used by LAs. Additionally, the results generated using the IO methodology from Wood *et al.*, (2018) will demonstrate the variation in EDR potential at a LA-level. Understanding whether the potential of different EDR strategies varies across different areas of GB, will establish whether a disaggregated, locally specific policy approach to EDR may be more beneficial than a nationally-led approach for different household ESDs.

Finally, research question #4 addresses an empirical research gap associated with the results generated in Chapter 5 and Chapter 6. Assessing the capacity of localities has been undertaken upon different segments of the population in the past (Robinson and Mattioli, 2020). However, specifically considering the capacity of households in GB will allow an insight into whether areas of high ESDs, high EDR and high capacity correlate. Conducting the CI analysis will allow a deeper insight into the variation of ESDs and EDR potential across space in GB, and help to assess whether a disaggregated, locally-specific approach to EDR would be appropriate for different ESDs in GB.

2 Literature Review: An energy demand framing review

This review will build upon the initial project rationale set out in Chapter 1. Chapter 2 will explore existing literature on energy demand, energy demand reduction (EDR) at national and local-levels and energy service demands (ESDs) to analyse the framing of the demand-side of the energy system by researchers in academic literature, and policymakers, in the UK. Alongside the framing of energy demand, the calculation and modelling methods used on the demand-side of the energy system in the UK will also be examined. Examining each of these aspects will give a complete overview of current thinking on the demand-side of the energy system, and allow research gaps to be identified which build upon current demand-side research, and facilitate effective EDR for the transition towards a net-zero society.

To undertake a full analysis of energy demand and EDR, Chapter 2 will be split down into four sections focusing on different aspects of the issues raised in the thesis introduction. Section 2.1 focuses upon the framing of energy demand within academic literature and UK policy to identify the dominant demand-side discourse. The governance of the UK energy demand will subsequently be analysed in Section 2.2. Section 2.2 will comment upon the UK's multi-level governance structure before analysing the energy governance. The variation in ambition at different levels of the UK's governance structure will also be considered, with reference to the concept of subsidiarity.

Section 2.3 will undertake an analysis of ESDs and their representation in academic literature and policy. The review in Section 2.3 will focus upon the framing of ESDs by examining their definitions, their representation in energy system frameworks, and the categorisation of ESDs across different studies, papers and policy.

Subsequently, Section 2.4 builds upon Section 2.1 and Section 2.3 by examining the methodologies used to generate ESD figures. The models used to design UK policy will be examined, as will energy footprinting. The UK uses a mix of model types – e.g. econometric models, energy system models, policy models, etc. – while energy footprints have become a common method to calculate energy consumption at different scales. The benefits and disadvantages of each accounting method will also be considered in Section 2.4.

Finally, at the end of the literature review, there will be a short section which draws together the main points of the literature and re-establishes any research gaps. From this the remaining roadmap of the thesis will be set-out. Table 2.1 shows how each section of the literature review maps to the research chapters of the PhD thesis.

Table 2.1 Mapping table of literature review sections to PhD thesis chapters.

Literature review section	PhD chapter mapping
Section 2.1: Energy demand framing review	**Chapter 4**: The service-driven energy demand chain framework **Chapter 5**: Great Britain's energy service demands at a Local Authority-level **Chapter 6**: Energy demand reduction strategies at a Local Authority-level **Chapter 7**: Household capacity to adopt energy demand reduction strategies at a Local Authority-Level
Section 2.2: UK energy policy and governance	**Chapter 4**: The service-driven energy demand chain framework **Chapter 5**: Great Britain's energy service demands at a Local Authority-level **Chapter 6**: Energy demand reduction strategies at a Local Authority-level **Chapter 7**: Household capacity to adopt energy demand reduction strategies at a Local Authority-Level
Section 2.3: Energy service demand framing	**Chapter 4**: The service-driven energy demand chain framework **Chapter 5**: Great Britain's energy service demands at a Local Authority-level **Chapter 6**: Energy demand reduction strategies at a Local Authority-level
Section 2.4: Modelling energy service demands	**Chapter 5**: Great Britain's energy service demands at a Local Authority-level **Chapter 6**: Energy demand reduction strategies at a Local Authority-level

2.1 Energy demand framing review

Section 2.1 examines the framing of energy demand in different contexts (Figure 2.1). Energy is demanded for a wide variety of services across different sectors, however, for households, energy is demanded predominantly to achieve wellbeing (Le Gallic *et al*., 2017; Brand-Correa *et al*., 2018; Kalt *et al.*, 2019). Current levels of energy demand are however unsustainable if the UK wishes to transition to a net-zero society (BEIS, 2021c; IEA, 2022b).

The relationship between EDR and climate change mitigation will therefore be considered (Section 2.1.1), before analysing the dominant framing of the relationship (Section 2.1.1) – energy efficiency – alongside the relationship between energy demand and wellbeing (Section 2.1.2), after which the link between energy demand and wellbeing will be examined – ESDs. The limitations of the current energy discourses will then be summarised (Section 2.1.3).

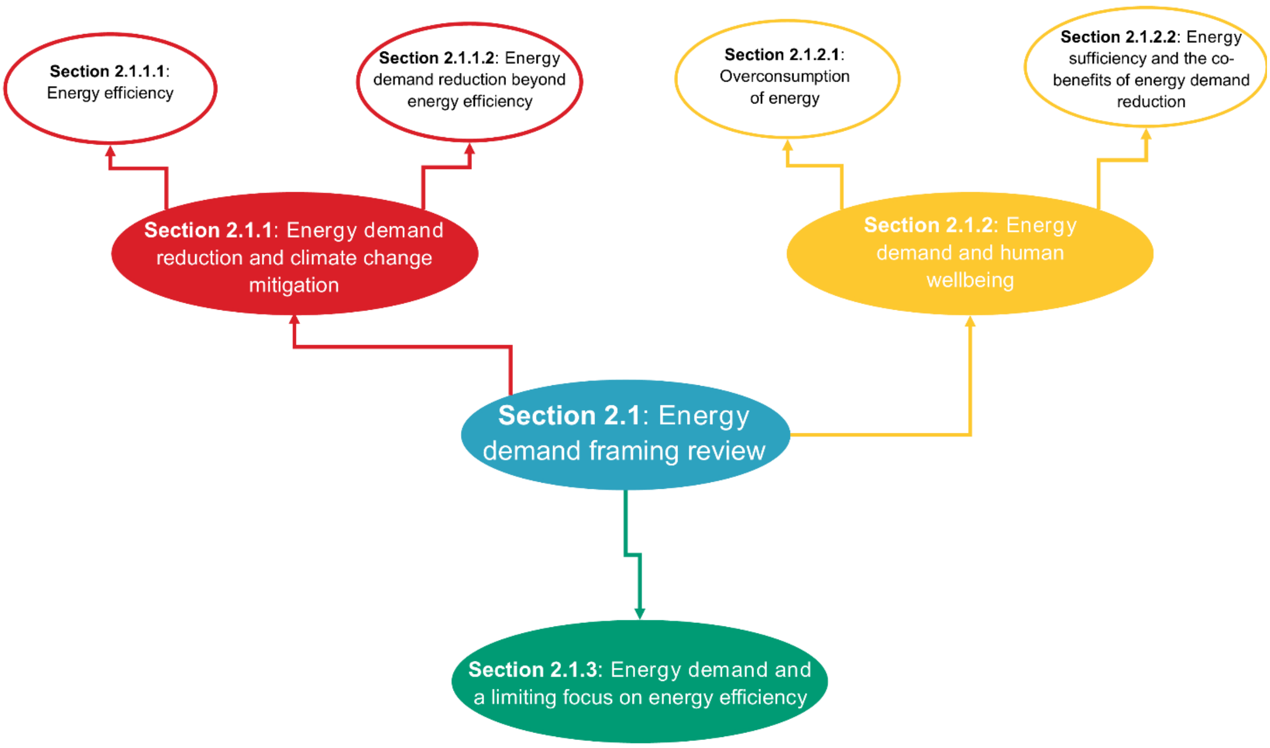

Figure 2.1 Section 2.1 sub-sections bubble diagram.

2.1.1 Energy demand reduction and climate change mitigation

EDR is essential to successful emission reduction, climate change mitigation and the realisation of the Paris Agreement's long-term temperature goals for the 21st century (Grubler *et al.*, 2018; Masson-Delmotte *et al.*, 2018; Fawzy *et al.*, 2020; BEIS, 2021c; Barrett *et al.*, 2022; Scott *et al.*, 2022). As stated in Section 1.1.1, EDR allows future energy-related emissions to be avoided, while also reducing the burden of the energy system to meet high levels of household demand and reducing the reliance upon negative emission technologies to meet long-term climate targets (Anderson and Peters, 2016; Grubler *et al.*, 2018; Kriegler *et al.*, 2018). A transition towards a net-zero society is therefore difficult without EDR (Masson-Delmotte *et al.*, 2018).

Future net-zero scenarios examining the energy transition which do not simulate reduced or stabilised energy demand assume some level of fossil fuel generated energy supply remains, but this is counteracted through the increase of greenhouse gas (GHG) removal to offset the remaining carbon emissions from high energy demand (Anderson and Peters, 2016; Cox *et al.*, 2018; McGlade *et al.*, 2018). The current rates of GHG removal however means that it is unlikely to be able to negate continually rising demand before the 1.5°C climate target is breached (McGlade *et al.*, 2018; Waller *et al.*, 2020).

Mitigation efforts in developed countries, such as the UK, have predominantly focused on supply-side fuel switching from fossil fuels to renewable energy resources and the implementation of energy efficiency options to reduce energy demand (Lees and Eyre, 2021). UK supply-side decarbonisation has been successful thus far with territorial GHG emissions dropping by 44.4% between 1990 and 2019 (Figure 1.6), and renewable energy generation increasing 23-fold from 5,812GWh to 134,741GWh in the same time period (BEIS, 2022b; DUKES, 2022b). However, Figure 1.6 shows that UK final energy consumption has not been reduced over the same time period despite improvements in energy efficiency (Hardt *et al.*, 2017; ECUK, 2022).

2.1.1.1 Energy efficiency

Energy efficiency has been popularised as the demand-side strategy that will reduce energy demand to a level at which it can be produced by renewable energy technologies (Sorrell, 2015; Shove, 2018). Energy efficiency remains a popular EDR policy option due to its limited effect upon each household's lifestyle practices and behaviours (Mallaburn and Eyre, 2014; Shove, 2018). However, as stated in Section 1.1.2, there are concerns that the rebound effect and technical potential of energy efficiency may not provide the EDR necessary for a 1.5°C future (Brockway *et al.*, 2017; Shove, 2018).

The term 'efficiency' is no longer solely associated with machinery and processes and is used across political, managerial, economic and engineering spheres, and is interpreted in different ways across each sphere (Sorrell, 2007; Shove, 2018). In some aspects, definitions of efficiency can be precise, for example, when considering the conversion rates of boilers and heat pumps, whereas, in a business context, the definition of efficient practice can vary from business to business (Sorrell, 2007; Shove, 2018).

Energy efficiency as a form of EDR can be seen as simplistic and inherently unequipped to deal with issues such as excess consumption as it plays into preconceived notions that EDR can be solved through technological solutions without the need for any form of lifestyle changes (Shove, 2018). Energy efficiency has dominated understandings of EDR since the 1970s and bypasses questions regarding why energy is demanded, what energy is demanded for, and how we live our lives (Shove, 2018; Lees and Eyre, 2021). For example, in the energy sector, energy efficiency policy is closely associated with improvements in the systems and devices that deliver ESDs to households, such as shifting to battery-electric vehicles (BEVs) or insulating houses, but this does not address excessive heating and transport demand by households (Creutzig *et al.*, 2018).

Energy efficiency improvements are expected to bring benefits to households and are expected to out-perform previous iterations of the same systems and devices (Sorrell, 2007; IEA, 2014; Shove, 2018). These benefits are quantifiable and can be modelled which therefore sets the boundary of the energy efficiency discourse at the boundary of the quantifiable energy system (Sorrell, 2007). It is mostly accepted that energy efficiency refers to the technical gains that will contribute towards

EDR, therefore energy efficiency policy is limited to technical solutions either through thermodynamic efficiency improvements of technology switching (Sorrell, 2015).

Fawcett and Rosenow (2017) wrote a response to Shove (2018) arguing that by criticising energy efficiency and examining the limits of the discourse is damaging as the policy option, and the demand-side of the energy system, is not mainstream in the policy sector. However, energy efficiency policies form a core part of the UK's current climate change mitigation plan. For example, two of the government's recent flagship energy policies were the Green Deal and the Green Homes Grant (Rosenow and Eyre, 2016; BEIS, 2021a). The Green Deal and the Green Homes Grant focused heavily on EDR through energy efficiency, but weren't particularly successful (Mallaburn and Eyre, 2014; Rosenow and Eyre, 2016; BEIS, 2021a). Additionally, the Clean Growth Strategy and the Green Industrial Revolution policy papers both refer heavily to energy efficiency, while the UK's 2019 National Energy and Climate Plan (NECP) contains the goal of 'improving energy efficiency' as one of its five core aims (BEIS, 2019, 2020b, 2021a).

Despite the limits of the energy efficiency discourse, energy efficiency should not be discounted completely (Fawcett *et al*., 2019). Energy efficiency is now synonymous with EDR which limits progress on reducing the demand-side of the energy system in line with the levels necessary for a 1.5°C future, however, it will be an essential part of the policy mix during the transition towards a low energy society (Creutzig *et al.*, 2018; Grubler *et al.*, 2018). The limits of energy efficiency to reduce emissions and energy demand to the level required for a 1.5°C future means that implementing effective EDR policies which go beyond technology improvements are vital for the future achievement of the Paris Agreement's long-term climate goals (Creutzig *et al.*, 2016, 2018; Barrett *et al.*, 2022).

2.1.1.2 Energy demand reduction beyond energy efficiency

The Avoid-Shift-Improve (ASI) framework, set out by Creutzig *et al.*, (2018) is built on three pillars of avoiding energy demand, shifting energy demand to a less energy intensive alternative method of meeting needs, and improving the systems that deliver energy to households to make them more efficient (Table 1.1). Energy efficiency is commonly associated with the improve pillar of the ASI framework – despite arguments that the discourse can refer to every area of the ASI framework – (Creutzig *et al.*, 2018). The energy efficiency discourse can therefore not be used to identify options which avoid energy demand or shift energy demand to a less energy intensive alternative and also reinforces narratives of technological solutions to reducing energy demand (Shove, 2018).

The UK government understands that demand-side mitigation must go beyond energy efficiency. For example, the UK's net-zero energy strategy makes reference to increasing cycling and walking as part of its plan to transition to a net-zero transport system (BEIS, 2021c). Cycling would shift transport ESDs to a less intensive form of transport, while walking would avoid emissions and energy demand for transport entirely (Creutzig *et al.*, 2018).

However, the Climate Change Committee's (CCC's) independent analysis of the UK's net-zero strategy states that addressing household behaviour and encouraging shifting or avoiding demand for ESDs is not considered enough in the net-zero strategy (CCC, 2021). This is particularly evident when considering shifts in household dietary habits (CCC, 2021). There is therefore definitely scope for more demand-side action in the UK which will allow decarbonisation to happen faster (CCC, 2021).

Policymakers are often less keen to promote EDR strategies which go beyond technological solutions, despite their cost-effectiveness, as such policies involve lifestyle shifts and are perceived to be unpopular amongst voters (Shove and Walker, 2014). However, the sustained increase in commuters cycling to work – rather than driving – and working from home – rather than commuting at all – since the COVID-19 pandemic, demonstrate that lifestyle shifts which reduce energy demand are not necessarily unpopular.

2.1.2 Energy demand and human wellbeing

Political hesitancy surrounding EDR beyond energy efficiency can also be attributed to the tight coupling between household ESDs and wellbeing (Brand Correa *et al.,* 2018). ESDs are vital to achieve the basic human needs, and therefore the wellbeing, of households, meaning that EDR options which reduce the level (avoid), or change the nature of the service (shift), received by households are sometimes viewed as having a negative impact upon people's lives (Brand-Correa *et al*., 2018). However, numerous studies have demonstrated that ESDs and wellbeing are not directly coupled, particularly in developed countries, such as the UK, meaning that a reduction in household ESD levels does not necessarily lead to a reduction in household wellbeing (Steinberger and Roberts, 2010).

Energy demand also drives economic growth which increases the wealth of households, therefore, in theory, allowing them to spend more on ESDs, increasing wellbeing, and allowing further economic growth (Brand-Correa *et al*., 2018; Sakai *et al.*, 2018). The concerns that a reduction in ESDs will result in a reduction in wellbeing therefore comes from the theory that reduced ESDs lead to slowed economic growth which causes a reduction in the quality of life of households (Jackson, 2019). Such concerns have popularised the energy efficiency discourse and, alongside global capitalism, have perpetuated the idea of limitless economic growth and ever-increasing ESDs as essential for human wellbeing (Brand Correa and Steinberger, 2016; Brand-Correa and Steinberger, 2017; Johnsen *et al.*, 2017).

However, as stated previously, ESDs and wellbeing are not directly coupled after a certain level of ESDs are received by households, with diminishing increases in wellbeing for the increased level of consumed ESDs (Steinberger and Roberts, 2010; Millward-Hopkins *et al.*, 2020). Attempting to achieve ever-increasing energy demand and perpetual economic growth therefore leads to overconsumption of resources, and is not in line with the concepts of sustainability and the 1.5°C long-term climate target set out in the Paris Agreement (Foxon and Steinberger, 2013; Jackson, 2019; Hickel *et al.*, 2021).

2.1.2.1 Overconsumption of energy and wellbeing

Infinite growth in energy demand on a planet with finite resources is considered impossible (Jackson, 2019). The limits to growth and energy consumption are highlighted by the concept of planetary boundaries (Figure 2.2) (Raworth, 2012). The concept of planetary boundaries defines quantifiable sustainable thresholds for the tipping points of different biochemical and physical processes which are required to fulfil human needs and achieve wellbeing (Raworth, 2012; O'Neill *et al.*, 2018). Planetary boundaries were set out by Rockström *et al.*, (2009) and further developed by Raworth (2012) and Steffen *et al.*, (2015) (Figure 2.2).

The planetary boundaries theory ensures that basic needs are met (the inner boundary) without exceeding the limits of the planet's biological and physical ecosystems (the outer boundary) (Figure 2.2) (Rockström *et al.*, 2009; Raworth, 2012; Steffen *et al.*, 2015; O'Neill *et al.*, 2018; Hickel, 2019). Exceeding the limits of the outer boundary is considered overconsumption (Rockström *et al.*, 2009; Raworth, 2012; Hickel, 2019). Energy consumption is not one of the planetary boundaries set out in Rockström *et al.*, (2009), or used in subsequent papers, such as Steffen *et al.*, (2015), Hickel, (2019) and Rockström *et al.*, 2021), however it is one of the eleven social foundations required for sustainable development, and contributes towards the climate change planetary boundary (Figure 2.2).

The concept of planetary boundaries can be used to demonstrate the relationship between energy consumption and wellbeing, and the issue of overconsumption of energy. Consumption of energy is a social foundation required for households to exist in the safe operating space for humanity (Figure 2.2) (Raworth, 2012). The energy consumption required for households to exist in this space is important for wellbeing (Rockström *et al.*, 2009; Raworth, 2012; Steffen *et al.*, 2015). However, continued energy consumption leads to an overconsumption of energy, which breaches the 'environmental ceiling' of the climate change boundary in Figure 2.2, which can lead to ecological breakdown of the planet (Rockström *et al.*, 2009; Steffen *et al.*, 2015).

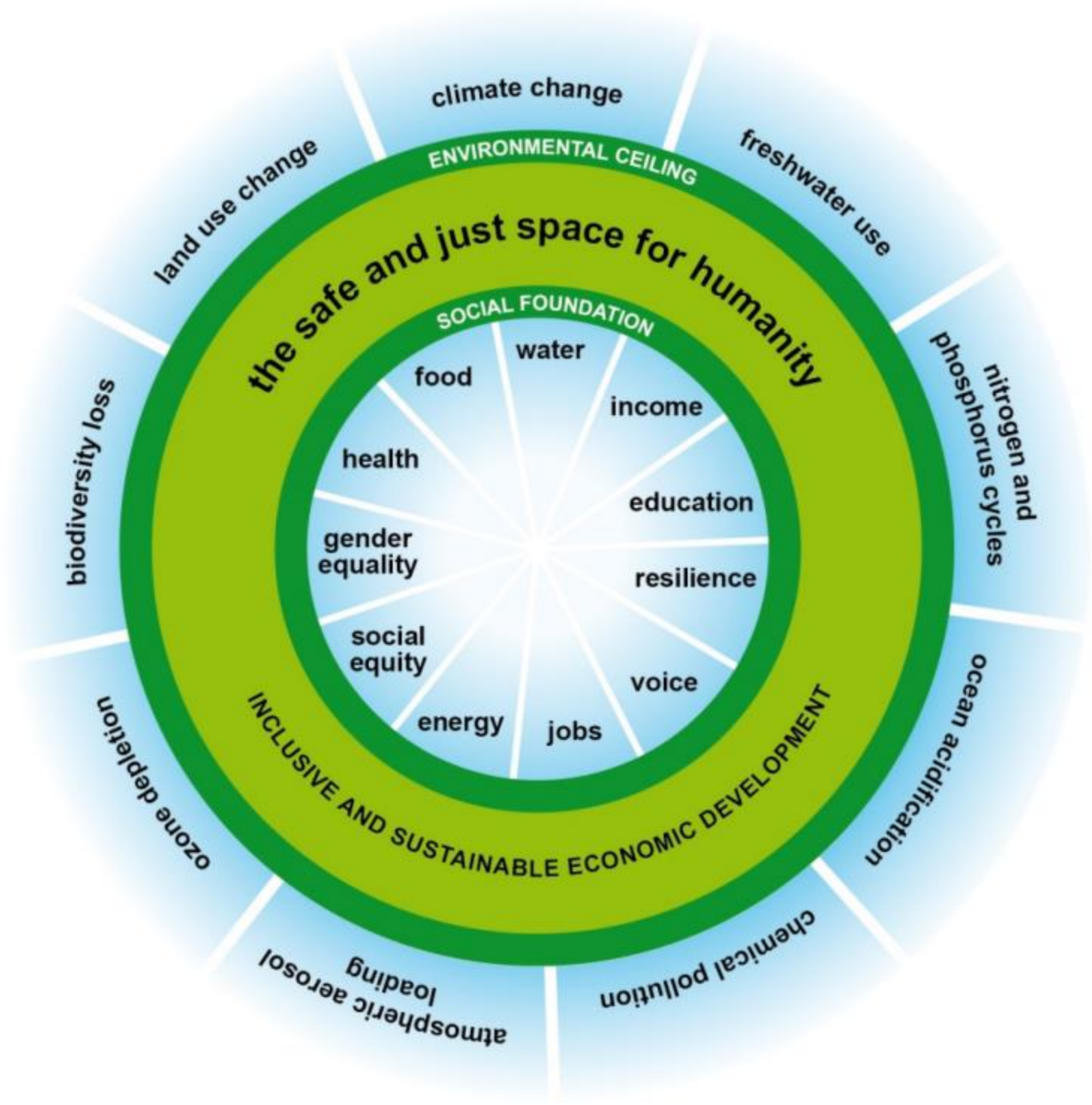

Figure 2.2 The nine planetary boundaries and the eleven dimensions needed for social foundation (Source: Raworth, 2012).

In developed countries, such as the UK, excess energy consumption is causing the 'environmental ceiling' of climate change planetary boundary to be breached[7] (Figure 2.2) (Sorrell *et al*., 2020). Energy consumption can therefore be reduced without compromising one of the core social foundations of the UK. It is this space that the UK government needs to exploit, alongside shifting energy demand to less energy intensive behaviours and practices (Creutzig *et al.*, 2018; CCC, 2021).

[7] Energy demand varies across society with the most affluent households having the highest, unsustainable, levels of energy consumption. The level of average UK energy consumption is therefore being considered here as, while the UK, on average, has high levels of energy consumption, there are areas of the UK which are in fuel poverty, whereby increasing energy consumption may improve wellbeing. The nuances of energy consumption across space will be discussed in Section 2.4.

However, two of the UK's core aims are incompatible at present. The current political discourses in the UK for economic growth and climate change assume that economic growth has no limits, while the climate change discourse is attempting to reduce the UK's consumption of natural resources through decarbonisation (Raworth, 2012; Jackson, 2019; BEIS, 2021c).

Acknowledging the limits of achieving wellbeing through economic growth is therefore important in addressing overconsumption of energy (Jackson, 2019). Moving beyond this discourse allows EDR options which avoid energy consumption, and the concept of energy sufficiency, to be considered by policymakers (Toulouse *et al.*, 2017; Johnsen *et al.*, 2017; O'Neill *et al.*, 2018).

2.1.2.2 Energy sufficiency and the co-benefits of energy demand reduction

Energy sufficiency is a concept which aligns with the planetary boundaries theory (Daly, 1991; Rockström *et al.*, 2009). Energy sufficiency defines a level of energy consumption that allows households to operate in the safe operating space for humanity (Daly, 1991; Sachs, 1993; Princen, 2005). Energy consumption at a sufficient level maximises wellbeing – before overconsumption leads to diminishing increases of wellbeing with increased energy consumption – and equity without exceeding environmental limits (Sorrell *et al*., 2020). The concept of energy sufficiency is not universally defined but is being increasingly explored since being set out by Daly (1991) and Sachs (1993), and expanded upon by Princen (2005).

Energy sufficiency runs contrary to theories of capitalism which places emphasis on increased wellbeing through increased consumption (Toulouse *et al.*, 2017; Sorrell *et al*., 2020). However, it promotes a method of thinking that promotes shifts towards new social norms that use less energy as opposed to implementing efficiency measures (Toulouse *et al.*, 2017). It is estimated that promoting energy sufficiency and building policy around such a concept could reduce energy demand in France by between 14% and 39% by 2050 (Toulouse *et al.*, 2017). The upper limit of the Toulouse *et al.*, (2017) estimate is comparable to the level of EDR required globally without the need for GHG removal (Masson-Delmotte *et al.*, 2018).

However, as with energy efficiency, energy sufficiency can also suffer from rebound effects (Sorrell *et al*., 2020). Firstly, from households spending money saved through energy sufficiency on other products and services (Sorrell *et al*., 2020). Secondly from 'spill-overs' whereby households believe they have 'done their bit' for the environment so they begin spending more time and money on energy-intensive activities – e.g. It may be used to justify an additional holiday abroad per year (Sorrell *et al*., 2020). Finally, time-use rebounds can occur, whereby households spend more time on activities that are energy intensive (Sorrell *et al*., 2020).

Sorrell *et* al., (2020) conclude that EDR made through actions which promote energy sufficient behaviours have a limited effect on national-level accounts of energy use and emissions due to the rebound effect. However, sufficiency is yet to be considered as a realistic macro policy option at present and is instead largely discussed at a micro-level with regards to individual consumption, therefore shifting and avoiding energy demand should not be discounted (Zell-Ziegler *et al.*, 2021).

Energy sufficiency and reducing energy consumption can also have benefits beyond EDR in the form of co-benefits (Ürge-Vorsatz *et al.*, 2014). Co-benefits improve the wellbeing of households as a result of lifestyle changes from shifting energy consumption to less energy intensive practices or avoiding energy consumption altogether (Creutzig *et al.*, 2018). For example, shifting transport habits from car transport to cycling can have health benefits through increased exercise, and air pollution reduction, as well as financial benefits from less expenditure on vehicle fuel. Similarly, avoiding food consumption through a food sufficiency diet can also lead to health and financial benefits. Through co-benefits from reducing or shifting energy service consumption, wellbeing of households can therefore actually be raised (Ürge-Vorsatz *et al.*, 2014).

Increased household ESDs bring about diminishing returns on wellbeing increases, whereas maintaining or reducing energy service levels using different EDR options can actually raise wellbeing, while also reducing environmental and energy system pressures (Toulouse *et al.*, 2017; Brand-Correa *et al*., 2018; Jackson, 2019). Although there are limits to the co-benefits associated with EDR for ESDs as reducing a household's ESDs to a level where household needs are no longer met, would be detrimental to household wellbeing (Brand-Correa *et al*., 2018).
However, despite the potential benefits of maintaining or reducing energy service levels using EDR options which do not focus upon energy efficiency, the current political discourse on EDR remains focused upon energy efficiency (BEIS, 2019, 2020b; CCC, 2021). The continued focus upon energy efficiency perpetuates current attitudes towards ever-increasing levels of household ESDs demanded from the energy system to improve wellbeing, and therefore ignores the potential individual and societal benefits that can be gained from reducing energy service consumption, such as health and financial benefits (Ürge-Vorsatz *et al.*, 2014). However, important consideration must be given to household capital when reducing ESDs without compromising wellbeing.

2.1.2.3 Households and the five type of capital model

The five capital model is a framework for examining the wellbeing of households through a capital lens, and is important for a sustainable society (Tinch *et al.*, 2015). The five capital model is used by researchers to assess societal vulnerability through determining capacity to act upon the threat of climate change (Tinch *et al.*, 2015). Capital and wellbeing are therefore tied closely together as an inability to adapt to climate change will reduce wellbeing over time (Mohanty and Tanton, 2012; Tinch *et al.*, 2015).

As stated previously, wellbeing is often assumed to rise with income, and therefore ESD increases, but is more complicated due to the number of factors which affect wellbeing other than income (Maack and Davidsdottir, 2015; Toulouse *et al.*, 2017; Brand-Correa *et al*., 2018; Jackson, 2019). Human wellbeing depends upon five different capital types – financial, human, physical (manufactured), natural and social capital (Maack and Davidsdottir, 2015). The five capital types are complementary, meaning that one is not a greater indicator, or driver, of wellbeing than the other types (Maack and Davidsdottir, 2015). Energy demand reduction must therefore be taken in the context of the five types of capital to avoid compromising wellbeing (Maack and Davidsdottir, 2015; Tinch *et al.*, 2015).

However, household capital, and each individual capital type, is complex (Pasteur and McQuistan, 2016). Many different underlying factors affect each capital type, and therefore how capital contributes to wellbeing (Pasteur and McQuistan, 2016). Additionally, capital contributions to wellbeing vary in different contexts, while, across different household contexts, different capital types are more sought after by consumers, and would be more beneficial to immediate wellbeing increases than others (Pasteur and McQuistan, 2016). For example, considering two households that have similar financial capital, but are located two different geographic contexts – e.g. dense urban vs. spare rural – an increase in physical capital through a new bus service would have a greater wellbeing effect upon the rural household, where public transport infrastructure is poor, than the urban household where public transport infrastructure is denser.

The five capitals models provides a useful lens through which to consider EDR alongside wellbeing, despite the five capital model often being used in a climate change adaptation context, rather than a climate change mitigation context (Tinch *et al.*, 2015). Households must be able to adapt to new technologies, behaviours and lifestyle practices when adopting EDR measures under the ASI framework (Creutzig *et al.*, 2018). Lower levels of household capital could therefore lead to household wellbeing being compromised when implementing EDR strategies (Mohanty and Tanton, 2012; Maack and Davidsdottir, 2015; Tinch *et al.*, 2015; Pasteur and McQuistan, 2016). For example, enforcing owners of owner-occupied housing to implement better thermal insulation to improve the level of energy consumption associated with heating ESDs could widely reduce household energy consumption, despite the potential rebound effect (Creutzig *et al.*, 2018; Ivanova *et al.*, 2020). However, if this policy is only enforced upon owner-occupied housing, tenants in rented accommodation may not benefit from the scheme, therefore consumers with less physical capital are not gaining the wellbeing improvements, or EDR benefits, that those with larger physical capital are from the policy.

The five types of capital model allows EDR studies to draw different dimensions of wellbeing into EDR studies, and examine both the wellbeing impacts of policies, as well as the underlying factors which affect variations in the ability of households to adopt EDR measures across different contexts (Mohanty and Tanton, 2012; Tinch *et al.*, 2015). Understanding that different levels of the five different types of capital both affects, and is affected by, the implementation of EDR strategies is an important consideration when planning an effective, just demand-side transition that goes beyond energy efficiency using measures from the ASI framework (Tinch *et al.*, 2015; Creutzig *et al.*, 2018).

2.1.3 Energy demand and a limiting focus on energy efficiency

Energy efficiency reinforces current narratives surrounding EDR, continued economic growth and energy consumption (Brockway *et al.*, 2017; Shove, 2018). Alternatively, considering a decrease in energy service consumption highlights the wellbeing co-benefits of reducing household ESDs, therefore offering the potential for EDR through avoiding energy use, safe in the knowledge that wellbeing has not been compromised (Brand-Correa *et al*., 2018; Zell-Ziegler *et al.*, 2021).

Energy efficiency alone is unlikely to deliver the level of EDR needed for the UK's net-zero strategy (Grubler *et al.*, 2018; Shove, 2018; Barrett *et al.*, 2022). However, considering ESDs may offer opportunities for increasing the level and scope of EDR in the UK by overcoming overconsumption of energy services, and shifting ESDs to less intensive practices which provide the same level of service (Creutzig *et al.*, 2018). Demonstrating that energy consumption can be reduced through technological shifts and behavioural changes without reducing the level of service received by households – and therefore wellbeing – may encourage and allow governments to explore a wider range of measures for EDR. The continued focus of academia and policy work upon energy efficiency may therefore be limiting the scope of EDR (Shove, 2018).

A simple literature search[8] demonstrates that the concept of "energy efficiency" dominates academic literature over the concept of "energy services". The annual number of "energy services" publications are relatively scarce compared to the number of "energy efficiency" publications as shown in Figure 2.3. Energy services papers only comprise an average of 5%/year of publications within the search's scope, whereas the number of energy efficiency publications make-up an average of 95%/year.

The annual number of publications shown in Figure 2.3 has increased partly due to an increasing number of academic papers being published in general. However, the focus on climate change mitigation since 1990 has likely been a driver of the high rate of growth for papers on energy-related topics. Despite the increase in climate change mitigation papers, 'energy efficiency' papers are presently growing at a faster rate than 'energy service' papers (21.7%/year vs. 14.4%/year from

[8] The literature search undertaken here was not a full systematic literature review, as Fell (2017) undertook a systematic review of the 'energy services' term. The analysis presented here simply demonstrates that energy efficiency papers dominate academic literature.

2010-2019). This is likely partly to do with energy efficiency being the dominant framing of EDR over this time period, and shows the continued dominance of this framing in the 2010s. The rate of growth of ‘energy service’ papers seems to be decreasing in the 2010s compared to the 1990s and 2000s (14.4%/year vs. 23.2%/year), however the high percentage changes over this time period are due to the low number of papers being published (Figure 2.3).

A similar search of the UK’s net-zero strategy shows 101 instances of ‘energy efficiency’ being mentioned in the 368 page document (BEIS, 2021c). Whereas only 3 instances of ‘energy service’ were mentioned in the same strategy, with only one of the instances being mentioned in a context unrelated to the strategy methodology (BEIS, 2021c). Similarly in the CCC’s net-zero report, there are 54 instances of energy efficiency mentioned versus 2 mentions of energy service (CCC, 2019).

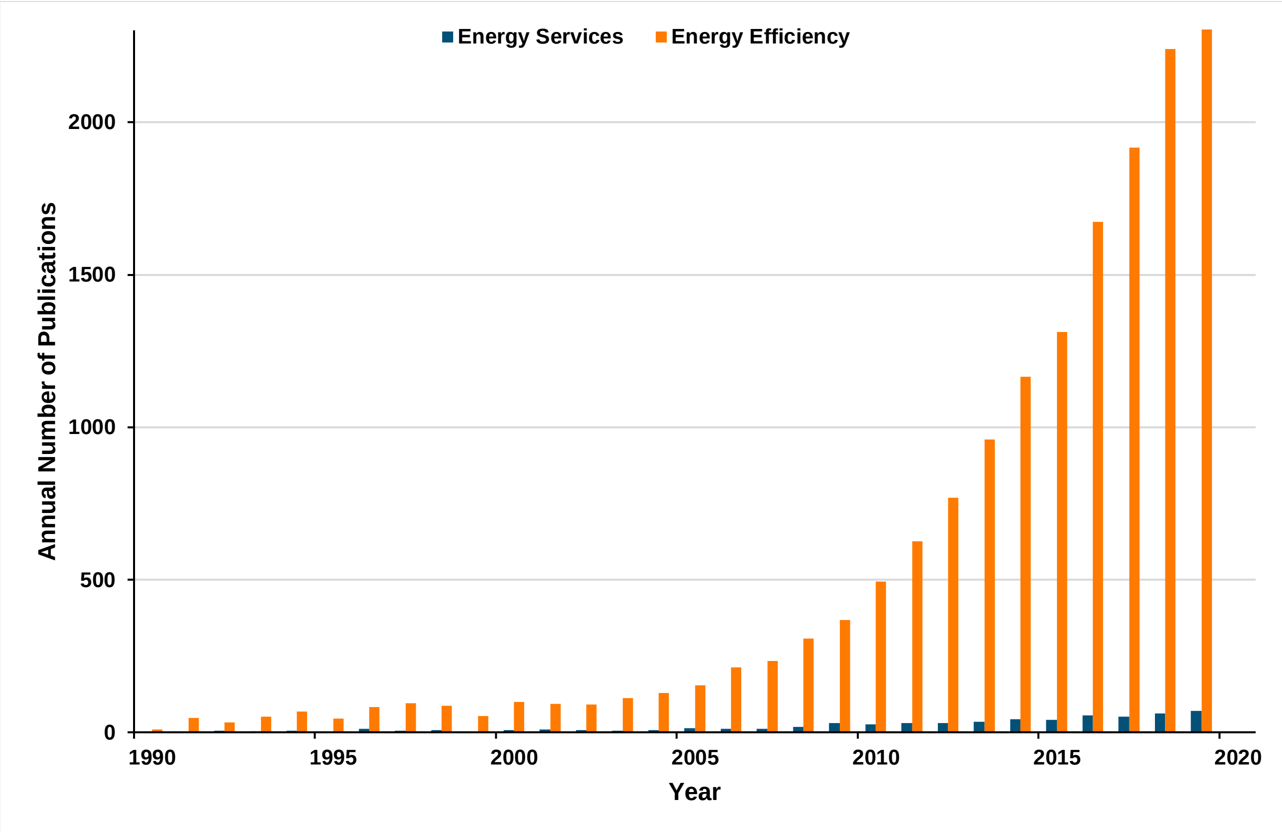

Figure 2.3 Annual number of publications whose topics focus upon “Energy Services” and “Energy Efficiency”. (Search Engine: Web of Science) (Search Date: 30/11/2022)[9]

The analysis in this chapter demonstrates that energy efficiency dominates both academic literature and policy documents compared to considerations of energy services. The dominance of energy efficiency demonstrates the continued popularity of the concept, but more papers are beginning to

[9] The search parameters for this were chosen to cover all the categories on Web of Science with “energy” in the title. Search Parameters: Topics Searched: “Energy Services” and “Energy Efficiency”; Document Type: Article; Web of Science Categories searched: Energy Fuels, Environmental Sciences, Environmental Studies, Engineering Environmental and Public Environmental Occupational Health; Search Range: 1990-2020 (Inclusive).

be published upon energy services with increases in energy services publications at the same rate as increases in energy efficiency publications across the 1990-2020 time period (Figure 2.3).

However, while the national discourse of EDR remains focused upon energy efficiency, at a Local Authority (LA) level in the UK, EDR measures which shift and avoid energy use are actively being considered by local-level policymakers. The UK's energy policy at different levels of government, and the governance structure of the UK itself will be considered in Section 2.2.

2.2 UK energy policy and governance

The governance of the UK is undertaken using a multi-level approach (Figure 2.4) (ONS, 2020). Multi-level governance is a concept first introduced in the 1990s to explain the inherent complexity of political decision making and policymaking across local, regional, national and international space (Stephenson, 2013). The concept suggests a distinction between different levels of government and the policy areas which they control, however, most importantly, it identifies the links between the different governance levels in order to better understand how these areas of government interact highlighting the dependence of different governance levels upon one another (Stephenson, 2013).

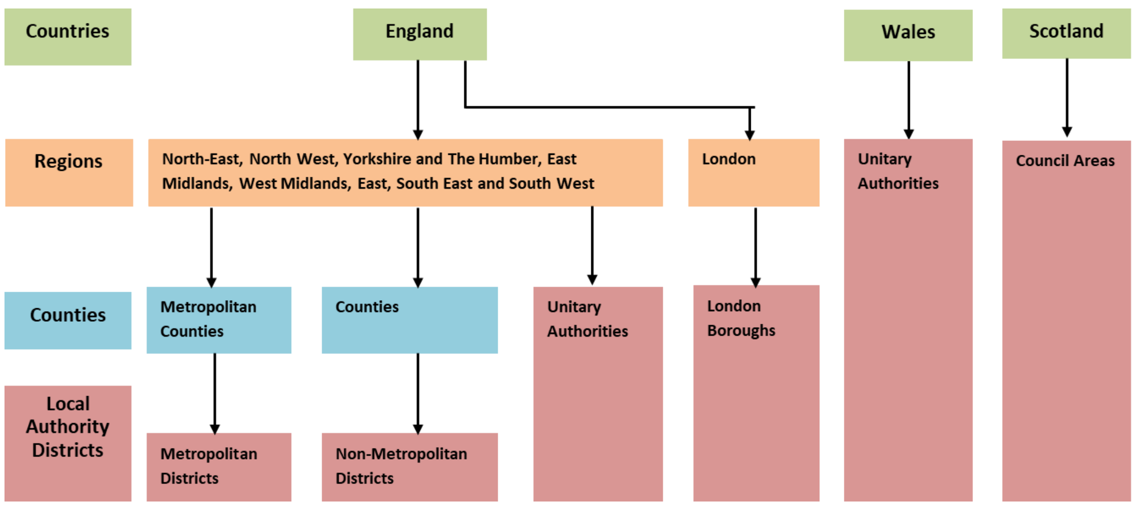

Figure 2.4 The structure of UK government (excluding Northern Ireland) (ONS, 2020).

National-level policy is set out within the UK Parliament and affects all four countries of the UK – England, Scotland, Wales and Northern Ireland (Bache and Flinders, 2004; ONS, 2020). However, the countries of UK also retain some level of autonomy and the ability to set their own policies which set them apart from the other UK nations (Bache and Flinders, 2004). These powers were devolved to Scotland and Wales after the 1997 devolution referendums (Bache and Flinders, 2004). At a regional level, the UK is divided into twelve different regions – nine in England, plus Scotland, Wales and Northern Ireland (Musson *et al.*, 2005). The regions of England do not hold any power to set individual policies, with the exception of London, which has a directly elected mayor, as do nine other combined authorities, such as the Greater Manchester Authority.

LA districts are the lowest level of the UK governance structure (Paun *et al*., 2019). UK LAs have significant control over various areas of policy involving housing and transport, as well as local tax collection and many other issues including recreational services, educational services and health and social care (Figure 2.5) (Paun *et al*., 2019).

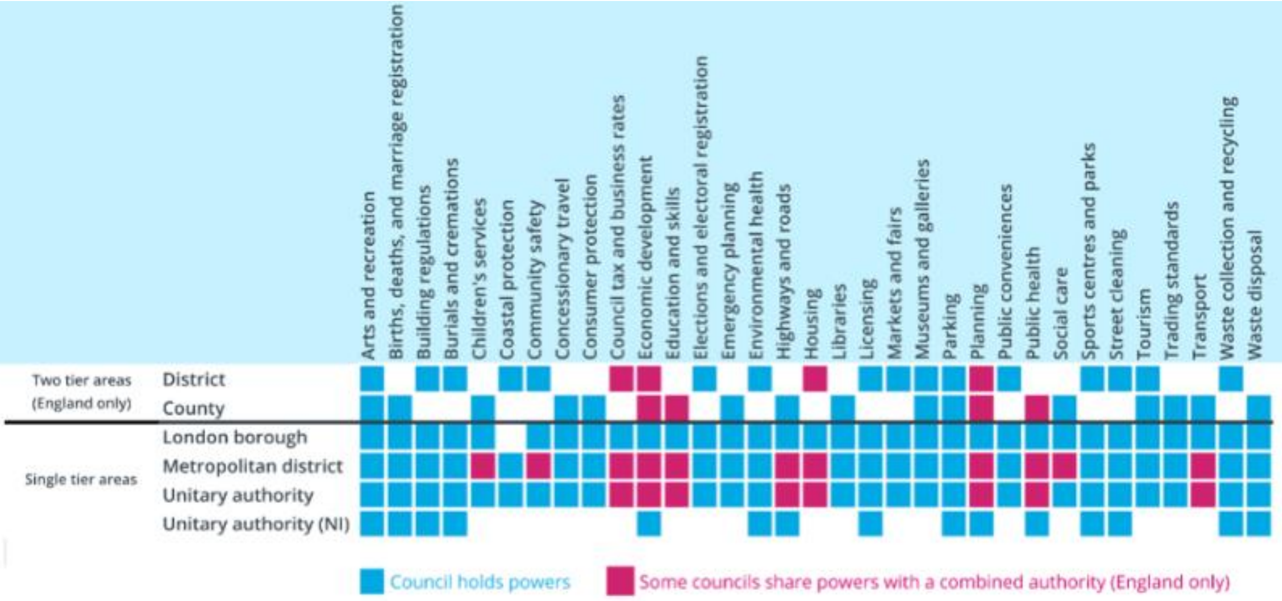

Figure 2.5 List of policy areas which councils within local authorities are responsible for (Image source: Paun *et al*., 2019).

2.2.1 UK demand-side energy policy

In the UK, energy policies are defined at a national-level (Smith, 2007; Cowell *et al.*, 2017). Despite Wales and Scotland having the ability to set out their own energy efficiency policies, energy and climate governance is broadly considered to be a national issue with limited direct powers for sub-national government to play a role in decarbonisation (Smith, 2007; Bridge *et al.*, 2013; Ellis *et al.*, 2013; Cowell *et al.*, 2015, 2017).

At present, the primary focus of the Department of Business, Energy and Industrial Strategy (BEIS) – the civil service department responsible for energy governance – is to consider the energy trilemma of security, affordability and decarbonisation with a primary focus on decarbonising energy supply through policies such as “advancing offshore wind” and “driving the growth of low carbon hydrogen” or “Jet Zero” (BEIS, 2017, 2020b). Much of the language in policy documents, such as the Clean Growth Strategy and the Green Industrial Revolution, is focused on fuel switching and increasing the capacity of renewables, as opposed to EDR (BEIS, 2017, 2020b).

The most recent national-level flagship policy centred around EDR was the Green Homes Grant, which aimed to encourage homeowners and landlords to improve the energy efficiency of their homes using grants of up to £5000 (BEIS, 2021a). The Green Homes Grant scheme can be considered a failure due to a low uptake and a short policy lifetime[10] (Kenyon, 2021a). Another similar national-level demand-side policy failure in the UK is the Green Deal which ran from 2012 to 2015 (Rosenow and Eyre, 2016). The Green Deal was an energy efficiency policy also focused upon improving household efficiency, but only managed to retrofit 14,000 out of a projected 14 million households, mainly due to the high rate of interest on the loans given to households, making them an unattractive prospect (Rosenow and Eyre, 2016).

National-level EDR policies and strategies in the UK, often consider EDR using an efficiency framing (BEIS, 2017, 2020b). For example, in the Clean Growth Strategy, "Improving business and industry efficiency" and "improving efficiency of homes" are both mentioned as policy aims (BEIS, 2017). However, in the Green Industrial Revolution, EDR is not specifically mentioned, but instead pledges to introduce "green public transport, cycling and walking" (BEIS, 2020b). The wording in the Green Industrial Revolution implies the strategy will aim to shift transport ESDs to less energy intensive options, however this is not stated outright (BEIS, 2020b).

The Green Industrial Revolution therefore shows that the UK government is seeking to reduce energy demand through measures from the 'shift' column in the ASI framework (Creutzig *et al.*, 2018; BEIS, 2020b). Additionally, the UK's national transport and heating strategies show evidence of 'shift' options being considered through the planned phase-out of fossil fuel powered vehicles for BEVs, and the increase of heat pumps to deliver heating ESDs to households (BEIS, 2021b; DfT, 2021). However, measures from the 'avoid' column of the ASI framework are generally neglected, with the exception of increasing the number of households walking instead of using personal transport (BEIS, 2020b, 2021b; DfT, 2021).

At a national-level, UK energy demand policy has thus far offered a narrow perspective for EDR, favouring efficiency measures in the past, and more recently technological shifts to reduce energy demand, while the 'avoid' measures for EDR from the ASI framework have been generally neglected in policy (BEIS, 2019, 2020b, 2021b, 2021c; CCC, 2021; DfT, 2021). Different levels of government in the UK do not possess powers to enact energy policy, however, the principle of subsidiarity, and the implementation of EDR strategies and policies at a more localised level are expected to form a core component of the demand-side transition in the UK and beyond (Lewis and Coinu, 2019).

2.2.2 Subsidiarity and energy demand reduction

Subsidiarity is a concept relating to governance within the European Union (EU) (Lenaerts, 1993). All tasks of government should be undertaken at the most localised-level possible, with the central

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[10] The policy was launched during the latter half of 2020 (30th September 2020 to March 31st 2021) after the beginning of the Coronavirus pandemic and was unsuccessful due to the backlog of work from early 2020, and the November 2020 and early 2021 national lockdowns which prevented work being undertaken.

EU government only performing tasks which cannot be performed at a lower level (Lenaerts, 1993; Gagnon and Keil, 2017). This is evident across the EU when considering that member countries retain powers to set taxes, and devolve powers to regional and local governments to implement policies (Franchino, 2007).

The UK left the EU in January 2020, partly due to what was perceived by UK citizens as a loss of sovereignty to the EU, with powers which could be controlled by the UK and other member states being under EU control (Gee, 2016; Agnew, 2020). However, the concept of subsidiarity does not solely apply to EU law, and could be utilised by the UK in the transition to a low energy demand society (Lewis and Coinu, 2019).

In the context of environmental issues, including climate change and energy demand reduction, the principle of subsidiarity is expected to align with the implementation of policies designed to mitigate climate change (Lewis and Coinu, 2019). However, the question of which level of government within a territory is the best level at which to implement EDR policy, is not often addressed (Wanzenböck and Frenken, 2018). Mitigation strategies and scenarios are therefore based within the current power dynamics of the multi-level governance structure of countries (Wanzenböck and Frenken, 2018). For example, in the UK, energy governance remains under the control of the national-level government (Smith, 2007; Cowell *et al.*, 2017) and EDR scenarios are therefore modelled at this level (Barrett *et al.*, 2022).

However, implementing national-level solutions to issues assumes that one solution to a problem is applicable to the whole population of a territory (Wanzenböck and Frenken, 2018). In the context of energy demand and EDR, this discourse assumes that an EDR measure will have the same effect upon two households with differing geographic and socioeconomic factors, without compromising their wellbeing. For example, attempts to reduce households ESDs for personal transport in the LA of Highland, in Scotland, could be undertaken by increasing the density of public transport infrastructure, however, in the Central London LA of Islington, public transport infrastructure is already very dense which means that increasing the density of public transport further may not discourage households from using personal transport. Whereas, implementing EDR at a lower level of governance would allow policymakers to address the drivers of high personal transport ESDs, specific to each LA.

Additionally, devising and implementing EDR policy at a national-level reduces the level of democracy in the mitigation process (Borrás and Ejrnæs, 2011; Heritier and Rhodes, 2011; Wanzenböck and Frenken, 2018). Transparency, deliberation and engagement are an important part of the demand-side policy process, particularly when considering options which require large behavioural and technology shifts from households (Cagnin *et al*., 2012; Borrás and Edler, 2014;

Wanzenböck and Frenken, 2018; UNDP, 2021). Therefore, excluding citizens from the planning process, increases the risk of policy uptake, and therefore policy failure (Wanzenböck and Frenken, 2018).

EDR policy implemented at different levels therefore has different objectives, rationale, policy scale and legitimacy compared to nationally-led solutions (Cagnin *et al.*, 2012; Borrás and Edler, 2014; Wanzenböck and Frenken, 2018). Table 2.2 shows the objectives, rationale, scale and legitimacy of policies implemented at high and low levels of governance (Wanzenböck and Frenken, 2018).

Table 2.2 Policy objectives, rationale, scale and legitimacy when implemented at a national (Image source: Wanzenböck and Frenken, (2018).

	Sub-national	*Supra-national*
Objective	Challenges specific to local conditions and circumstances	Broad transnational challenges affecting all regions
Rationales	Finding effective ways to tackle local contextual problems Improving democratic decision-making Increasing variety	Avoiding free-rider problem Avoiding duplication Sharing risks Benefitting from scale economies
Scale	Small-scale and contextual (tailor-made) solutions	Large-scale strategies requiring large investments and coordination
Legitimacy	Contested problem requiring responsiveness to citizens and multi-stakeholder participation in formulating the needs and search paths	Uncontested problem with clear problem definition, often associated with need for scientific advancement and technology diffusion

A more localised approach to EDR is considered to be vital in achieving the UK's national-level climate targets, as well as the long-term global climate goals set out in the Paris Agreement (LGA, 2019). Councils and other forms of sub-national government can draw together local partners and advocates for climate action to decide the best direction for climate action in their respective localities (LGA, 2019). However, the UK government are not keen to engage with LAs over climate change (LGA, 2019; Hill, 2022). Recently, the UK government declined to set up a local climate change taskforce designed to tackle climate change problems at a LA-level, and to bring about a greater level of EDR across the UK (LGA, 2019).

Considering other EU countries in the International Energy Agency (IEA), energy governance is managed in different ways across the EU. An analysis suggests that governments which set out energy policy centrally – e.g. Hungary, Estonia and Greece – are failing to meet their expected energy targets (IEA, 2017a, 2017b, 2019a). Whereas, other countries – such as France, Austria and

Ireland – adopt a decentralised approach and are ensuring that EDR is being undertaken in an equitable and just manner (IEA, 2016, 2019b, 2020a). However, Ireland maintain a dialogue with the national-level government to ensure that mitigation is being undertaken in the national interest (IEA, 2019b).

Subsidiarity, and the LA-level implementation of EDR policy is therefore an area of the demand-side transition which is neglected by UK policy. More work needs to be undertaken in order to identify the benefit of devolving powers to LAs to implement locally-specific EDR measures. Implementing EDR strategies at this level could improve the legitimacy of EDR strategies through the democratisation of the policy process and address issues related to EDR specific to each LA (Wanzenböck and Frenken, 2018). The devolution of funding to LAs to enact EDR policy may therefore improve the speed, effectiveness and equitability of the demand-side transition in the UK, and needs to be explored further as the UK attempts to reach its long-term climate goals.

However, despite energy governance currently being under the control of the national-level government in the UK (Smith, 2007; Cowell *et al.*, 2017), with no specific funding, or powers, devolved to LAs to devise and implement EDR policy, LAs have significant control of policy areas which can be used to reduce energy demand in their local area – e.g. transport planning and landlord regulation (Figure 2.5) (Paun *et al*., 2019). Additionally, Figure 1.7 shows that the ambition of LAs when considering climate targets, surpasses the ambition of the UK national-level government (BEIS, 2021c). EDR already undertaken in the UK at a LA-level will therefore be considered in Section 2.2.3.

2.2.3 LA-level energy demand reduction in the UK

As stated in Section 2.2, LAs in the UK have no specific powers to set demand-side energy policies which differ from the national agenda (Figure 2.5) (Paun *et al*., 2019; ONS, 2020; Tingey and Webb, 2020). There is no funding ring-fenced for UK LAs to devise and implement energy policies, therefore ensuring large-scale, well-funded energy policies remain in control of the UK's national-level government (Muinzer and Ellis, 2017; Eckersley, 2018; LGA, 2019; Kenyon, 2021b; Sugar *et al.*, 2022).

Despite, the lack of powers to set out energy policy, and the financial constraints imposed upon LA governments in the UK since 2010, many councils have already declared climate emergencies (Figure 1.7) (Climate Emergency UK, 2022; mySociety, 2022), and some of these have created plans to reduce their CO_2 emissions through reduced energy consumption (Leeds City Council, 2021). LAs in the UK have control over many different policy areas that can impact energy consumption, but are not directly related to the energy transition or climate change mitigation (Figure 2.5) (Paun *et al*., 2019; Tingey and Webb, 2020).

A real-world example of sub-national EDR in the UK is the London congestion charge. The congestion charge was introduced in 2003 and aims to reduce traffic levels in the city of London, with the added bonuses of also reducing air and noise pollution (Leape, 2006). The scheme was designed so that money raised through the congestion charge is invested in London's public transport system, therefore improving and subsidising the system for users. The original congestion charge zone has changed over the years, with an Ultra-Low Emissions Zone introduced in 2019 (Ku *et al.*, 2020). The congestion charge has reduced the number of cars in London, while also improving air quality throughout the area and has led to an increase in the number of buses and bicycles being used to travel in central London (Green *et al*., 2020). However, the impact of the congestion charge has not been as great as was hoped prior to the charge's introduction, while the number of taxis in Central London has increased (Metz, 2018; Green *et al*., 2020).

The LA-level climate plans in the UK are often more ambitious in their climate goals than national governments (BEIS, 2021c; Climate Emergency UK, 2022; mySociety, 2022). For example, Leeds City Council has set a goal of reaching net-zero emissions by 2030, 20 years sooner than the national target of net-zero (Figure 2.6) (BEIS, 2021c; Leeds Climate Commission, 2021a). Some local councils engage with households in their locality through climate commissions and assemblies using a representative sample of the population to develop climate-related policy recommendations which provides governing bodies with a mandate for greater ambition in climate plans than the national government (LGA, 2019; CCC, 2020; Tingey and Webb, 2020; Kenyon, 2021b).

Greater ambition at a LA-level can bring about wellbeing benefits for households in a LA, alongside EDR (Wanzenböck and Frenken, 2018; Friends of the Earth, 2019). For example, the Ipswich and Cambridge councils have set standards for all new homes built in their localities to meet a standard equivalent of Level 4 of the Code for Sustainable Homes (Friends of the Earth, 2019). Friends of the Earth (2019) have calculated that this is a 19% improvement on national standards. A higher standard of sustainability on new homes means that households are more efficient and are therefore warmer and have cheaper bills, thereby providing health and financial benefits to households.

Another example of wellbeing co-benefits, in the LA of Solihull, there are plans to replace all of its street lights with LED street lights by 2024 (Friends of the Earth, 2019). This will involve the replacing of 24,000 street lights and is expected to reduce the council's energy costs by up to 50%, which equates to £612,000 (Friends of the Earth, 2019). These cost savings can then be passed onto local residents by the Solihull LA investing the savings in public services and other EDR schemes (Friends of the Earth, 2019).

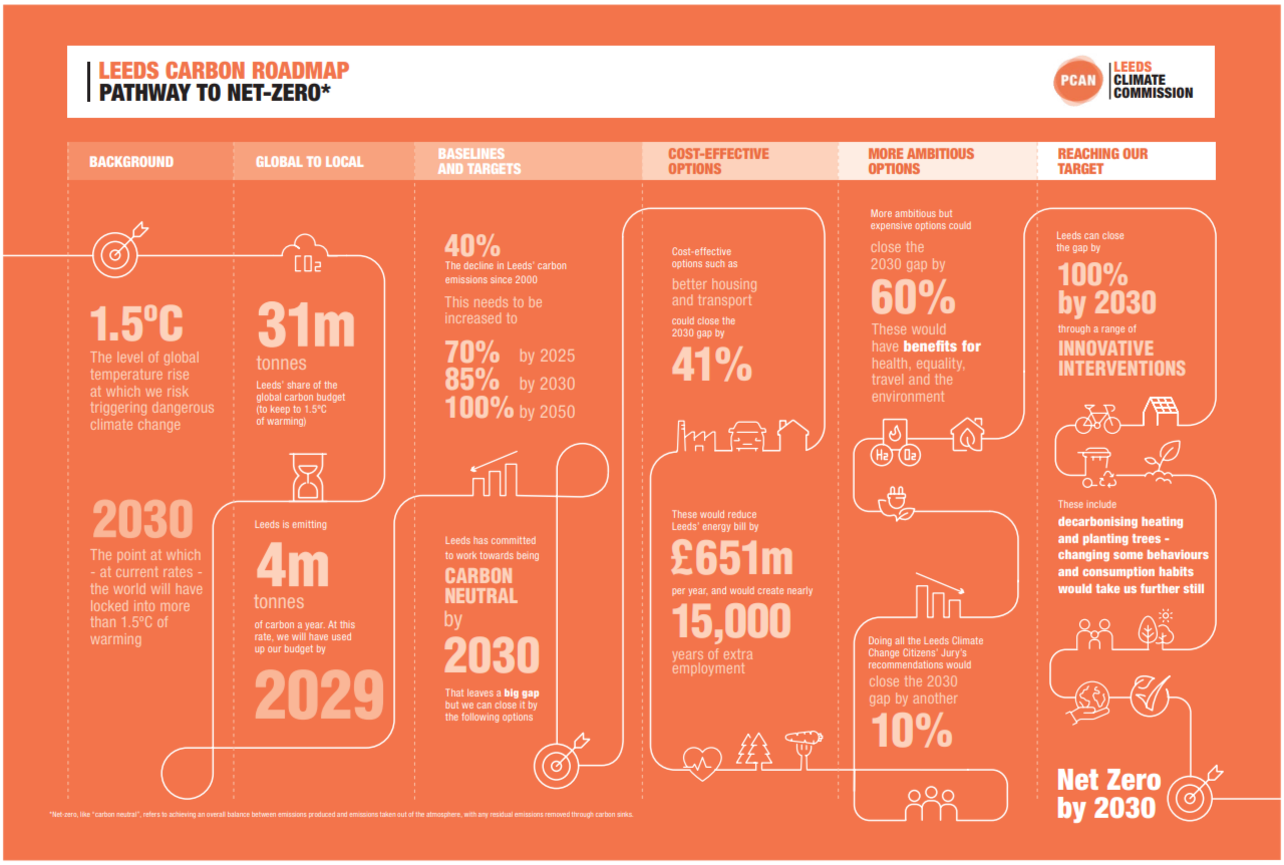

Figure 2.6 Leeds carbon roadmap pathway to net-zero by 2030. (Image source: Gouldson *et al.*, (2020)).

The schemes in Ipswich, Cambridge and Solihull are not large, flagship, energy programmes, as is the case with national-level EDR strategies such as the Green Industrial Revolution or the Green Homes Grant (BEIS, 2020b, 2021a). Instead, at a LA-level, EDR measures focus upon small, no-cost, low-cost actions, particularly due to the financial constraints imposed upon LAs by the national government in the UK (LGA, 2019; Tingey and Webb, 2020). Due to financial constraints, many LA schemes to reduce energy demand are yet to be implemented. For example, Greater Manchester is planning to build 120km of segregated cycle routes on main roads over the next 10 years (Friends of the Earth, 2019).

However, despite greater EDR policy ambition being visible at a LA-level in the UK, there is evidence of misaligned policy goals when considering EDR. For example, despite Leeds City Council having a 2030 target for net-zero, the council approved the expansion of the Leeds-Bradford airport in 2021 (Leeds Climate Commission, 2021a, 2021b). The clash of priorities at a LA-level is a barrier to the UK government devolving more powers to LAs (Palle and Richard, 2022). LA-level EDR policies clashing with related, and unrelated, national-level policies can lead to conflict between the two levels of government and reduce the effectiveness of policies implemented at both levels (Palle and Richard, 2022). However, despite this reservation from an environmental perspective, policy clashes are already evident at a national-level through the UK's net-zero climate goal and the subsidisation of fossil fuel industries in the UK by the government (BEIS, 2021c; McCulloch, 2023). Therefore, providing EDR policy at a LA-level was undertaken in the context of national-level policy goals, 'scalar clashes' should not cause an issue to utilising the concept of subsidiarity for EDR policy in the UK (Palle and Richard, 2022).

Section 2.2.3 has highlighted examples of LAs attempting to reduce local energy consumption in order to reduce energy use and emissions both locally and further up the supply chain, and maximise the wellbeing of residents by reinvesting money saved in local services (Friends of the Earth, 2019). However, the potential for local action to reduce energy demand is not limited to the schemes set out in Section 2.2.3. Ivanova *et al.*, (2020) set out a wide range of 61 consumption-based EDR options which aim to mitigate energy use, and therefore emissions, by challenging dominant household consumption practices. The consumption-based measures in Ivanova *et al.*, (2020) aim to reduce the energy consumption of individuals and households across a range of areas including housing, transport and nutrition.

Policymakers in LAs have direct control over policy areas which directly affect these mitigation domains (Figure 2.5), therefore there is significant opportunity for LAs to remove localised barriers to sustainable lifestyles, which encourage consumer lock-in to a high energy consumption lifestyle (Ivanova *et al.*, 2018; Paun *et al*.,, 2019). The measures in Ivanova *et al.*, (2020) could therefore form a basis from which LAs could devise an EDR strategy which significantly reduces the household energy demand of their local area. However, studies have shown that different LAs have different underlying socioeconomic characteristics – e.g. income, population density – therefore an effective EDR strategy in one LA, may not be effective in another (Ivanova *et al.*, 2018). LAs must understand the effectiveness of different measures upon households in their locality, as well as the potential wellbeing implications of EDR action, before implementing an EDR strategy. However, as yet, the measures in Ivanova *et al.*, (2020) have not been modelled upon different localities with varying underlying socioeconomic charcteristics.

Analysis of UK demand-side energy policy in Section 2.2.1 and LA-level EDR in the UK in Section 2.2.2 demonstrates that different levels of ambition exist at different levels of the UK multi-level governance structure. National-level government has been unsuccessful in the past, and is generally centred around energy efficiency measures through strategies such as the Green Deal and Green Homes Grant, while the ambition of LAs is limited by funding (Rosenow and Eyre, 2016; BEIS, 2021a).

2.2.4 Governance and agency summary

Section 2.2 examined the governance of demand-side energy policy in the UK, and the concept of subsidiarity. The national-level government sets out energy policy in the UK (Tingey and Webb, 2020). National-level demand-side policy in the past has focused primarily upon energy efficiency measures to reduce energy demand, while LAs in the UK have used a broader range of EDR options to reduce the energy demand of households (Section 2.2.1 and Section 2.2.3) (Friends of the Earth, 2019; BEIS, 2020b). The flagship national-level policies, such as the Green Homes Grant and the Green Deal, which were centred around reducing domestic energy demand have been considered policy failures, due to a lack of uptake (Section 2.2.1) (Rosenow and Eyre, 2016; Kenyon, 2021a).

The concept of subsidiarity, in the context of EDR, suggests that LAs should play a large role in the demand-side transition, in the UK and beyond (Wanzenböck and Frenken, 2018). However, within the UK, the national-level government appears unwilling to engage with LAs in order to bring about greater reductions in energy demand (LGA, 2019). LAs in the UK have no power to set out energy policy (Tingey and Webb, 2020). However, LAs, and therefore households, display greater ambition when considering demand-side policy than the UK's national government, but lack the finances to effectively implement EDR strategies (Section 2.2.3) (Paun *et al*., 2019; Tingey and Webb, 2020).

More work therefore needs undertaken on the potential of LAs to reduce energy demand without compromising wellbeing. Current EDR scenarios conduct modelling studies based within the current power structures of the territory within which a study is conducted (Barrett *et al.*, 2022). Studies must therefore examine EDR at a LA-level in order to assess whether a disaggregated approach to EDR would be beneficial for the demand-side transition.

However, the current framing of energy demand, set out in Section 2.1, would be unable to cope with disaggregated approaches to EDR. LAs are the point of energy consumption, and govern a small area of the UK, which is often geographically distinct from production of energy. Therefore, a different framing of energy demand, which can be quantified at a LA-level, does not examine energy demand solely as a product of the energy system, and is relevant to the needs of households – so that EDR does not reduce wellbeing – needs to be considered.

2.3 Energy Service Demand Framing

The demand for energy services is commonly accepted as the driver of household energy consumption across different spheres of work including in academia and politics, and are considered to be the end point of the technical energy system (Sorrell, 2007; Le Gallic *et al*., 2017). Considering ESDs at a LA-level, rather than energy demand, is necessary due to the dispersed nature of energy infrastructure and the globalised nature of the economy (Schulze and Ursprung, 1999; Tingey and Webb, 2020). ESDs relate directly to the needs of households, therefore framing energy demand through a services lens relates EDR directly to the level, and type, of energy consumption undertaken by households in each LA.

The concept of ESDs has been discussed for many years (Hafele, 1977; Reister and Devine, 1981; Goldemberg *et al.*, 1985). However, there is yet to be a universal definition of ESDs set out, with the framing of ESDs varying significantly across different studies, frameworks and models (Fell, 2017). Section 2.3 therefore examines the current framing of ESDs across academic literature and policy work beginning with different ESD definitions, before analysing the representation of ESDs in frameworks, models, and the different categories of ESDs used across studies to establish whether the concept can be used to reframe EDR at a LA-level.

2.3.1 Energy service definitions

During a conceptual review of ESDs, Fell (2017) undertook a content analysis and identified 27 unique energy service definitions. For example, Sorrell (2007) equates energy services to the 'useful work obtained' from the energy system, while another definition describes energy services as "the benefits that energy carriers produce for human wellbeing" (Modi *et al.*, 2005, p9)[11].

The Sorrell (2007) definition frames energy services as a product of the energy system – the end point of the energy system – and focuses upon the amount of energy required to deliver energy services to households. Studies utilising this definition tend not to examine the energy services which are delivered to households in greater depth than simply providing a quantitative value of the energy required to deliver specific energy services (Morley, 2018). Considering energy services as the 'useful work obtained' from the energy system is a simplistic understanding of ESDs, but framing ESDs in this manner is useful for assessing the level of energy consumption required to deliver different energy services to households, and for modelling the effect of energy efficiency improvement measures implemented at different stages of the energy system.

The Sorrell (2007) definition encourages the framing of EDR through an efficiency lens by focusing on the quantity of energy delivered to households. Measures to reduce energy demand therefore focus upon delivering the same level of useful work to households for less energy output from the energy system. The Sorrell (2007) definition focuses purely on the quantitative side of energy demand and neglects the social drivers of energy service consumption. Therefore if energy services were defined using the Sorrell (2007) definition of energy services, consideration of energy services would neglect the association between wellbeing and ESDs, and the co-benefits that can be gained from not consuming energy services.

Alternatively, the energy services definition proposed by Modi *et al.*, (2005) attempts to extend the scope of energy service studies beyond the quantity of energy required from the energy system to

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[11] Rather than discuss all 27 of the energy service definitions set out in Fell, (2017), the two most extreme definitions of energy services are mentioned in this section – Modi *et al.*, (2005); Sorrell, (2007).

the social benefits gained from consuming energy. Modi *et al.*, (2005) focus upon the actual energy services demanded by households – the 'benefits' – and also emphasise that ESDs are required to achieve wellbeing. The Modi *et al.*, (2005) definition is therefore, in effect, linking the social and technical aspects of energy demand by considering energy services (Nørgård, 2000; Brand-Correa *et al*., 2018). According to Brand-Correa *et al*. (2018), building upon statements by Ban Ki Moon, energy services are the 'Golden Thread' that can link human wellbeing and the technical energy system as energy services are quantifiable, in terms of energy units, and are consumed directly to achieve wellbeing.

Linking the technical energy system with wellbeing using energy services is advantageous as it links households with the global energy system, and also broadens the scope of the definition proposed by Sorrell (2007), and allows a deeper insight into household ESDs, and the needs each ESD is meeting (Jonsson *et al.*, 2011). Additionally, acknowledging the diminishing returns of increasing wellbeing through increases in ESDs, as mentioned in Section 2.1.1.2, increases the opportunity for EDR through measures which change the nature of an energy service, or reduce the energy service levels of households, rather than energy efficiency (Steinberger and Roberts, 2010).

The Modi *et al.*, (2005) definition of energy services presented in this chapter shows that the link between ESDs, household wellbeing and the technical energy system is well understood. However, despite this understanding, definitions of energy services vary across studies depending upon the scope of the study being conducted. The variance in energy service definitions is not limited to descriptions of the concept however as the representation of energy services is inconsistent across different analytical frameworks of the energy system (Hafele, 1977; Jonsson *et al.*, 2011; Cravioto *et al.*, 2014).

2.3.2 Energy system frameworks

Examples of energy system frameworks which extend to energy services have been present within academic publications since the 1970s, (Figure 2.7) (Hafele, 1977). However, of the energy system frameworks examined in this chapter, nine frameworks were published since 2010 (Table 2.3).

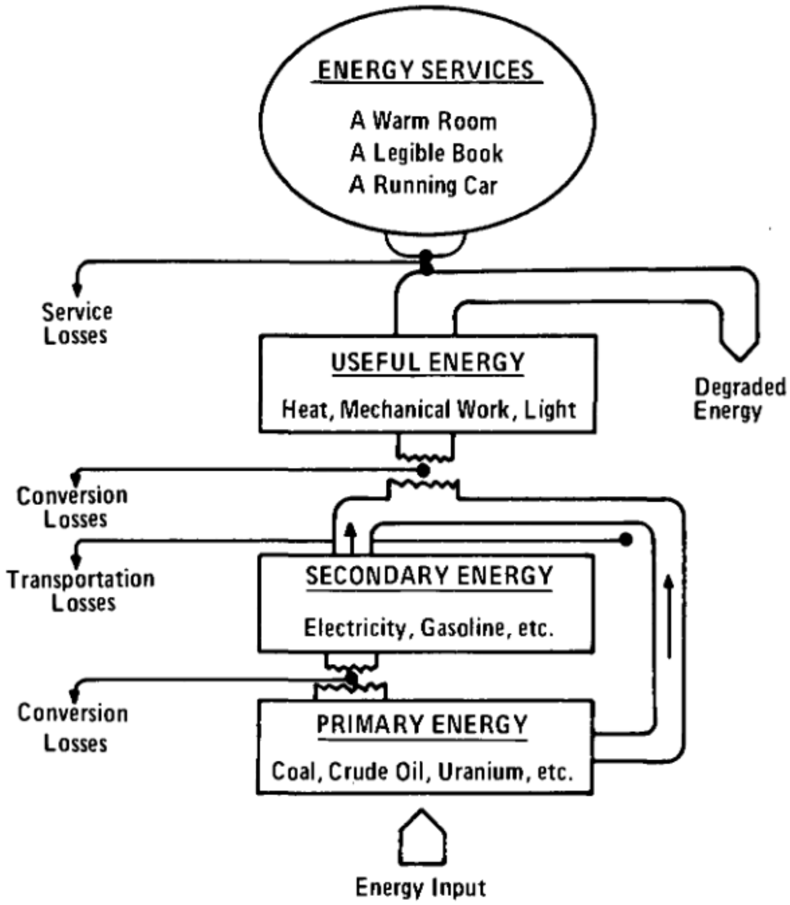

Figure 2.7 An early example of an energy system framework that extends to energy services (Image Source: Hafele, (1977).

Figure 2.7 shows that older energy system frameworks tend to focus upon the technical energy system and classify the delivery of energy services to households as the ultimate goal of the energy system therefore treating ESDs as a peripheral part of the energy chain (Hafele, 1977; Jonsson *et al.*, 2011). Such frameworks are not designed to assess the impact of changes in household demand upon the energy required from the energy system to deliver energy services. Considering ESDs as a product of the energy system is not limited to older energy system frameworks however, see Cullen & Allwood (2010) and Heun et al., (2018), meaning that demand-side interventions continue to focus upon energy efficiency.

More recently however, there has been an increase in the diversity of energy system frameworks which attempt to draw together the social and technical aspects of energy demand, and portray ESDs which achieve wellbeing as the ultimate driver of the energy system, (Jonsson *et al.*, 2011). Despite this increase however, few of the examined frameworks in Table 2.3 actively consider energy services within the context of the full energy chain, as this is considered to be outside the scope of these papers, such as Cravioto *et al.*, (2014). Energy system frameworks which examine the whole energy chain are more representative of the real-world dynamics of energy use and the energy system (Nakićenović *et al.*, 1996). Additionally, these frameworks provide analytical benefits as they can be utilised to deepen our understanding of the interactions between the technical energy system and the drivers of household energy demand (Kahane, 1991; Jochem *et al.*, 2000; Nørgård, 2000; Haas *et al.*, 2008; Jonsson *et al.*, 2011; Day *et al.*, 2016).

Table 2.3 Stages included within the energy system frameworks used by a sample of studies. An 'X' means that this stage was included within a study's framework.

	Framework Stages				
Author	**Primary Energy**	**Final Energy**	**Useful Energy**	**Energy Services**	**Human Needs**
Hafele (1977)	X	X	X	X	
Kahane (1991)	X	X	X	X	X
Nakićenović (1993)	X	X[1]	X	X	
Nakićenović *et al.*, (1996)	X	X[1]	X	X	
Nørgård (2000)	X	X	X	X	X
Cullen & Allwood (2010)	X	X	X	X	
Neves & Leal (2010)	X	X	X	X	X
Jonsson *et al.* (2011)	[2]	[2]	[2]	X	X
Cravioto *et al.* (2014)	[2]	[2]	X	X	[2]
Brockway *et al.* (2015)	X	X	X	[2]	
Day *et al.* (2016)	X	X		X	X
Brand Correa & Steinberger (2016)				X	X
Brand-Correa & Steinberger, (2017)	[2]	[2]	[2]	X	X
Heun *et al.*, (2018)	X	X	X	X	[2]
Mastrucci *et al.*, (2020)	[2]	X		X	

[1]Nakićenović, (1993) and Nakićenović *et al.* (1996) include a 'Secondary Energy' framework stage as well as a 'Final Energy' framework stage. In this analysis, these stages are considered to both be separate sections of the 'Final Energy' stage included within other frameworks.

[2] These framework stages are acknowledged within each paper, but are considered to be outside the study boundary.

The three papers in Table 2.3 which examine the energy system using the full energy chain – (Kahane, 1991; Nørgård, 2000; Neves and Leal, 2010) – were published across a nineteen-year time period. Each author emphasises that limiting analyses to a specific section of the energy system limits the potential for intervention, whether for implementing demand-side mitigation (Kahane, 1991; Nørgård, 2000), or, identifying additional energy sustainability indicators (Neves and Leal, 2010). Examining energy demand within the context of a full energy chain framework therefore extends analyses to the drivers of the energy system, and therefore household ESDs (Jonsson *et al.*, 2011).

The full energy system frameworks in Table 2.3 adopt a top-down consideration of the energy system from supply to demand, meaning that household demand for energy services is quantified in energy units, aligning with the definition of energy services set out by Sorrell (2007). Neither Kahane (1991), nor Neves & Leal (2010), suggest examining ESDs within the context of the energy chain from a consumption perspective, although Nørgård (2000) suggests that the direction of analysis within energy system frameworks should be reversed. Reversing the direction of analysis within an energy system framework would allow EDR planning to begin at the consumption end of the energy chain, and terminate at the primary energy stage of the energy system (Nørgård, 2000). Analysing the energy system from this perspective challenges the conventional view of the energy system within frameworks, as this framing recognises that ESDs are not simply a product of the energy system, but are driven by households, embedded within different socio-economic contexts, attempting to achieve wellbeing (Hui and Walker, 2018). Additionally, the ultimate goal of EDR is to avoid emissions and reduce pressure upon the supply-side of the energy system so it can be decarbonised faster, therefore placing energy supply at the end of a framework may provide analytical benefits when considering EDR (Grubler *et al.*, 2018; Kriegler *et al.*, 2018). Examining the energy system in this manner would help draw in the concept of subsidiarity to EDR planning (Nørgård, 2000; Wanzenböck and Frenken, 2018).

However, despite the potential benefits provided to LAs by analysing the energy system from a service-oriented perspective for EDR, the ESD categories considered by different papers varies significantly (Fell, 2017). Depending upon the ESD categories considered in an energy system framework, the scope of EDR for a LA could be limited. The ESD categories utilised when considering EDR must therefore be relevant to all aspects of household consumption, especially when considering subsidiarity and EDR at a LA-level.

2.3.3 Energy Service Demand Categories

The representation of ESDs varies across different academic publications and policy documents. During a conceptual review of the concept of energy services, Fell (2017) found many unique types of ESD across different academic papers (Figure 2.8).

The most popular ESDs considered by studies are lighting, cooking and heating (Figure 2.8) (Fell, 2017). Lighting, cooking and heating are considered to be direct energy services – i.e. are fulfilled by consuming energy from the energy system (Fouquet, 2010). Direct ESDs can be quantified in energy units, thus making the consideration of direct ESDs more appealing than considering energy services which require indirect energy to be fulfilled.

Figure 2.8 focuses exclusively on ESDs provided by direct energy, thereby neglecting ESDs associated with indirect energy, embodied within products and services purchased by households. ESD categories requiring indirect energy are often more wide-ranging than ESD categories related to direct energy[12]. ESD categories provided by indirect energy can include nutrition, – accounting for the energy with producing and transporting food products to households – clothing – which accounts for the energy associated with the manufacture of items of clothing – and services – the embodied energy associated with using services, such as financial services.

[12] The ESD categories in Figure 2.8 are varied, however less frequent examples of ESD categories, such as clothes washing and drilling, are sub-categories of the energy service of 'power' – defined by Fouquet (2010) as one of the four main energy services – meaning that each of the ESD categories in Figure 2.8 are provided by direct energy.

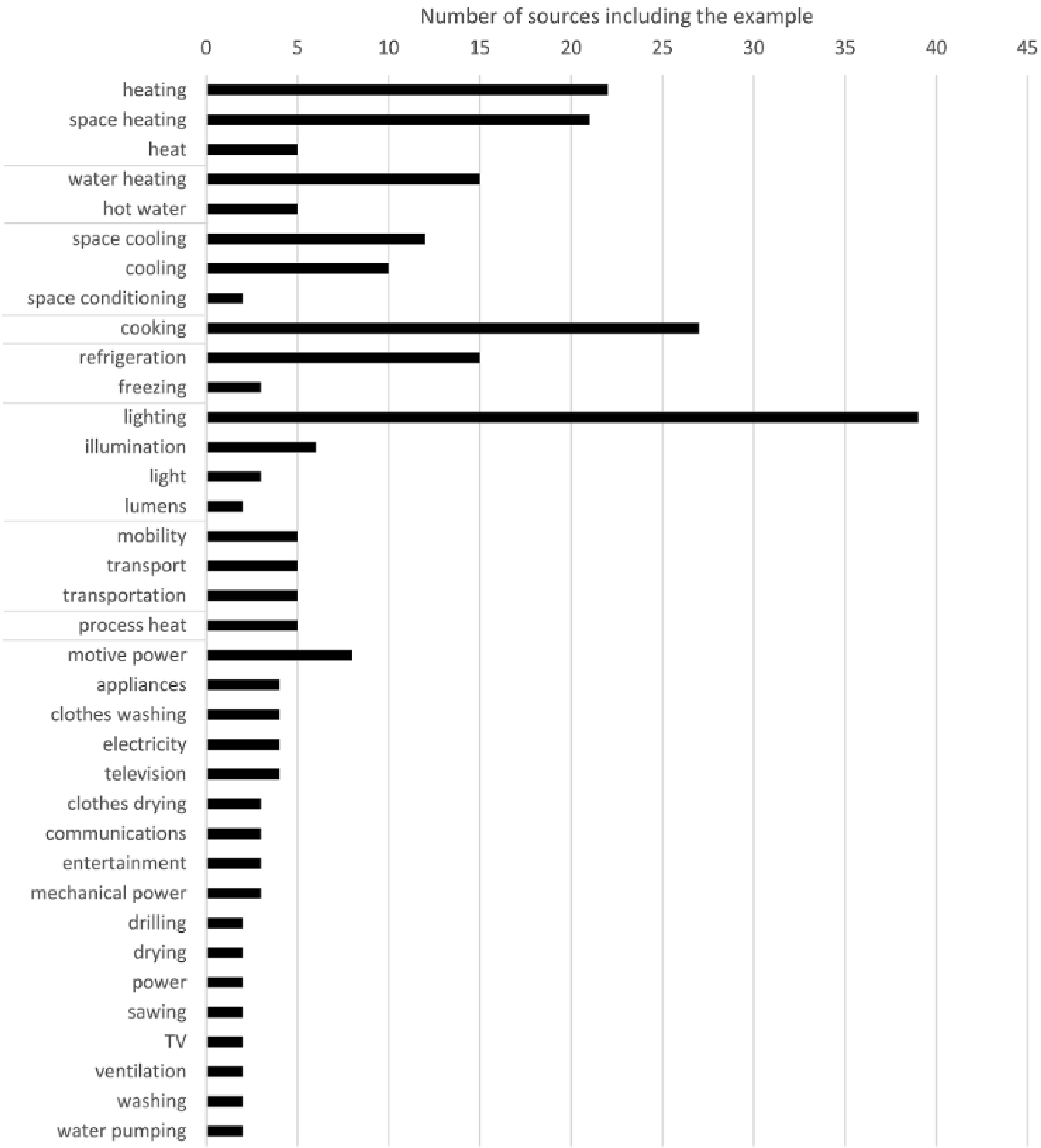

Figure 2.8 List of ESDs identified by Fell (2017) in their conceptual review of the term "energy services" (Image source: Fell (2017)).

ESDs provided by indirect energy are less prevalent in literature than direct ESD categories (Fell, 2017), however they more accurately reflect household consumption patterns have been considered for many years. Vringer and Blok (1995) examine ESD categories associated with indirect energy, as well as direct energy. A broader consideration of ESDs in Vringer and Blok, (1995) is included in an analysis of household-level energy footprints, as it is argued that indirect ESDs represent a significant proportion of a household's energy footprint, and should be acknowledged.

ESDs delivered through direct energy consumption, such as heating, generally tend to make up the highest proportion of an energy footprint, more so than ESDs supplied by indirect energy embodied in products and services. However, including a broader range of ESD categories in an analysis of domestic energy demand is important to understand household behaviour, while considering ESDs associated with indirect energy also offer different opportunities for EDR.

Haas *et al.*, (2008) argues in favour of considering ESDs provided by indirect energy in models and studies to bring about increases in the level of EDR. Considering only ESDs associated with direct energy limits the focus of EDR to services supplied directly from the energy system, rather than considering all consumption undertaken by a household. For example, when considering a broader range of ESDs supplied by indirect energy, EDR measures, such as changing household dietary habits to a plant-based diet – 'shift' in the ASI framing of EDR – becomes a viable option available to households and policymakers.

Additionally, going beyond direct ESD categories can identify overconsumption of energy amongst households. Owen and Barrett (2020) calculated the household energy footprints of 20 income groups in the UK in 2016. Excluding mobility, considering the direct energy provided to households, the consumption of domestic gas and electricity was 1.9 times greater in the highest income group, than in the lowest income group, whereas considering the full scope of energy associated with a household's energy footprint showed that the energy footprint of the highest income group was 3.38 times higher than the lowest income group (Owen and Barrett, 2020). Considering ESD categories provided from both direct and indirect energy highlights the disparity in energy consumption between households which appeared less stark when considering only direct energy ESD categories (Owen and Barrett, 2020).

ESD categories provided by indirect energy therefore tie energy services even closer to issues of overconsumption and wellbeing (Section 2.1.2). The linkages between ESDs provided by indirect energy and wellbeing are further highlighted by Rao and Min (2018) whose indicators of 'decent living standards' broadly overlap with the ESD categories set out in Vringer and Blok (1995) and Owen and Barrett (2020)[13]. The 'decent living standards' indicators have been designed to eradicate poverty and ensure more equality throughout society (Rao and Min, 2018).

Broadening out ESD categories to include energy services provided by both direct and indirect energy would tie ESDs even closer with considerations of wellbeing and also offer different opportunities for EDR to be considered by a LA. However, based upon the representation of ESDs

[13] There are two exceptions: 'air quality' and 'freedom to gather/dissent' (Rao and Min, 2018).

in energy system frameworks, discussed in Section 2.3.2, it is unlikely that ESD categories will be broadened beyond those which can be directly quantified from the energy system in policymaking.

2.3.4 Energy service demand framing summary

Section 2.3 aimed to examine the current framing of ESDs across academic literature and policy work. Many studies examined in Section 2.3.2 and Section 2.3.3 align with the Sorrell (2007) definition of energy services, rather than the Modi *et al.*, (2005) definition. This is evident in the frameworks which predominantly focus upon the technical energy system (Nakićenović, 1996; Heun *et al*., 2018), and the energy service categories which focus upon direct energy (Fell, 2017).

The top-down, direct energy focused perspective of ESDs encourages the framing of ESDs as products of the energy system, rather its drivers. There is evidence that studies are beginning to go beyond the traditional treatments of ESDs, portraying in a manner more alike the Modi *et al.*, (2005) by highlighting their link to wellbeing, and that as the point of consumption in the energy system, should be considered from this perspective (Nørgård, 2000).

Chapter 2 has shown that a consistent framing of how to consider energy demand, ESDs and EDR at a LA-level is lacking. If LAs were to adopt a larger role in EDR in the UK under subsidiarity, a framework, which considers ESDs provided to households by both direct and indirect energy, and allows EDR to be considered from a LA perspective – i.e. from the consumption end of the energy system – must be constructed. However, considering ESDs from a LA perspective is only one barrier to framing EDR using a services lens at a LA-level. If LAs are to assume a large role in EDR going forward, the potential of different EDR strategies must be modelled at this level.

2.4 Modelling energy service demands

Undertaking EDR at a LA-level using a services perspective of energy demand requires ESDs to be modelled at this level. Section 2.4.1 will consider the models used to define the UK's demand-side policy at a national-level and their representation of ESDs to assess whether these models are appropriate for modelling ESDs, and transferrable to a LA-level (Hardt *et al.*, 2019). Following an assessment of the framing of ESDs within current demand-side models, Section 2.4.2 and Section 2.4.3 will consider energy footprinting as a methodology for considering ESDs at a LA-level (Leontief, 1936; Lenzen *et al.*, 2003; Miller and Blair, 2009; Owen, 2018).

2.4.1 Energy services within models

As with energy system frameworks, the information included in energy demand models varies from model to model depending upon the model's purpose (Table 2.4) (Hardt *et al.*, 2019). In the UK, thirteen demand-oriented models are used in inform demand-side policy covering specific sectors, policies, and the UK as a whole (Table 2.4) (Hardt *et al.*, 2019). However, despite energy services being acknowledged as the drivers of the energy system in both academic and political spheres, only six of the thirteen models simulate ESDs (Table 2.4). Similarly, socioeconomic drivers of energy demand throughout the UK are not considered in every energy system model either (Table 2.4) (Bhattacharjee and Reichard, 2011). However, final energy demand is considered within every model (Table 2.4).

Table 2.4 List of factors considered within energy demand models used by the UK Government. The table below is adapted from information in Hardt *et al.*, (2019).

Model	Socio-economic drivers	Energy service demands	Final energy demand
All-sector models			
BEIS EDM	X		X
E3ME	X		X
NISMOD	X		X
HMRC environmental CGE model	X		X
UK TIMES		X	X
ESME		X	X
Sector-specific models			
National Transport Model	X	X	X
ENUISM	X	X	X
BEIS Industry Pathways Model			X
BEIS Non-domestic Building Model		X	X
National Household Model	X	X	X
Policy-specific models			
Green Deal Household Model	X		X
EDR Take-up Model			X

The inclusion of final energy demand in each of the models used to devise UK EDR strategies shows that energy demand, is considered to be a product of the energy system within these models, and therefore by national-level policymakers (Hunt and Ryan, 2015). Energy demand models at a national-level adopt a top-down perspective of the energy system as there is often data on the consumption of different energy sources available, thus making energy demand easier to quantify in this manner (Hunt and Ryan, 2015).

The models in Table 2.4 cover different mitigation areas, in which EDR is required for the UK to transition to a net-zero society meaning that each model is constructed from different data, models a different aspect of UK society, and offers different outputs used to define UK demand-side energy policy (Table 2.5) (Hardt *et al.*, 2019). For example, (macro)-econometric models use economic data to simulate economic responses to policies to identify the effects of policy upon the economy, emissions and energy demand within a defined system, while energy system models model the energy system within a defined boundary, and are driven by economic conditions and technological assumptions.

(Macro)-econometric models and energy system models are common in policymaking. However, they maintain a strong focus upon the technical energy system, and the economy, rather than the consumption end of the energy system (Sakai *et al.*, 2018). The outputs from all the models in Table 2.5 also state a preference for assessing economic impacts of mitigation policy options – thus prioritising economic considerations over wellbeing considerations – and the potential of technological options for EDR – thus neglecting options which change the behavioural practices of households (Sakai *et al.*, 2018; Hardt *et al.*, 2019). Using the models in Table 2.4 for considering EDR therefore plays into current narratives of EDR by focusing on energy efficiency and technological change.

The wide variety of models in Table 2.5 also model a wide variety of ESDs (Table 2.6) (Hardt *et al.*, 2019). None of the models used to define the UK's demand-side policy use the same ESD categories as another, while there is also an inconsistency with the units used within each model (Table 2.6) (Hardt *et al.*, 2019). Additionally, the ESDs considered in Table 2.6 are generally modelled exogenously from the models in Table 2.4. Modelling ESDs exogenously means that while direct energy service levels are used to inform the models, change in fuels, technologies and the efficiency of the energy system do not feedback into the ESDs of households, meaning that the impact of EDR measures upon ESD levels is not considered by these thirteen models.

Table 2.5 Types and outputs of the models used to define UK energy policy. The table below is based upon information derived from Hardt *et al.*, (2019)

Model	Type of Model	Model Outputs
BEIS EDM	Econometric Model	Annual energy and emission projections.
E3ME	Macroeconometric Model	Effectiveness of climate change mitigation policies and their impact upon the economy
NISMOD	Planning Model	Tests effects of future strategies on UK infrastructure
HMRC Environmental CGE Model	Econometric Model	Economic impacts of climate change mitigation policies
UK TIMES	Energy System Model	Future energy demand estimations
ESME	Energy System Model	Simulates the least-cost method of satisfy future ESDs through technological solutions
National Transport Model	Demographic Model	Estimations of energy use and air emissions of different forms of road transport
National Household Model	Policy Model	Assesses impact of technology change upon household-level energy demand
BEIS non-domestic Building Model	Policy Model	Assessment heating, cooling and ventilation in non-domestic buildings
BEIS Industrial Pathways Model	Policy Model	Used to explore future energy use in industry
ENUSISM	Econometric Model	Projections of energy consumption in the UK's industrial sectors
Green Deal Household Model	Policy Model	Simulates uptake of insulation measures under the Green Deal
EDR Take-up Model	Policy Model	The effectiveness of financial incentives in reducing electricity demand in the business sector

The ESD categories in Table 2.6 tend to focus upon ESD categories which are supplied through direct energy consumption by households (Fouquet, 2014; Hardt *et al.*, 2019). Heating ESDs – e.g. space heating, water heating and space cooling – feature in all the models from Hardt *et al.*, (2019) which consider ESDs. Considering the heating ESDs of households across the models which include ESDs is to be expected as the decarbonisation of buildings is expected to form a significant part of the UK's demand-side pathway to net-zero (BEIS, 2021c, 2021b).

Table 2.6 Domestic energy service variables within the UK demand-side models analysed by Hardt *et al.*, (2019). This table was created by Hardt *et al.*, (2019).

Model	**Energy Service Variables (Units)**
BEIS EDM	None
E3ME Model	"Effective energy demand for space heating and hot water in residential buildings"
NISMOD	None
HMRC environmental CGE Model	"Not sufficient information"
UK TIMES	Space heating for existing homes (PJ) Space heating for new homes (PJ) Hot water demand for existing houses (PJ) Hot water demand for new houses (PJ) Lighting demand (number of units) Refrigerators demand (number of units) Freezers demand (number of units) Wet appliances demand (PJ) Consumer electronics demand (PJ) Computers (PJ) Cooking demands, other (PJ) Cooking demands, hobs (number of units) Cooking demands, ovens (number of units) Cooling demand (number of units) Others demand (PJ)
ESME	High density dwellings (number) Low density dwellings (number) Mid density dwellings (number) Domestic air conditioning (TWh) Domestic appliances (TWh) Domestic cooking (TWh) Internal temperatures
National Household Model	Internal temperature Hot water demand per person Heating schedules
Green Deal Household Model	None

Considering ESDs provided through direct energy is advantageous for studies as models are representations of reality, meaning that considering a closed system, such as the UK's energy system, is easier to consider than the global supply chain of indirect energy for all products and services required by households to fulfil their ESDs and achieve wellbeing (Wood *et al.*, 2018; Hardt *et al.*, 2019). However, from a LA perspective, this focus upon production, which is geographically separate from consumption, does not provide LAs with the EDR potential of options which they could implement (Wood *et al.*, 2018; Tingey and Webb, 2020). Considering ESDs provided by indirect energy is therefore necessary to broaden the scope of EDR options, meaning that another technique which considers household ESDs provided through both direct and indirect energy must be utilised (Wood *et al.*, 2018).

An economic modelling technique using input-output (IO) frameworks and multi-regional input-output (MRIO) models, is becoming an increasingly common methodology for considering household energy provided by both direct and indirect energy to assess the full environmental footprint of UK energy consumption (Leontief, 1936; Miller and Blair, 2009). IO modelling and environmental footprints are not used extensively in policymaking, however the IO modelling technique will be considered in Section 2.4.2.

2.4.2 Environmental footprinting

IO modelling using MRIO can consider both the direct and indirect energy consumption of a household. MRIO analyses are extended to environmental factors to construct consumption-based accounts of environmental factors, within a set boundary, using a Leontief Inverse matrix (Leontief, 1936; Lenzen *et al.*, 2003; Kitzes, 2013).

Environmental footprinting was first popularised as a concept for measuring the environmental impacts of human activities by Rees (1992) (Fang *et al*., 2013). Research into the environmental impacts of products and practices had been popular since the 1960s and 1970s in the form of life cycle assessments, however these tended to focus on issues such as resource requirements, emissions and waste within industries and companies (Guinée *et al.*, 2011). In the present day, footprinting has evolved to become one of the most common and intuitive tools utilised to communicate environmental impacts to academics, policymakers and households (Matuštík and Kočí, 2021).

There are different methodologies used to calculate and report energy footprints. The two methods predominantly used to report energy footprints are territorial-based footprints and consumption-based accounts (Figure 2.9) (Barrett *et al.*, 2013). Considering different footprinting methodologies is important for this project as territorial-based accounting can lead to the geographical separation of the energy required to fulfil ESDs from the energy service consumption of households (Barrett *et al.*, 2013).

Territorial-based accounting is the more traditional form of accounting when considering energy footprints and is utilised as an official measure of energy consumption by every country which keeps accounts of energy consumption (IPCC, 1996). Territorial-based accounting sets a boundary – e.g. a national border, a LA, or a systems process – and the energy footprint considers the direct energy consumed within that set boundary (Barrett *et al.*, 2013). For example, at a national-level, territorial-based accounting techniques which assign energy use to “national territories and offshore areas over which the country has jurisdiction” (IPCC, 1996, p5).

Conversely, consumption-based accounting instead attributes energy use based upon final consumption (Barrett *et al.*, 2013). Therefore, energy demand from outside a set boundary is embodied within products and services utilised within a footprint analysis’ boundaries (Davis & Caldeira, 2010). For example, considering the UK, if a product was produced abroad, but ultimately consumed in the UK, then the energy demand associated with the manufacture and transport of a product would be embodied within the product’s final energy demand, and would be attributed to the UK’s energy footprint; while energy embodied within products exported from the UK is attributed to the territory of final consumption (Davis & Caldeira, 2010). The UK’s consumption-based energy account was an average of 12.2% higher than the territorial-based energy account for the period 1990-2020 (Figure 2.9) (DEFRA, 2021; BEIS, 2022).

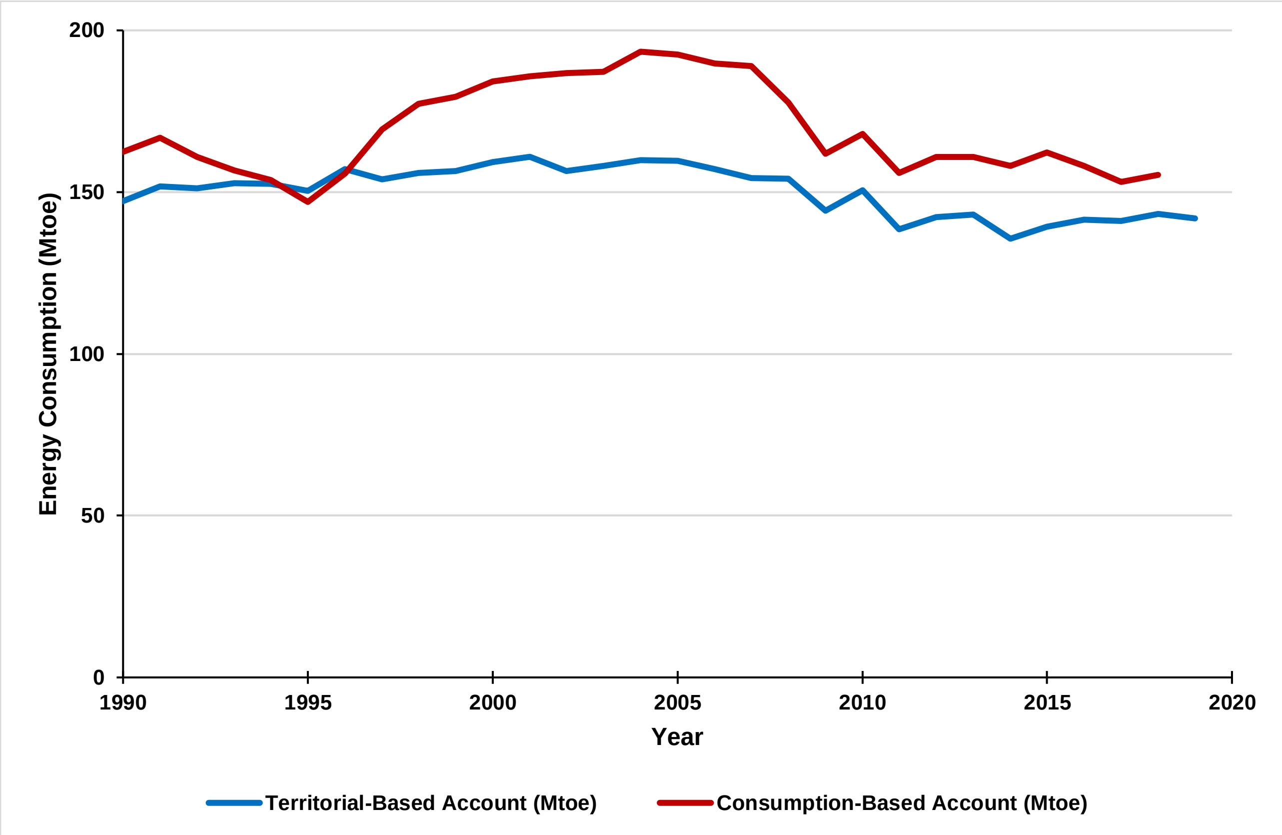

Figure 2.9 Territorial and consumption-based accounts of energy consumption in the UK between 1990 and 2019 (Data sources: BEIS (2021d); Owen (2022)).

Territorial accounting techniques are utilised by governments due to the ease with which energy footprints can be calculated (Barrett *et al.*, 2013). The methodological approach to calculating territorial energy accounts is well established, and each country has its own supply of readily available data to maintain the account, such as type of fuel consumption, and amount of fuel consumption (IPCC, 1996). This ensures the robustness of data when comparing the energy footprints of different nations (IPCC, 1996). Energy footprints using this methodology therefore focus upon direct energy and do not consider embodied energy that is generated in other territories, or from the international transport of goods and services using shipping and aviation (Barrett *et al.*, 2013).

Consumption-based accounting however, is less predominant, with few countries, such as the Department of Environment and Rural Affairs (Defra) in the UK, the Department of Climate Change, Energy, the Environment and Water in Australia, the department of Environment and Climate Change Canada, the Environmental Protection Agency through the Prince Project in Sweden and Statistics Netherlands, maintaining consumption-based environmental footprint accounts (Barrett *et* *al.*, 2013; CBS, 2022; DCCEEW, 2022; Defra, 2022; ECCC, 2022; Prince Project, 2022). For example, using the UK as a case study, the Department of Environment and Rural Affairs (DEFRA) maintains the UK's official carbon footprint statistics, publishing both a territorial and consumption-based account of the UK's carbon footprint (Defra, 2022). UK climate policy is not based on the UK's consumption-based carbon footprint account, which is produced by the University of Leeds using an environmentally extended MRIO (EE-MRIO) model (Barrett *et al.*, 2013; Defra, 2022). However, the carbon footprint is the only official consumption-based account maintained by the UK government, for example, the Department of Business, Energy and Industrial Strategy (BEIS), which produces energy consumption statistics for the UK, does not produce a consumption-based account of energy consumption statistics (BEIS, 2022a).

Consumption-based accounting more accurately reflects the landscape of actual energy consumption throughout the world by addressing the issue of carbon leakage, through the outsourcing of ESD production, and attributes environmental footprints to the final consumers of products and services – i.e. households (Barrett *et al.*, 2013). However, there are no standards established to ensure a harmonisation of consumption-based accounting methods using EE-MRIO between studies and institutions (Owen *et al.*, 2017; Owen, 2018). For example, different energy vectors – extracted energy (primary energy – e.g. coal, oil, gas) or energy use by industry (final energy – e.g. electricity) – attribute energy consumption to different sources which has implications for the analysis of energy accounting using a consumption-based account (Owen *et al.*, 2017). In the past, linking consumption-based accounts and more dynamic models used in policymaking (Table 2.4) has also proven difficult – although more work is being done on this (Owen, 2018).

At a LA-level, considering ESDs using territorial footprinting accounts of energy would exclude a significant portion of a household's energy footprint from a study boundary. Outsourcing is the main driver of the reduction in the UK's greenhouse emissions, and has maintained UK energy consumption at the same level, since 1990 (Figure 1.6) (Baiocchi and Minx, 2010; Hardt *et al.*, 2017). Therefore the level of ESDs supplied by indirect energy would be underestimated if a territorial boundary is established for the UK. Additionally, basing policy around consumption-based account of energy demand can broaden the agenda of EDR to include "policies that both affect total final demand of households and the composition of consumption" (Barrett *et al.*, 2013, p465) – i.e. avoiding and shifting energy consumption (Creutzig *et al.*, 2018; Karakaya *et al.,* 2019). Presently, consumption-based accounting is under-utilised by governments in policymaking but could play a significant role when considering the full impact of energy service consumption by households at a LA-level (Barrett *et al.*, 2013).

2.4.3 Footprinting studies

When Rees (1992) popularised the concept of environmental footprints, it was done so under the term 'ecological footprints'. Energy footprints are a subset of ecological footprints and were initially communicated as a measurement of the area of forest required to sequester the carbon associated with energy consumption (Fang *et al*., 2014). However, as the concept of footprinting has evolved, it is rare to see energy footprints given as a measurement of area, instead they are given in energy units such as joules (J), tonne of oil equivalent (toe) or kilowatt hours (kWh) (e.g. Min and Rao, 2018; Baltruszewicz *et al.*, 2021).

The increasing prevalence of footprinting means that information on the environmental impacts of different forms of consumption are increasingly available at different levels, across different scales and sectors and for different environmental issues, including energy (Minx *et al.*, 2013; Gill and Moeller, 2018; Owen and Barrett, 2020; Baltruszewicz *et al.*, 2021). Energy footprinting is reported in the UK at a national-level (Figure 1.6), however, due to the link between energy consumption and wellbeing, households have become the level at which energy footprints are reported as the distributional differences in energy consumption can be reported at this level (Vringer and Blok, 1995; Owen and Barrett, 2020; Baltruszewicz *et al.*, 2021; Baltruszewicz *et al.*, 2021; Oswald *et al.*, 2021; Vita *et al.*, 2021; Defra, 2022).

In the UK, and beyond, studies have examined the energy footprints of households across different countries (Oswald *et al*., 2020), income deciles (Owen and Barrett, 2020; Baltruszewicz *et al.*, 2021), as well as identifying the direct and indirect energy requirements of households in different countries (Vringer and Blok, 1995; Park and Heo, 2007; Druckman and Jackson, 2009; Eriksson *et al*., 2021), and across the rural-urban divide (Ding *et al.*, 2017). Understanding the distribution of energy consumption across different groups of households is important for EDR as this knowledge helps understand the areas in which energy consumption should be undertaken – e.g. housing, transport or nutrition. From a policy perspective, footprinting is therefore important for ensuring a just demand-side transition.

Footprinting studies analysing consumption have identified income as a driver of household-level consumption for energy, and other environmental footprints, such as carbon footprints (Abdallah *et al.*, 2011; Ivanova *et al.*, 2016; Owen and Barrett, 2020; Baltruszewicz *et al.*, 2021). Households with higher income have to use a smaller proportion of their expenditure on essential ESDs, such as heating and nutrition, and have a larger level of disposable income to spend on less essential activities, such as recreation, therefore leading to a higher energy footprint (Owen and Barrett, 2020).

However, other studies have identified income as only one of many socioeconomic factors associated with high consumption (Minx *et al.*, 2013; Eriksson *et al*., 2021; Salo *et al.*, 2021). Minx *et al.*, (2013) identified car ownership per household and education level have a strong positive effect upon the size of a household's footprint, while household size had a strong negative effect upon household footprints. Other studies have suggested a geographical dimension to large environmental footprints across the rural-urban divide in developing countries (Baltruszewicz *et al.*, 2021), although this is less pronounced in developed countries such as Germany and the UK, whereby it is more likely that socioeconomic factors lead to a lack of service access rather than geographical factors (Minx *et al.*, 2013; Gill and Moeller, 2018).

At present, in the UK, the environmental footprints of households are well understood, particularly across income groups (Minx *et al.*, 2013; Owen and Barrett, 2020). However, for energy footprints, how ESDs map to different LAs across the country remains a gap in the UK's extensive energy statistics datasets. As stated in Section 1.1.4, the UK government keeps detailed records of energy consumption at different levels, across different sectors and for different fuels (BEIS, 2021d). However, the extent of end-use data is limited to a national-level for fuel type, therefore only considering the ESDs provided by direct energy (ECUK, 2022).

Beyond UK Government data, studies have quantified the UK household environmental footprint at a local level (Minx *et al.*, 2013; Eriksson *et* al., 2021). However, Minx *et al.*, (2013) consider only the total carbon footprint of households in 434 UK municipalities, while Eriksson *et al*., (2021) consider the energy footprint of households at a LA-level in the UK, but do not break down the energy footprint beyond the direct energy footprint and indirect energy footprint of households.
The Centre for Research on Energy Demand Solutions (CREDS) place-based carbon calculator is another tool for examining environmental footprints across space in England (Figure 2.10). The CREDS place-based calculator is an informational tool which calculates consumption-based per capita carbon footprints of all sectors at the Lower Layer Super Output Area (LSOA) level, as well as the average energy performance certificate (EPC) rating of homes in an area (CREDS, 2022).

However, the CREDS place-based carbon calculator is designed to estimate carbon footprints, not energy footprints (CREDS, 2022). There is generally correlation between the size of an energy footprint and the size of a carbon footprint, however, they are not directly comparable, meaning that it would be difficult for this tool to fully inform energy demand policy at a LA- level.

There is therefore a lack of information about the ESDs of households. Considering EDR from a perspective which places ESDs at the forefront of demand-side planning is therefore difficult without a database of how ESDs presently vary across the area within which EDR will be considered.

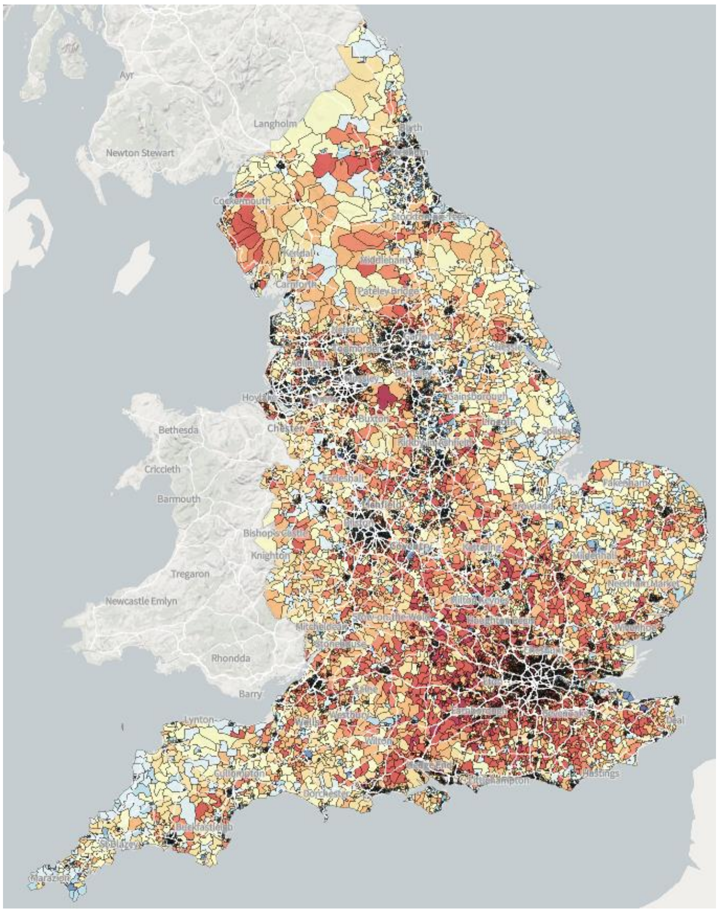

Figure 2.10 An image taken from the CREDS carbon calculator. The image shows the carbon footprint of different LSOAs throughout England (Source: CREDS, 2022).

2.5 Summary and conclusions

As established in Chapter 1, EDR is vital in order to meet the UK's long-term climate goals, and the international climate goals in the Paris Agreement (Masson-Delmotte *et al.*, 2018; BEIS, 2021c). However, as yet, despite large reductions in UK territorial emissions since 1990, UK final energy consumption is yet to significantly decrease below 1990 levels (Figure 1.6) (BEIS, 2022b; ECUK, 2022).

The literature review in Chapter 2 has analysed the current discourses surrounding energy demand and EDR to identify potential gaps and barriers to effective EDR. The dominant framing of energy in frameworks and models presents energy demand as a product of the energy system, with a focus on the direct ESDs provided to households to achieve wellbeing (Section 2.1 and Section 2.3) (Sorrell, 2007). The focus upon delivering direct ESDs to households without compromising wellbeing has led to energy efficiency becoming the dominant framing of EDR in the UK, and beyond (Section 2.1) (Sorrell, 2007).

However, the dominance of the energy efficiency framing for EDR, has led to a reliance upon technical improvements in energy service delivery, to deliver EDR, with changes in household behaviour and practices being given less attention by the UK government (Section 2.1.1) (Shove, 2018; BEIS, 2020b). In particular, measures which would avoid household energy demand have been specifically neglected by the UK government (CCC, 2021). Arguments against reducing energy service levels have centred on the coupling of wellbeing and energy demand as citizens should not have to compromise their wellbeing to achieve EDR (Section 2.1.2) (Brand-Correa *et al*., 2018). However, energy demand and wellbeing are not directly coupled, as evidenced by the concepts of overconsumption, energy sufficiency, the wellbeing co-benefits of EDR, and the five types of capital model (Section 2.1.2) (Daly, 1991; Sachs, 1993; Princen, 2005; Rockström *et al.*, 2009; Raworth, 2012). It is therefore possible to reduce energy service levels, by avoiding energy use of shifting to less energy intensive practices, without compromising the wellbeing of citizens (Section 2.1.2) (Creutzig *et al.*, 2018).

The UK's demand-side policy discourse has focused predominantly on energy efficiency, with some flagship policies, such as the Green Deal and Green Homes grant being less successful than initially expected (Section 2.2.1) (Rosenow and Eyre, 2016; BEIS, 2020b, 2021c; Kenyon, 2021a). However, despite the UK government's reluctance to devolve powers to LAs, LAs have shown greater ambition with reducing energy demand through measures which avoid and shift energy demand, than the UK national government despite having no specific powers to set energy policy (Section 2.2.2; Section 2.2.3) (Friends of the Earth, 2019; LGA, 2019; Tingey and Webb, 2020; Climate Emergency UK, 2022; mySociety, 2022). The ambition of LAs raises questions around the concept of subsidiarity and whether EDR would be quicker, and more effective, using a disaggregated approach to EDR, whereby more funding is devolved to LAs to allow them to enact their own EDR measures for households (Wanzenböck and Frenken, 2018).

The concept of ESDs provides a lens through which the social and technical aspects of energy demand can be analysed in tandem as providing ESDs to households is the ultimate goal of the energy system, which are demanded by households to achieve wellbeing (Chapter 1) (Brand-Correa *et al*., 2018). As with energy demand, ESDs are often framed as the product of the energy system provided by direct energy, thus reinforcing the energy efficiency discourse when considering EDR for energy services (Section 2.3) (Sorrell, 2007). However, ESDs do not necessarily have to be limited to services provided directly from the energy system, ESDs can also be provided through indirect energy embodied in products and services (Section 2.3.3) (Haas *et al.*, 2008). Considering ESDs provided through indirect energy, as well as direct energy, provides a more realistic representation of the energy demand required to fulfil household ESDs and broadens the scope of EDR options for households (Barrett *et al.*, 2013).

The ESDs framing of energy demand and EDR is advantageous for LAs when considering EDR, as local councils are responsible for households, which are linked to the energy system through the consumption of products and services. By considering the ESDs of households, LAs can therefore consider the effect of different consumption-based EDR options upon the entire energy system.

The ESDs of households at a LA-level can be modelled using IO modelling (Section 2.4). Modelling energy footprints using IO modelling allows insights into energy consumption across space, income groups and different geodemographic groups, therefore using the socioeconomic information associated with microeconomic data collected in surveys, ESD footprints of each LA can be calculated (Druckman and Jackson, 2009; Minx *et al.*, 2013; Owen and Barrett, 2020). However, at present, the UK does not keep consumption-based accounts of the UK's household energy consumption (Section 2.4). The UK maintains statistics on domestic fuel consumption by fuel type at a LA-level, however when considering ESD statistics, the UK government only maintains national-level statistics on services provided by direct energy use (Section 2.3.2) (BEIS, 2021d).

Based on the review of presently available literature on demand-side mitigation, LAs possess greater ambition than the national government when considering EDR, however they do not possess the funding, to enact EDR policy specific to their locality (Tingey and Webb, 2020; Climate Emergency UK, 2022; mySociety, 2022). Subsidiarity offers the opportunity to accelerate the demand-side transition in the UK, however there are significant gaps which need to be addressed to assess whether more funding should be devolved to LAs to enact EDR.

Firstly, the framing of the energy system needs to evolve in academic publications, and policy considerations, in order to shift the EDR discourse beyond energy efficiency, and examine the entire energy system from a LA perspective. Framing the energy system around household ESDs places consumption at the forefront of demand-side considerations, and therefore the drivers of energy use at the beginning of demand-side analyses. Additionally, the energy system framing should be able to account for the household ESDs provided by indirect energy to more realistically reflect household energy consumption in the UK, and to expand the number of EDR options available to LAs. A framework for examining the energy system in this way will be set out in Chapter 4, and will be entitled the service-driven energy demand chain (SEDC) framework.

Secondly, as identified in Section 2.4.3, there is no database of household ESDs at a LA-level in the UK beyond the national-level account of direct energy use, a gap which needs to be addressed. Going beyond direct energy to consider the indirect energy embodied in products and services, and the services they provide, gives a more accurate representation of energy consumption in the UK which is a net importer of energy. Additionally, understanding ESDs at a LA-level is important as energy consumption varies across space and household type (Section 2.4.3), meaning that a LA-level ESD footprint will be more representative of the energy consumption of households, and will provide more insight, than a national average footprint. The LA-level ESD footprints can then be analysed to assess whether the range, and clustering of ESD footprints across space suggests that a disaggregated approach to EDR, through subsidiarity, may benefit reducing energy consumption for each ESD category. The LA-level ESD footprints are modelled in Chapter 5.

Thirdly, Section 2.1 identified the dominant discourse in EDR policy – energy efficiency – and that it is unlikely that energy efficiency alone can achieve the reductions in energy demand necessary to reach the UK's net-zero target and the global 1.5°C temperature target. Understanding the EDR potential of strategies which go beyond energy efficiency whilst maintaining service levels, and without compromising wellbeing is important to demonstrate that effective EDR can be undertaken beyond technical energy efficiency improvements without a reduction in quality of life. The database of ESDs established in Chapter 5 will be used as a baseline from which four service-oriented strategies are modelled to show the potential of EDR in GB in Chapter 6. Chapter 6 also examines the variation in EDR across space in GB by modelling EDR at a LA-level, as well as a national-level. Modelling EDR for LAs is important to identify whether the potential of each strategy varies significantly across space, and therefore a more localised approach to EDR would be appropriate.

Finally, Chapter 7 will then draw this work together by identifying whether LAs with higher capacity to adopt EDR measures also exhibit higher ESDs and higher EDR potential under the four service-oriented strategies. Assessing the correlation between areas of high consumption, high reduction and high capacity to act will allow an assessment of whether funding to enact EDR options should be devolved to LAs or kept at a national-level.

The results of the thesis will be discussed in Chapter 8 to whether the thesis answered the research questions set out in Section 1.2, before conclusions are drawn in Chapter 9. Before the research in this thesis can commence however, Chapter 3 will set out the methodological basis from which the subsequent chapters will be based, and the different methodologies used throughout the thesis.

3 Methodology

The following chapter sets out the methodological basis for the subsequent research reported in this thesis. The methodology chapter will provide methodological descriptions and justifications for the techniques undertaken to examine the Local Authority (LA) level energy service demand (ESD) footprints of households in the Great Britain (GB), model the LA-level energy demand reduction (EDR) potential of different strategies, and assess household capacity to adopt EDR strategies across GB.

Firstly, Section 3.1 sets out the methodological basis for input-output (IO) modelling and the UK multi-regional input-output (MRIO) modelling database. IO Modelling is the method fundamentally underpinning the work in this thesis, with the generation of LA-level consumption-based ESD footprints, and the potential of different EDR strategies both calculated using IO methods. The LA-level ESD footprints modelled using IO modelling will be analysed in Chapter 5, and the EDR potential of different service-oriented EDR strategies will be set out in Chapter 6 (Table 3.1).

Secondly, Section 3.2 sets out the methodological approach to modelling household ESD footprints for GB, and outlines the method for disaggregating the ESD footprints to different LAs throughout GB. As stated previously, the ESD footprints will be analysed in Chapter 5 (Table 3.1). Section 3.2 also discusses the dataset used to calculate the LA-level ESD footprints.

Thirdly, Section 3.3 outlines the paper from which the policy options, modelled in the four EDR strategies in Chapter 6, are identified (Ivanova *et al.*, 2020). Section 3.3 will define the four EDR strategies, and outline the EDR options omitted from the strategies. Subsequently, Section 3.4 will set out the IO-based equations used to model the EDR strategies in Chapter 6 (Table 3.1). The present-day ESD levels of each LA, modelled in Chapter 5, will serve as a baseline for the EDR strategies in Chapter 6.

Finally, Section 3.5 sets out the method for calculating household capacity to adopt EDR strategies for each LA throughout GB (Table 3.1). The capacity index (CI) scores of each LA will be analysed against the household ESD footprints modelled for each LA (Chapter 5), and the EDR potential of the Full Consideration (FC) strategy (Chapter 6) to assess whether there is correlation between LAs modelling high levels of ESDs, EDR potential, and CI scores.

Table 3.1 Mapping table of methodology sections to PhD thesis chapters.

Methodology section	PhD chapter mapping
Section 3.1: Input-output modelling.	**Chapter 5**: Great Britain's energy service demands at a Local Authority-level. **Chapter 6**: Energy demand reduction strategies at a Local Authority-level.
Section 3.2: Modelling energy service footprints at a LA-level.	**Chapter 5**: Great Britain's energy service demands at a Local Authority-level.
Section 3.3: Energy service policy options at a LA-level.	**Chapter 6**: Energy demand reduction strategies at a Local Authority-level.
Section 3.4: Modelling the EDR potential of four service-oriented strategies.	**Chapter 6**: Energy demand reduction strategies at a Local Authority-level.
Section 3.5: Feasibility of EDR strategies	**Chapter 7**: Household capacity to adopt energy demand reduction strategies at a Local Authority-level.

3.1 Input-output modelling

IO modelling is the methodological basis for generating LA-level ESD footprints in Chapter 5, and the EDR potentials modelled in Chapter 6. Section 3.1 sets out the calculations needed to utilise IO modelling for generating LA-level energy footprints.

3.1.1 Multi-regional input-output models

A MRIO table is an IO table which contains the economic transactions that occur to produce products between different sectors across multiple regions (Figure 3.1) (Miller and Blair, 2009). IO modelling is a form of economic modelling, which was initially designed to demonstrate the interdependence of different sectors within the US economy upon each other (Leontief, 1936).

However, IO modelling has evolved since 1936. Due to the globalised nature of the economy, IO modelling now must encompass trade between different sectors of countries throughout the world. Computer modelling allows IO modelling to be undertaken much more quickly than in 1936. The speed at which IO can be undertaken allows the basic IO modelling framework to be extended in order to include different elements of economic activity within IO calculations (Miller and Blair, 2009).

The environmental factors associated with economic activity and the production and consumption of goods and services are one such extension of IO modelling (Miller and Blair, 2009). Extending the IO framework to environmental factors has allowed studies to construct consumption-based accounts of a country's environmental impacts, including emissions and energy use (Miller and Blair, 2009; Kitzes, 2013). A Leontief Inverse Matrix is used to do this (Miller and Blair, 2009). Using a Leontief Inverse Matrix allows the economy to be disaggregated, and allows the full supply chain requirements required to make a single unit of final demand to be calculated. The Leontief Inverse Matrix incorporates the requirements from every industry in every world region and can also be used to calculate the economic effect as a result of increasing or reducing production (EUStat, 2023).

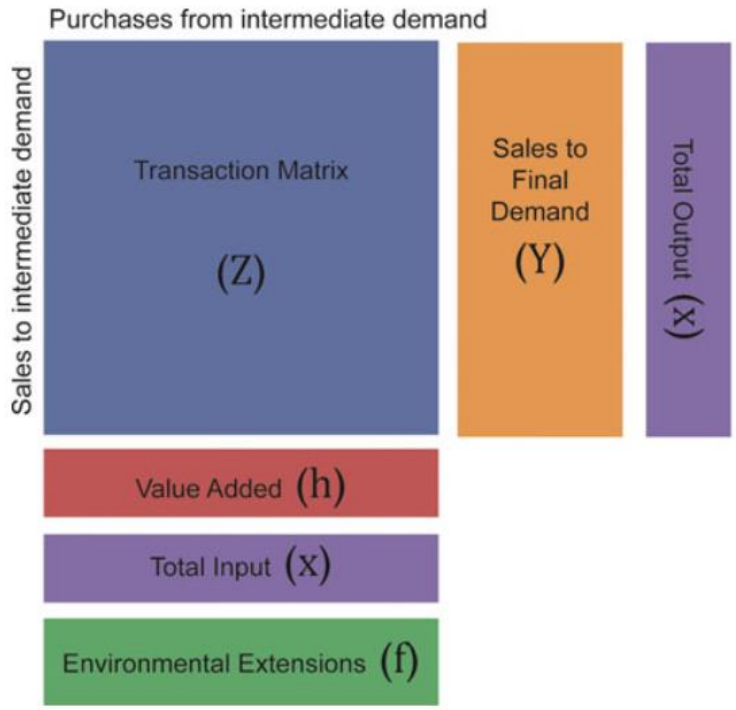

Figure 3.1 Structure of an MRIO framework. An MRIO table is balanced, meaning that the Total Input (x) equals Total Output (x) (Source: Owen, 2018).

To calculate the Leontief Inverse (L), the Transaction Matrix (Z) needs to be transformed into a Requirements Matrix (A). A equates to the total contribution that each element within Z makes towards the total output (x) of the MRIO (Miller and Blair, 2009; Owen, 2018). A is generated by an element-wise division of Z by the corresponding value of x (Equation 1). Each element of Z can be expressed as Zmn, where m is the row location of the element and n is the column location of the element (Miller and Blair, 2009; Owen, 2018). This allows the replacement of each element within Z with:

$$A_{mn} = Z_{mn}/x_n$$

Equation 1

to form A, which is then used to calculate L (Equation 2). L is the inverse of A subtracted from an Identity Matrix (I) I is a matrix the same size as A but containing only ones on the matrix's diagonal elements (Equation 2) (Miller and Blair, 2009; Owen, 2018). The equation to calculate L from these matrices is:

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}}$$

Equation 2

L links total output (x) with final demand (y) (Equation 3):

$$x = Ly$$

Equation 3

L is calculated on a product-by-product basis and sets out the effects of changes in demand on the production of goods (Miller & Blair, 2009). L can also be used to extend the MRIO table to environmental indicators. Using energy footprints as an example, an energy intensity vector (e) needs to be calculated, which is done by multiplying f, a row vector of the annual energy demand by each sector, by the inverse of x (Miller and Blair, 2009; Owen, 2018). However, it is not possible to calculate the inverse of a non-square matrix, therefore x needs to be converted to a diagonal matrix ($xdiag$) (Equation 4):

$$\boldsymbol{xdiag} = \boldsymbol{diag}(\boldsymbol{x})$$

Equation 4

$$\boldsymbol{e} = \boldsymbol{f}(\boldsymbol{xdiag})^{-\mathbf{1}}$$

Equation 5

Generating e allows the amount of energy use per currency unit of output to be calculated for every industry throughout the world (Equation 5) (Miller and Blair, 2009; Kitzes, 2013). e therefore represents the energy intensity of specific economic activities and is used to identify the energy associated with the production and consumption of goods and services, which can then be summed to generate a consumption-based account of the energy footprint of economic systems (Equation 5) (Miller and Blair, 2009). Multiplying e by final demand (y) and the Leontief Inverse (L) allows the consumption-based account of the energy use of the total output of the MRIO to be quantified (Q) (Equation 6):

$$\boldsymbol{Q} = \boldsymbol{eLy}$$

Equation 6

Consumption-based energy accounts can then be broken down by countries and industries to assess the energy footprint of specific areas of the MRIO (Equation 7; Equation 8) (Miller and Blair, 2009; Kitzes, 2013). For example, to calculate the consumption-based account of the UK's and the EU's energy use from the MRIO, the specific columns of the UK's (y_{UK}) (Equation 7) and the European Union's (y_{EU}) (Equation 8) final demand need to be isolated. y_{UK} and y_{EU} can then be used to calculate the consumption-based energy accounts of these two regions (Equation 7; Equation 8):

$$Q_{UK} = eLy_{UK}$$

Equation 7

$$Q_{EU} = eLy_{EU}$$

Equation 8

3.1.2 UK MRIO Database

The UK's officially reported consumption-based account for carbon dioxide (CO_2) and other greenhouse gases is calculated by the University of Leeds using the UK-MRIO database, which they also construct (Defra, 2022). The UK-MRIO database is used to create the consumption-based account of ESD footprints at a LA-level across GB in Chapter 5. As a consumption-based account, this therefore includes the energy embodied in products and services used to meet demand (Barrett *et al.*, 2013).

The consumption-based account is an official statistic, meaning that the MRIO database must be generated using IO data produced by the Office of National Statistics (ONS) (Defra, 2022). Additional data on UK trade with other nations, as well as how these other nations trade between themselves, is collected from the EXIOBASE MRIO database and used to supplement the UK-MRIO (Wood *et al.*, 2015).

Supply and Use Tables (SUT) are produced by the ONS on an annual basis using a 106 sector disaggregation (Wiedmann *et al.*, 2010). The combined use tables represent the inter-industry transaction table as the sum of both domestic transactions and intermediate imports, while the final demand table shows the sum of both domestic and imported final products (Wiedmann *et al.*, 2010). The ONS produces a set of analytical tables on a 5-yearly basis, where only domestic use is shown by the table (ONS, 2022). Domestic purchases are shown separately from final demand (ONS, 2022).

Domestic data is extracted from the annual SUT tables by taking proportions of domestic versus imports from the analytical tables. Intermediate industry imports become a single row of data and both intermediate exports, and final demand, are a single column of data.

EXIOBASE MRIO data is used to disaggregate the imports and exports other sectors from across different world regions. However, before doing this, the data is converted to Great Britain Pounds (GBP) and mapped onto the UK's 106 sector aggregation. The UK-MRIO model uses monetary variables in constant prices by applying the double deflation method.

UK-MRIO data is then aligned with UN Classification of Individual Consumption by Purpose (COICOP) product categories, of which there are 307 (UN, 2018). The UN COICOP product categories and the associated energy data for products, as well as spend per product and energy intensity were aggregated further into 10 ESD categories, and 42 sub-categories (Appendix 2). It is these ESD categories that will be used in a concordance matrix in Chapter 5 to attribute energy consumption to different ESD categories (Appendix 1).

3.2 Modelling energy service footprints at a LA-level

Modelling ESDs at a LA-level using IO modelling, means that the footprints will be consumption-based accounts of energy consumption, and will therefore include both the direct energy and indirect energy required to satisfy household ESDs. The ESDs footprints in Chapter 5 are attributed to LAs using expenditure survey microdata.

3.2.1 The Living Costs and Food Survey

The use of expenditure surveys to generate spatially distributed environmental footprints is common practice in many studies (Donato *et al*., 2015; Ivanova *et al.*, 2017; Wiedenhofer *et al.*, 2018; Ivanova and Wood, 2020; Owen and Barrett, 2020). The footprints generated from expenditure data have been utilised for a variety of different studies including an analyses of urban and regional sustainability (Donato *et al*., 2015) and reducing the level of inequality associated with a UK low carbon tax (Owen and Barrett, 2020). While other studies have analysed footprints across continents (Ivanova and Wood, 2020), across regions within countries (Gill and Moeller, 2018), and across income groups (Wiedenhofer et al., 2019).

Household-level expenditure in the UK has been collected annually by the ONS since 1957 (UK Data Service, 2023). This expenditure microdata has been collected using the Living Costs and Food survey (LCFS) since 2008 (ONS, 2017). The LCFS generally receives responses from between 5,000 and 6,000 households per year, and is used to provide information on UK household expenditure, as well as the effect of taxes and benefits upon expenditure (ONS, 2017; Owen and Barrett, 2020).

LCFS respondents are asked to keep a detailed expenditure diary over a two-week period which tracks expenditure alongside the products that expenditure is spent upon (ONS, 2017; Owen and Barrett, 2020). Expenditure data is collected on frequent purchases, such as grocery and petrol, infrequent purchases, such as sports club memberships, and flights, meaning that international aviation can be accounted for in these expenditure microdata profiles. The LCFS contains over 300 unique product types which align with Eurostat's COICOP product categories (ONS, 2017; Owen and Barrett, 2020; UK Data Service, 2023). Raw LCFS data is then processed to create a derived dataset which shows each household's average weekly expenditure on different COICOP products (ONS, 2017).

Raw data is then weighted to ensure that the sample is representative of all households throughout the UK. The ONS provides the household weights in the LCFS (UK Data Service, 2023). Household weights are used to calculate the proportion of households within the UK that each survey respondent represents (UK Data Service, 2023). The household weights allow the LCFS dataset to be scaled up to be representative of the UK population (UK Data Service, 2023). For example, in the 2017/18 survey, the sum of the weights is 27,138,781 which is the total number of households in the UK, and the first survey's weight 8,957, which means that the first survey represents 0.03% of all households in the UK with similar socioeconomic characteristics to the surveyed household. Weighting the LCFS expenditure data accounts for sample size issues, as well as sampling errors and differences in household compositions which can lead to inaccurate results being generated from social expenditure surveys (Owen and Barrett, 2020; UK Data Service, 2023).

Expenditure microdata collected in social surveys is a useful data source for footprinting studies (Büchs and Schnepf, 2013). The ESD footprints in Chapter 5 will be generated from the expenditure data collected in the 2015/16, 2016/17 and 2017/18 LCFS. However, the LCFS expenditure microdata must be converted to energy data for LA-level energy service footprints to be generated.

3.2.2 Converting Expenditure Data into Energy Service Footprints

The multipliers used to generate the ESD footprints from the LCFS in Chapter 5 are calculated by dividing energy consumption per COICOP category – calculated in the UK MRIO – by the total spend per COICOP category in the LCFS[14] (Wiedmann *et al.*, 2010; UK Data Service, 2023). The multipliers represent the energy intensity per pound for different products. Therefore by using element-wise multiplication on the spend per product, which is taken from the LCFS, and the energy intensity per pound spent multiplier, calculated in the UK MRIO, the energy consumption of a household on a specific product or set of products can be calculated (Wiedmann *et al.*, 2010; UK Data Service, 2023). This allows the energy footprint of a household to be generated. Table 3.2 and Figure 3.2 show how the expenditure data from the LCFS and the multipliers are used to generate energy footprints for products and services. The results of applying this conversion method to LCFS data from 2015/16, 2016/17 and 2017/18 can be seen in Section 5.1.

[14] Calculating the multipliers using this methodology allows the multipliers to account for VAT as the spend data in the LCFS contains VAT.

Table 3.2 Extract of a sub-chapter of LCFS data from 2016/17 to show different expenditures, multiplier of kg of oil equivalent per £ spent, and energy consumption across different products and services. Expenditure and energy consumption statistics are for UK-wide totals.

Product	Expenditure	Multipliers (kgs of oil equiv. per £ spent)	Energy Consumption (kgs oil equiv.)	Energy Consumption (Mtoe)
Electricity	£15,677,392,903	0.069016581	1082000050	1.08
House Maintenance	£7,222,303,332	0.034866299	251814990	0.25
Petrol	£17,799,608,278	1.344450038	23930674027	23.9
Air Fares (International)	£39,453,143,290	0.37548513	14814068656	14.8
Beef	£2,709,951,441	0.200865744	544336412	0.54
TV Purchase	£1,024,411,889	0.216327992	221608967	0.22
Toilet Paper	£1,080,225,707	0.579128598	625589600	0.63
Contents Insurance	£3,223,010,365	0.048427599	156082655	0.16

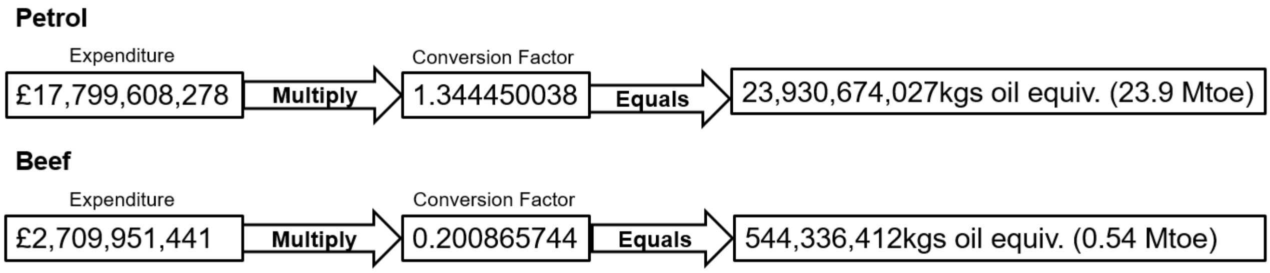

Figure 3.2 Example to illustrate how the multipliers are used to generate energy consumption data for different products.

3.2.3 Attributing Energy Consumption to Energy Service Demands

In Chapter 5, allocating energy consumption data generated from LCFS expenditure microdata to different ESD categories, requires the use of a concordance matrix. The concordance matrix used in this study is based upon an approach used by Vita *et al.* (2019). Using a concordance matrix offers the ability to proportion an energy footprint between different ESD categories (
Figure **3.3**).

Figure 3.3 Example to illustrate how the concordance matrix proportions energy data into different energy service categories.

For each product or service, a weight can be applied to calculate the amount of energy consumption of the total that fulfils each different ESD category being analysed in this study (Vita *et al.*, 2019). For example, the amount of energy consumed from the use of gas in the household can be apportioned between space heating, water heating and cooking. This is useful as it allows energy consumption to deliver multiple ESDs (Grubler *et al.*, 2018).

Integrating a concordance matrix at the end of the MRIO framework extends the MRIO to account for the ESDs of surveyed households in social surveys (Wiedmann *et al.*, 2010; Vita *et al.*, 2019; UK Data Service, 2023). This allows the easy conversion of different COICOP product categories into the respective ESD categories which they are fulfilling. The concordance matrix multipliers for each COICOP category can be seen in Appendix 1.

3.2.4 Energy Service Categories

Section 2.2.2 and Section 2.2.3 highlight the inconsistency in ESD categories used across different studies and models in both academia and policymaking (Fell, 2017; Hardt *et al.*, 2019). Using a consumption-based approach to model the LA-level ESD footprints of households, ESD categories therefore need to account for indirect energy, as well as direct energy.

Table 3.3 sets out the energy service categories that will be used to generate local-level energy service footprints for this study. The energy service categories in Table 3.3 are adapted from the categories set out by Owen & Barrett (2020).

The ESD categories in Table 3.3 represent all aspects of household energy footprints. Each category can include direct energy, as well as indirect energy embodied in the products and services purchased to achieve household ESDs. This is important to remove the distinction between direct and indirect energy in order to focus on all aspects of energy consumption, as well as direct energy.

Table 3.3 Different forms of ESD used for analysis in this study, and a description of what is included within each category. The COICOP codes used in each category are set out in Appendix 1.

Energy Service	Description
Heating	Includes direct energy, such as gas and electricity, to provide space and water heating, as well as indirect energy services to maintain the domestic appliances that deliver heating energy services to households.
Other Shelter	Includes direct energy associated with lighting and powering appliances, and the indirect energy required to produce and deliver new household appliances to households.
Personal Transport	Includes the direct energy produced by fuel to power personal vehicles such as cars and motorcycles, as well as the indirect energy associated with the production of new vehicles and the repair of older vehicles.
Public Transport	Energy associated with the use of different forms of public transport.
Aerial Transport	Energy associated with the use of air travel, whether that is for commuting or recreational purposes.
Nutrition	Includes the indirect energy associated with the production and transport of food required for nutrition to households, as well as direct energy required for cooking.
Recreation & Communication	Indirect energy associated with recreational activities and communication.
Consumer Goods	Includes the indirect energy associated with the production of items such as clothing, footwear, jewellery, hair products and toilet paper.
Services	Includes the indirect energy required to provide services such as healthcare and education, as well as other services, such as financial services.

The primary differences between the ESD categories in this study, and those of Owen & Barrett (2020), are the removal of the 'domestic gas & electricity' category, and the inclusion of the 'heating' and 'public transport' ESD categories. 'Domestic gas & electricity' has been removed as this represented all direct energy associated with the household heating and power, and did not set out the specific ESD categories that this direct energy use is associated with (Owen and Barrett, 2020). By including a heating ESD category, and splitting the remaining direct energy use across the other shelter and nutrition ESD categories, it becomes easier to identify how direct energy is utilised by households.

The inclusion of a 'public transport' ESD category was undertaken as the extent, density and type of public transport infrastructure differs significantly at a LA-level. Additionally, the 'mobility (other)' and 'consumables' ESD categories from Owen & Barrett (2020), have not been removed, but have been renamed to 'personal transport' and 'consumer goods' respectively.

3.2.5 Disaggregating ESD footprints to LAs

LAs have been selected as the level at which ESD footprints will be modelled as LAs possess powers that govern many areas of policymaking (Section 2.5) (Paun *et al*., 2019). Additionally, LAs are the lowest level of the UK multi-level governance structure (Section 2.4) (ONS, 2020). The ESD footprints of LAs in Northern Ireland will be excluded from this analysis as the LAs in Northern Ireland are ceremonial and possess very limited powers (Greer, 2019).

However, the LCFS does not report expenditure microdata at a LA-level (UK Data Service, 2023). Each respondent provides address-level expenditure microdata to the LCFS, however the sample size for each LA is so small that the sample would not be representative if LA ESD footprints were calculated directly from LCFS data from within each LA (UK Data Service, 2023). Therefore, LA ESD footprints must be modelled from the complete expenditure microdata sample collected in the LCFS (UK Data Service, 2023).

Social surveys, such as the LCFS, collect household-level expenditure microdata across nations in order to understand the expenditure patterns of households across different socioeconomic groups (UK Data Service, 2023). From this data national-level consumption-based accounts of energy footprints can be generated (Owen and Barrett, 2020). Therefore in order to use the LCFS to build LA-level ESD footprints for LAs across GB, the national-level footprint must be disaggregated using the social microdata collected alongside the expenditure microdata in the LCFS (Büchs and Schnepf, 2013; Owen and Barrett, 2020).

The LCFS collects information on the region in which of the twelve Government Office Regions across the UK within which each individual LCFS is conducted (Figure 2.6) (ONS, 2021). For example, a survey undertaken in North-East England is classed as Region 1, whereas a survey conducted in Scotland is classed as Region 11 (ONS, 2021). Households across regions share similarities, such as households in the London region being classed as predominantly urban households, households in the Wales region will predominantly be classed as rural households (ONS, 2021). However, regions are not homogenous entities, with regions such as North-West England containing predominantly sparsely populated rural LAs, such as Allerdale and South Lakeland, while also containing densely populated urban LAs such as Liverpool and Manchester (ONS, 2021). ESD footprints therefore cannot be generated from expenditure microdata and regional information alone.

In addition to regional information, each LCFS also contains household-level geodemographic information known as an output area classification (OAC) (Appendix 3) (ONS, 2015, 2018, 2021). OACs are a set of criteria generated from UK census data which define the social, economic and geographic characteristics of households in the UK across different output areas (Appendix 3) (ONS, 2018; Doorda, 2021). The OACs in LCFSs used in this thesis are generated from the 2011 census data (Figure 3.4) (ONS, 2018). OAC groups are defined based upon a set of 167 statistics covering socioeconomic and demographic factors which are transformed and standardised before households are clustered based upon 59 of the initial 167 statistics (Figure 3.4) (ONS, 2018).

OACs are set out into three different categories: super-groups, groups and subgroups, with each of these three groups providing further detail into a household’s geodemographics (Doorda, 2021). Individual households in the UK are not defined under this system, however groups of households with similar characteristics are collated into census output areas (geographic areas comprising ~150 households) which are classified into different OAC categories (ONS, 2018; Doorda, 2021).

OAC data in the LCFS allows the segmentation of expenditure microdata, and therefore household ESD footprints, as the number and proportion of households by each OAC in each LA can be calculated from publically available data (Druckman and Jackson, 2009). Spend profiles for each OAC subgroup can be calculated from LCFS data (Druckman and Jackson, 2009). LA spend profiles, and ESD data, are then generated based upon the proportion of households of each OAC subgroup that are found in the LA (Druckman and Jackson, 2009).

Ideally, the spend profiles, and therefore ESD profiles, of each LA, will be modelled based upon OAC subgroup data for the Government Office Region in which the LA is located. However, if the sample size is not large enough (>20 responses) for the OAC subgroup for a particular region, the LA profile will be generated from OAC group data, or OAC supergroup data if the number of OAC group survey responses does not exceed 20 in a particular Government Office Region. If the survey responses in a particular Government Office Region for OAC supergroup, group and subgroup do not exceed 20, then the LA spend profile will be generated from national data for the initial OAC subgroup instead. Similarly, if the OAC subgroup data at a national-level do not exceed 20 survey responses, then spend profile, and therefore ESD data, is generated from national-level OAC group data or OAC supergroup data if the requisite number of survey responses are not exceeded at a national-level for the respective OAC group.

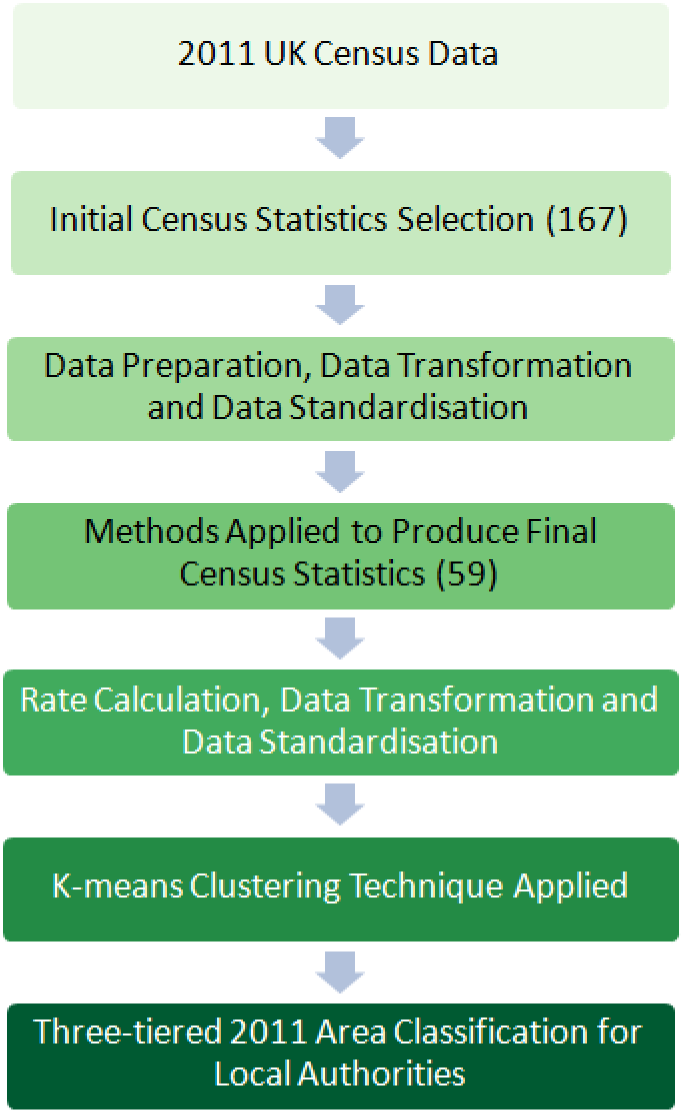

Figure 3.4 Calculation method used to generate output area classifications for the UK (ONS, 2018).

Modelling ESD footprints using this methodology guarantees the robustness of the spend profiles, and ESD data generated from the LCFS by ensuring that LA data is not modelled based upon a small sample size or single survey response. The spatial disaggregation of the LCFS data using OAC data has been used previously be papers such as Druckman and Jackson (2009).

3.2.6 ESD footprint analysis

3.2.6.1 Energy service demand footprint analyses

Once the ESD footprints have been generated in Chapter 5, analyses will be undertaken upon the results. The highest and lowest consuming areas of GB will be identified, as well as the range of values modelled across GB, within each ESD category (Minx *et al.*, 2013). A large range of ESD footprint values would indicate that a disaggregated policy approach to EDR should be considered.

Alongside the modelling of the ESD footprints, a spatial autocorrelation analysis will be undertaken to identify the level of clustering of the modelling results across GB (Getis, 2005; Griffith, 2005; Robinson and Mattioli, 2020). A spatial autocorrelation analysis generates a Moran's I value which indicates the level of clustering across space within the dataset (Robinson and Mattioli, 2020). A value of 1 means the results are perfectly clustered, while a value of 0 means the results are randomly dispersed. Utilising the spatial autocorrelation analysis alongside the modelling of ESD footprints will identify whether clusters of high and low consuming LAs exist in GB. A high Moran's I value indicating high levels of clustering, in the context of a large range in ESD footprint values for a specific ESD category, would show that LAs across different areas of GB exhibit different levels of ESDs, and that a disaggregated approach to EDR may be appropriate.

3.2.6.2 Socioeconomic analyses: Correlation and regression

Correlation and regression analyses will be undertaken upon the LA-level household ESD footprints and each LA's underlying socioeconomic and geographic factors. The correlation analysis will be undertaken using Spearman's Rank analysis, and the regression analysis will be undertaken using a linear regression analysis. Correlation analysis is undertaken to assess whether there is a connection between the ESD footprint size and a LA's underlying socioeconomic factors, while the regression analysis will be used to assess the dependency of the ESD footprint size upon the LA's underlying socioeconomic factors.

The correlation and regression analyses are undertaken to assess whether the household-level relationships exhibited between footprint size and socioeconomic variables, identified in previous footprinting studies, are exhibited by the LA-level ESD footprints (Minx *et al.*, 2013; Ivanova and Wood, 2020; Salo *et al.*, 2021). The variables examined in Section 5.4 can be seen in Table 3.4.

Table 3.4 Socioeconomic and geographic variables analysed alongside the ESD footprints in Section 5.4.

Socioeconomic Variables
Average household income
Average household size
Number of vehicles per household
Unemployment rate (%)
Population density (per km^2)
Median age of the population
Median household EPC rating
Proportion of households not on the gas grid (%)
Proportion of the population with degree-level qualifications (%)

Household income, household size and the number of vehicle per household have previously been identified as strong drivers of energy footprint size at a household-level (Minx *et al.*, 2013; Ivanova *et al.*, 2016; Oswald *et al.*, 2020; Owen and Barrett, 2020; Salo *et al.*, 2021). These variables will therefore be examined together in Section 5.4.1.

However, the other variables analysed in Section 5.4 (Table 3.4), are a combination of variables which have exhibited a limited relationship with household energy footprints in the past (population density, median age of population, proportion of degree-level qualifications) (Minx *et al.*, 2013; Salo *et al.*, 2021), and relate to the efficiency of households (median household EPC rating and proportion of households not on the gas grid). Unemployment rate is also examined as household income is examined as an average across the LA. Unemployment rate may therefore be a better indicator of lower income at a LA-level as by taking an average of household income for each LA, areas of high and low consumption may nullify each other in an average. Whereas, this should not happen in the unemployment rate statistic.

After examining the ESD footprints modelled in Chapter 5 in the context of socioeconomic and geographic factors, EDR strategies, using the ESD values for each LA as a baseline will be modelled in Chapter 6. The policy options and modelling technique used in Chapter 6 will be set out in Section 3.3 and Section 3.4.

3.3 Energy Service Policy Options at a LA-level

The policy options which comprise the four service-oriented EDR strategies modelled in Chapter 6 are taken from Ivanova *et al.*, (2020). The policy options in Ivanova *et al.*, (2020) were selected for the EDR strategies in Chapter 6 as they are consumption-based policies. Consumption-based policy options go beyond technical interventions to reduce energy demand, and can be implemented within LAs, at a household-level. The service-oriented EDR strategies modelled in Chapter 6 will be discussed in more detail in Section 3.4.

The EDR potential of the policy options set out by Ivanova *et al.*, (2020) are given in tonnes of CO_2 (tCO_2) however. The figures given in Ivanova *et al.*, (2020) therefore need to be converted into tonnes of oil equivalent (toe) to be directly applicable to the ESD footprints in Chapter 5 (Appendix 4). The multipliers, used to generate the ESD footprints in Chapter 5, were used to convert tCO_2 into toe (Appendix 4).

In addition to the multipliers to convert expenditure to kilograms of oil equivalent for the 307 COICOP product categories (Section 3.2.2), there are also multipliers for each category to convert expenditure into $kgCO_2e$ (Appendix 4). An element-wise division of the embodied energy multipliers for each product by the respective embodied CO_2 multipliers for each product creates a multiplier between

tCO_2 and toe for every COICOP category (Appendix 4). These multipliers can be used to convert the tCO_2 data in Ivanova *et al.*, (2020) into energy units (Appendix 4).

However, the policy options in Ivanova *et al.*, (2020) apply to ESD categories and sub-categories rather than individual COICOP categories. Therefore, generating multipliers for the policy options in Ivanova *et al.*, (2020) requires multipliers for each ESD sub-category. Multipliers for each ESD sub-category were therefore generated using a weighted average based upon the multipliers for each individual COICOP category within each ESD sub-category. The relevant multipliers for each ESD sub-category were then used to convert each policy option's mitigation potential from CO_2 units to energy units to be used in Chapter 6. The method used to model the converted policy option mitigation potentials will be set out in Section 3.4.

3.4 Modelling the EDR Potential of four service-oriented strategies

3.4.1 Input-Output Methodology for Assessing Mitigation Potential

Chapter 6 will use equations derived from Wood *et al.*, (2018) to model the combined effect of the consumption-based policy options in Ivanova *et al.*, (2020) upon the ESDs of different LAs throughout GB (Appendix 6). The equations are underpinned by the overarching IO methodology and include the ability to assess the penetration rate of EDR measures, and their rebound effects upon different ESDs. This methodology in Wood *et al.*, (2018) was initially used on a macro-scale, however in Chapter 6, the model shall be used on both the macro-scale and micro-scale.

The initial reduction of the demand for different ESDs (y^{red}) (Equation 9) is given as:

$$\boldsymbol{y^{red}} = \boldsymbol{y} \odot (\boldsymbol{1} - \boldsymbol{r^y} \odot \boldsymbol{t^y})$$

Equation 9

where y represents final demand per energy service, r^y is the potential reduction per energy service, t^y is the assumed penetration rate of the mitigation measure, and $\odot$ is the symbol for element-wise multiplication of y by the corresponding values of r and t (Equation 9) (Wood *et al.*, 2018). Acceptance values, generated by reviewing three documents examining household preference for mitigation policies (Sköld *et al.*, 2018; Climate Assembly UK, 2020; UNDP, 2021), and the proportion of the population not already undertaking each measure will act as a proxy for penetration rate of the policy goal (t^y) (Sköld *et al.*, 2018) (Appendix 7). Proportion of the population not already undertaking the policy goal will be used to avoid double counting EDR potential, while the level of acceptance acts as an estimate of the proportion of the population willing to undertake each measure[15]. Each penetration rate (t^y) is cascading too, meaning that if, for example, a certain proportion of the population switched to vegetarian diets, this proportion of the population can then not also be included in the calculation of the effect of vegan diets upon nutrition ESDs across GB (Appendix 7).

However, as stated previously, reductions in energy demand for certain ESDs can lead to a rebound effect (y^{reb}) reducing the potential of each EDR strategy (Equation 11) (Stern, 2011). Additionally, shifts in behavioural practices, such as shifting to a plant-based diet, result a substitution effect (y^{sub}) (Equation 12), whereby demand for products is replaced by demand for different products to fulfil household ESDs. The actual effect of each mitigation measure (y^{int}) (Equation 10) in Ivanova *et al.*, (2020) is therefore calculated as:

$$\boldsymbol{y^{int}} = \boldsymbol{y^{red}} + \boldsymbol{y^{sub}} + \boldsymbol{y^{reb}}$$

Equation 10

The substitution effect and rebound effect of each mitigation measure are calculated using equations in Chitnis and Sorrell, (2015). The equations for the substitution and income effects from Chitnis and Sorrell, (2015) are used in place of the equations from Wood *et al.*, (2018) as the equation to calculate the scalar of price differences used in the Wood *et al.*, (2018) equations was taken from an unpublished paper and is therefore not available to use.

y^{reb} (Equation 11) is calculated using the following equation:

$$\boldsymbol{y^{reb}} = \left(\boldsymbol{w_e} * \boldsymbol{\eta_{qe,x}}\right) + \left(\boldsymbol{\Psi_i} \odot \boldsymbol{w_e} \odot \boldsymbol{\eta_{qi,x}}\right)$$

Equation 11

And is split down into the direct rebound effect $\left(\boldsymbol{w_e} * \boldsymbol{\eta_{qe,x}}\right)$ and the indirect rebound effect $\left(\boldsymbol{\Psi_i} \odot \boldsymbol{w_e} \odot \boldsymbol{\eta_{qi,x}}\right)$ (Equation 11). For the direct rebound effect, the share of the energy service sub-category affected in household expenditure (w_e) is multiplied by the elasticity of the energy service sub-category quantity demanded in relation to expenditure $\left(\boldsymbol{\eta_{qi,x}}\right)$ (Equation 11) (Chitnis and Sorrell, 2015). Price elasticities determine changes in expenditure by households based upon changes in the price of a product, and the quantity of a product available (Chitnis and Sorrell, 2015; Wood *et al.*, 2018).

15 Levels of social acceptance for each mitigation measure will change over time as social practice norms change. The penetration rate values therefore represent public perceptions presently, rather than perceptions of the mitigation measure evolve over time. Mitigation strategies in Chapter 6 will therefore not be considering strategy evolution over time.

The indirect rebound effect is calculated for every COICOP category considered in the ESD footprints in Chapter 5 and summed together to get the full rebound effect for all products (Chitnis and Sorrell, 2015). Ψ_i is the share of the product in total household expenditure relative to the share of the ESD the product is fulfilling in total household expenditure (Chitnis and Sorrell, 2015). Ψ_i for each product is multiplied by w_e and then the price elasticity of the product in relation to total household expenditure ($\eta_{qi,x}$).

y^{sub} (Equation 12) is calculated using the following equation:

$$\boldsymbol{y^{sub}} = -\boldsymbol{\eta_{qe,pe}} + \left(-\boldsymbol{\Psi_i} \odot \boldsymbol{\eta_{qi,pe}}\right)$$

Equation 12

and is also split down into the direct substitution effect ($-\boldsymbol{\eta_{qe,pe}}$) and the indirect substitution effect $\left(-\boldsymbol{\Psi_i} \odot \boldsymbol{\eta_{qi,pe}}\right)$ (Equation 12) (Chitnis and Sorrell, 2015). The direct substitution effect is an elasticity equation of the energy commodity quantity in relation to the energy commodity price ($-\boldsymbol{\eta_{qe,pe}}$) (Chitnis and Sorrell, 2015). In the indirect substitution effect, Ψ_i is multiplied by the elasticity of the quantity of a product available related to its price.

The substitution effect can be applied across the all COICOP categories used to make-up the ESD footprints in Chapter 5. However, a specific rebound can be modelled if newly available money is expected to be spent on specific products – e.g. shifting to public transport means less money spent on vehicle fuel, but greater money spent on bus travel – using Equation 12, but limiting it to the specific products that substitution is expected to occur upon.

The total effect of each mitigation strategy can be assessed with the following equation:

$$\boldsymbol{y^{tot}} = \boldsymbol{y} - \boldsymbol{\Sigma_{int}}\left(\boldsymbol{y} - \boldsymbol{y^{int}}\right)$$

Equation 13

whereby the actual effect of each mitigation measure is summed into the variable y^{tot} to allow the total effect of each mitigation strategy to be calculated (Equation 13) (Wood *et al.*, 2018).

The EDR potential of each of the four strategies in Chapter 6 is calculated using the equations in Section 3.4.1. Once the EDR potential has been calculated, correlation analyses will also be undertaken upon the EDR data to identify whether LAs exhibiting high ESD footprints align with areas modelling high levels of EDR. As with the ESD footprints in Chapter 5, a spatial autocorrelation analysis will also be undertaken on the EDR data to generate Moran's I values and assess the level of clustering in the EDR data across space in GB (Getis, 2005; Griffith, 2005). As with the ESD values in Chapter 5, a small range of values for each strategy's potential would suggest that a national-level approach is appropriate for EDR in GB. However, a large range of values and high clustering of values would indicate that different areas of GB would be expected to experience different levels of EDR under each strategy (Robinson and Mattioli, 2020). The EDR strategies themselves are set out in Section 3.4.2.

3.4.2 Policy Strategies

The analysis of consumption-based policy options for mitigation in Ivanova *et al.*, (2020) focuses upon the potential of single policy instruments. All of the policy options analysed in Ivanova *et al.*, (2020) have consequences for the level of energy demand associated with different ESDs in GB (Royston *et al*., 2018). However, while there is value in analysing singular policy options individually, instruments to reduce energy demand are rarely implemented alone, meaning that the effect of multiple policy options, working in tandem, needs to be considered (Kern *et al*., 2017). The equations from Wood *et al.*, (2018) (Section 3.4.1) allow the potential of multiple policy options in Ivanova *et al.*, (2020) to be analysed as EDR strategies.

The EDR strategies in this section examine the potential of the combined measures to reduce the energy associated with household ESDs at a fixed point in time. While academics and policymakers both have an interest into how EDR strategies, and their acceptance, changes over time, this will not be considered in this chapter (Kern *et al*., 2017). Additionally, the EDR strategies presented in Chapter 6 are discussed on a national-level, and a LA level to show how the level of EDR for each ESD varies throughout GB.

The EDR strategies set out in this section to be modelled will be aligned with the different columns of the 'Avoid-Shift-Improve' (ASI) framework in Creutzig *et al.*, (2018). The strategy aligned with the 'improve' column is titled the energy efficiency strategy, while the maintained service levels (MSL) strategy will include measures from Ivanova *et al.*, (2020) which 'shift' energy demand to less intensive alternatives (Creutzig *et al.*, 2018). The reduced service levels (RSL) strategy will utilise measures from Ivanova *et al.*, (2020) which 'avoid' energy use altogether, while the full consideration (FC) strategy will consider all three columns of the ASI framework, and combine all measures from Ivanova *et al.*, (2020) into a single overarching strategy (Creutzig *et al.*, 2018).

3.4.2.1 Energy efficiency strategy

The energy efficiency EDR strategy utilises measures which seek to improve the thermodynamic energy efficiency of conversion devices to deliver ESDs to households or the material efficiency of conversion devices bought by households (Sorrell, 2007). The measures for the energy efficiency approach primarily come under the 'improve' section of the ASI framework, meaning that they utilise existing energy delivery systems and practices, seeking to reduce the level of energy demand associated with them (Creutzig *et al.*, 2018). Energy efficiency is a common policy goal of governments throughout the world, including GB (BEIS, 2019, 2021c), and is popular due to the need for minimal government intervention and the perceived benefits energy efficiency can bring to households (Shove, 2018).

However, as stated in Section 2.1.3, energy efficiency does not challenge current unsustainable lifestyle practices, such as excess consumption (Shove, 2018). Additionally, there are concerns that any reduction in energy demand for ESDs through energy efficiency measures is likely to be reduced, or cancelled out, by the rebound effect (Brockway *et al.*, 2017).

Despite the concerns and issues surrounding energy efficiency, the strategy will be considered in Chapter 6. Energy efficiency will remain an important part of EDR going forward, and therefore needs to be considered in a demand-side study of EDR potential (BEIS, 2021c). Modelling the effects of energy efficiency upon GB's ESDs will allow the quantification of the potential effect of an energy efficiency EDR strategy upon the energy required for ESDs across GB, and demonstrate the differences between an efficiency approach to EDR, and one which considers maintaining or reducing ESD levels.

The measures included in the energy efficiency EDR strategy can be seen in Appendix 5, and the underlying assumptions of each measure utilised in the energy efficiency strategy can be seen in Appendix 6. The energy efficiency EDR strategy will serve as a baseline strategy in Chapter 6.

3.4.2.2 Maintained Service Levels

The MSL EDR strategy primarily utilises measures in Ivanova *et al.*, (2020) which can be classed under the 'shift' column of the ASI framework (Creutzig *et al.*, 2018). Measures in the MSL strategy therefore do not reduce the level of household ESDs, for example, shifting a journey made by car to public transport, meaning that a household keeps the same level of service (e.g. travelling to their destination), but at a lower rate of energy use (Creutzig *et al.*, 2018). The measures in the MSL strategy reduce energy demand through behavioural change, technology shifts and energy efficiency improvements. The measures included in the MSL EDR strategy can be seen in Appendix 5. The underlying assumptions of each measure utilised in the MSL strategy can be seen in Appendix 6.

The MSL strategy has been modelled in Chapter 6 to demonstrate the EDR potential possible in GB, while maintaining the same level of household ESDs. Understanding the level of EDR possible without reducing service levels is important as an often cited barrier to EDR through measures beyond energy efficiency is that households have concerns about compromising their wellbeing (Steinberger & Roberts, 2010; Brand-Correa *et al*., 2018; Burke, 2020). However, other studies have shown that reducing energy demand through behavioural change and technology shifts does not necessarily reduce wellbeing or quality of life (Grubler *et al.*, 2018; Vogel *et al.*, 2021; Barrett *et al.*, 2022). It is therefore important to demonstrate how considering maintained energy service levels can lead to a reduction in the energy required to deliver ESDs without compromising quality of life or wellbeing.

The measures utilised in the MSL strategy aim to reduce energy demand across a range of the ESDs modelled in Chapter 5. Transport-related measures focus on shifting transport by personal vehicle to public and active transport, while nutrition-related measures focus upon household changes in diet such as consuming less meat by shifting to reduced meat or plant-based diets (Creutzig *et al.*, 2018; Ivanova *et al.*, 2020).

The MSL strategy does not just consider measures from Ivanova *et al.*, (2020) which can be classed under the ‘shift’ column of the ASI framework however (Creutzig *et al.*, 2018). Energy efficiency measures are also included within this EDR strategy as energy efficiency measures are specifically designed to provide the same level of energy service for less energy (Shove, 2018). This leads to an overlap between the MSL strategy and the energy efficiency strategy. However, as this thesis is not advocating for ceasing the implementation of energy efficiency improvements, and improving energy efficiency is likely to remain an important aspect of EDR going forward (BEIS, 2021c), it is important to include energy efficiency measures in this EDR strategy.

3.4.2.3 Reduced Service Levels

The RSL strategy utilises EDR measures from Ivanova *et al.*, (2020) which affect eight of the nine ESD categories in Table 3.3. The EDR options included in this strategy centre around the ‘avoid’ column of the ASI framework, meaning that this strategy aims to avert the need for energy use altogether, through measures such as lowering internal room temperature, travelling less or making fewer purchases (Creutzig *et al.*, 2018). Reducing the service levels of households using these EDR measures relies upon behavioural change rather than technological shifts or energy efficiency improvements to reduce energy demand for energy services (Creutzig *et al.*, 2018).

The measures included in the RSL EDR strategy can be seen in Appendix 5. The underlying assumptions of each EDR measure utilised in the RSL strategy can be seen in Appendix 6.

Strategies aimed at reducing energy service levels have sometimes, in the past, been cited as undesirable as they reduce their level of wellbeing (Steinberger and Roberts, 2010; Brand-Correa *et al.*, 2018; Shove, 2018; Burke, 2020). However, while this may be true in developing countries, other studies have proven that once the level of ESDs demanded by households passes a certain threshold, reducing energy service levels does not bring about significant reductions in wellbeing (Brand-Correa and Steinberger, 2017; Vita *et al.*, 2019).

Reducing service levels in GB could therefore be important for limiting overconsumption as reducing ESD levels, reduces energy demand for an ESD, and may have benefits beyond EDR (Raworth, 2012; Hickel *et al.*, 2021). For example, in the UK, it has been found that throughout all income deciles throughout the UK, there is an overconsumption of daily calories per capita (Garvey *et al.*, 2021). Adopting a food sufficiency EDR measure would reduce the level of food consumed, and therefore energy demand for nutrition ESDs, which would potentially have health benefits of reducing obesity (Garvey *et al.*, 2021). Improved health of individuals can therefore lead to better wellbeing of households, through a reduction in ESD levels, therefore implying that a RSL approach may benefit households in GB (Ürge-Vorsatz *et al.*, 2014).

3.4.2.4 Full Consideration

The FC strategy utilises all the measures set out in Ivanova *et al.*, (2020). The FC strategy utilises a mix of energy efficiency measures, measures which maintain ESD levels and measures which aim to reduce ESD levels. It is expected that this strategy will have the largest effect upon GB's ESDs as it is not limited by the method through which the measure achieves EDR. The FC strategy therefore includes measures from across the ASI framework (Creutzig *et al.*, 2018). The measures included in the FC strategy can be seen in Appendix 5. As with the three previous three EDR strategies, the underlying assumptions of each measure utilised in the FC strategy can be seen in Appendix 6.

The FC strategy is modelled in Chapter 6 to demonstrate the full potential of consumption-based options upon the ESDs of households nationally, and throughout all LAs in GB. Other studies have modelled the effect of multiple EDR options upon society before – e.g. Grubler *et al.*, (2018); Barrett *et al.*, (2022). However, the modelling work in Chapter 6 models the effect of the four EDR strategies across space at a LA-level, and focuses specifically on households, and the changes in household energy demand for ESDs under different EDR strategies. Thus, the work in Chapter 6 gives a deeper insight into the effect that EDR will have upon household ESDs.

The ESD values for households, modelled in Chapter 5, serve as a baseline for the present-day level of each ESD demanded by households in different LAs across GB, the FC strategy will act as a threshold for the level of EDR which the energy efficiency, MSL and RSL EDR strategies are trying to attain, thus showing the full potential of maintaining and reducing service levels upon households in GB.

3.4.3 Summary

The four strategies set out in Section 3.4 cover all of the options set out in Ivanova *et al.*, (2020) with the exception of Bio-Plastics/Chemicals, Green Roofing and Low Carbon Construction mitigation options[16]. There is overlap between the MSL strategy and the energy efficiency strategies, however the RSL strategy only overlaps with the FC strategy. Each of the first three strategies considers a different aspect of the three sections of the ASI framework set out by Creutzig *et al.*, (2018), while the FC strategy includes measures from across all three sections of the framework.

It is expected before that the FC strategy will be the most effective EDR strategy modelled in Chapter 6 as more options from Ivanova *et al.*, (2020) are considered in this strategy, however the other three packages will outline the effectiveness of other approaches to EDR. Additionally, all four strategies will have benefits beyond EDR, potentially bringing about positive co-benefits, such as improved health through lower calorie consumption or shifting to active transport, however, these co-benefits are not modelled in this study as this is beyond the scope of the thesis.

After modelling the potential of the four service-oriented strategies in Chapter 6, the EDR potential of each strategy will be analysed alongside the capacity of households in each LA to assess whether high levels of EDR are modelled in areas which can adopt the measures within each of the strategies. Assessing the EDR potential of each LA in the context of household capacity to act in each LA will demonstrate whether a disaggregated approach to EDR may be necessary in GB. The method for calculating household capacity through CI scores is set out in Section 3.5.

3.5 Feasibility of EDR strategies

The final results chapter of the thesis (Chapter 7), will focus upon household capacity to adopt the EDR strategies set out in Section 3.4 by calculating CI scores for each LA. Technical potential of the four strategies designed to reduce energy demand for ESDs is modelled in Chapter 6, as is the behavioural plasticity of consumers through the societal acceptance values and proportion of the population not already undertaking each EDR option (Figure 3.5). Considering whether high ESD and high EDR levels align with CI scores will indicate whether the universal strategies reduce energy demand by the greatest level in areas with high CI scores, thus ensuring an equitable transition (Figure 3.5). If the strategies do not align with these areas, then a non-universal approach to EDR must be considered.

The CI analysis will focus upon the capacity of households in different LAs to adopt the EDR strategies modelled in Chapter 6. Section 7.1 will consider the capacity of households in different LAs to adopt measures in each EDR strategy through the levels of different types of capital available to households. The method used to identify which LAs have greater capacity to adopt each EDR strategy will be set out in Section 3.5.1.

[16] Bio-Plastics/Chemicals, Green Roofing and Low Carbon Construction have been excluded from consideration in Chapter 6 as they are unlikely to be undertaken by households in the near future, and therefore will provide limited mitigation benefit.

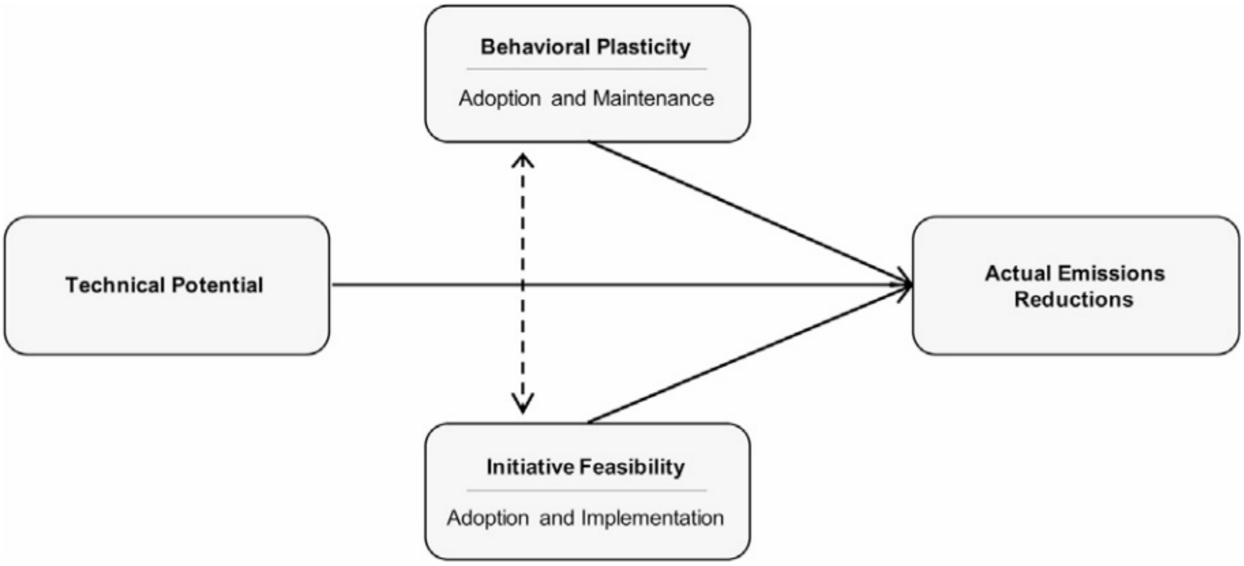

Figure 3.5 Framework for examining the feasibility of EDR options and EDR strategies at different scales – national, regional or local (Image source: Nielsen *et al.*, 2020).

Section 7.2 will then draw the elements from Chapter 5, Chapter 6 and Chapter 7 together by analysing the CI scores alongside the ESD and EDR results from Chapter 5 and Chapter 6 to identify whether areas of high ESD consumption or high levels of EDR potential align with LAs which possess higher levels of capacity to adopt EDR strategies. This analysis will allow an assessment of whether a national, regional or localised approach to EDR would be appropriate in GB.

3.5.1 Local Authority ability to adopt energy demand reduction strategies

The capacity of households within each LA to adopt the EDR strategies will be considered in Section 7.1. Section 7.1 will use a CI to assess the capacity of households to adopt the EDR strategies modelled in Chapter 6. CI s have been used by many previous to assess poverty and household capacity to adapt to different situations, including climate change (Pandey and Jha, 2012; Siders, 2019; Robinson and Mattioli, 2020).

The CI in Chapter 7 considers five dimensions of capital (Section 3.5.2) which are made up of different indicators (Siders, 2019). Once the indicator data for each LA has been gathered, the data will be indexed to place the different indicators on the same scale (0 to 1) (Equation 14), with a higher score representing the greater likelihood of residents within an LA being able to implement the EDR strategies in Chapter 6 (Pandey and Jha, 2012). The equation used to index the values is:

$$Index_{I_x} = \frac{I_x - I_{min}}{I_{max} - I_{min}}$$

Equation 14

whereby Ix is the indicator value for each LA. $Imin$ is the smallest indicator value, and $Imax$ is the largest indicator value (Pandey and Jha, 2012).

The results of the CI analysis will be set out on a dimension basis rather than considering the individual indicators themselves for each LA (Equation 15). Presenting this number of results would be difficult in a single thesis chapter. None of the factors are weighted as each of the dimensions are an equally important aspect of household capacity to adopt EDR strategies. The equation for calculating the results on a dimension basis is set out as follows (Pandey and Jha, 2012):

$$D_{LA} = \frac{\Sigma Index_{I_x}}{n}$$

Equation 15

The results for each dimension will be mapped using GIS. Mapping the results will provide a visual representation of how CI scores vary across GB. Finally, spatial autocorrelation and correlation analyses will be undertaken to analyse the data generated in the CI analysis (Getis, 2005; Griffith, 2005). Correlation analyses will be used to identify whether LAs with high levels of ESDs and EDR align with LAs which possess high CI scores (Robinson and Mattioli, 2020). Spatial autocorrelation will also be undertaken to generate Moran's I values for each capital dimension to identify whether LAs with similar CI scores are clustered, thus indicating that similar areas of GB possess similar capacity to adopt the EDR strategies modelled in Chapter 6 (Getis, 2005; Griffith, 2005; Robinson and Mattioli, 2020). Analysing the CI scores using correlation analyses and spatial autocorrelation will identify whether high ESD levels, EDR and CI scores all align. If all aspects of the research undertaken in Chapter 5, Chapter 6 and Chapter 7 align, then a national-level approach to EDR would be a suitable approach to EDR. However, a lack of correlation between the values would indicate that the national-level approach may lead to an unjust demand-side transition, with areas of low capacity to adopt EDR strategies expected to make the largest reductions in energy consumption of ESDs.

3.5.2 Capacity dimensions: Types of capital

The dimensions used in Chapter 7 focus upon different types of capital required for an equitable demand-side transition (Section 2.1.2.3), which are: (1) financial capital, (2) human capital, (3) physical capital, (4) natural capital and (5) social capital (Siders, 2019) (Table 3.5). All capital is also considered in Chapter 7. Each type of capital is made up of indicators which are indexed and averaged to give a score for each dimension of capital (Table 3.5). LAs exhibiting higher scores under each capital type will indicate a greater capacity to adopt the strategies modelled in Chapter 6.

Table 3.5 Capacity dimensions and their associated indicators. For indicators where a higher value would indicate a lower capacity to adopt the startegies modelled in Chapter 6 – e.g. Unemployment rate – the results will be subtracted from 1 to invert the results and ensure that a higher capacity index score indicates greater household capacity.

Dimension	Indicator
Financial capital	
	Average household income
	Unemployment rate
	Proportion of income on non-essential consumption
Human capital	
	Median age of the population
	Proportion of adults with degree-level qualifications
	Proportion of non-fuel poor households
	Number of food parcels per 100,000 population
	Multiple deprivation index
Physical capital	
	Proportion of owner-occupied housing
	Number of vehicles per household
	Distance to nearest public car charging infrastructure
	Number of mainline train stations
	Number of buses
	Median household EPC rating
	Proportion of population producing renewable electricity
	Proportion of population using renewable electricity
	Proportion of population using renewable-based heating
Natural capital[17]	
	Population density (per km^2)
Social capital	
	LA first climate target date
	Proportion of nutrition expenditure on meat
	Proportion of waste already recycled
	Proportion of population undertaking car-pooling

The indicators within each of the five dimensions of capital are based upon a combination of socioeconomic factors, geographic factors, data collected in the LCFS (i.e. expenditure data), as well as current acceptance rates of technological and behavioural EDR measures and poverty indicators.

[17] Natural capital generally refers to natural resources provided by the natural environment. In the context of household capacity to adopt EDR strategies, natural capital refers to the size of the LA environment that councils are responsible for.

Natural capital generally refers to the availability of natural resources – e.g. soil, water and minerals – in CI studies (Barbier, 2019). The demand-side transition in GB will require the availability of natural capital, such as lithium for battery-electric vehicles (BEVs), however, due to the globalised nature of GB's economy, the availability of natural resources is not specific to each individual LA in GB. Considering the natural resources required for EDR under each strategy is also beyond the scope of this thesis. Natural capital will therefore consider the 'geographic capital' of LAs by considering the land area needed to be addressed by each LA, using the population density data examined in Chapter 5 (Siders, 2019).

The CI of each capital type will generate CI scores for each LA which will draw the work of the thesis together to assess whether a universal approach to EDR is appropriate for different ESDs and different LAs throughout GB. This work is set out in Chapter 7.

3.6 Summary

In this chapter, the methodological basis for this study has been set out with signposting as to which chapter of the thesis each method will be utilised in (Table 3.1). IO modelling underpins the ESD and EDR modelling in Chapter 5 and Chapter 6 (Leontief, 1936; Miller and Blair, 2009), while a CI is used to generate scores to assess household capacity in Chapter 7 (Pandey and Jha, 2012; Robinson and Mattioli, 2020).

The methods utilised in this thesis are used to generate LA-level data for ESDs, EDR and the capacity of households to adopt EDR strategies. The LA-level data is then analysed to assess whether a national approach to EDR is appropriate for each ESD category modelled in this thesis.

However, before these methods can be applied in Chapter 5, Chapter 6 and Chapter 7, a framework for analysing the energy system from service-oriented LA perspective needs to be outlined. Setting out a framework which analyses the energy system from a services-oriented is important for allowing LAs to identify which stage each of the consumption-based policy options, in each of the EDR strategies, affect. The service-driven energy demand chain (SEDC) framework is set out in Chapter 4 and used in Chapter 6 to show which stage of the energy system that the consumption-based policy options from Ivanova *et al.*, (2020) affect.

4 The Service-driven Energy Demand Chain Framework

Chapter 4 develops a framework encompassing the full energy system which adopts a service-oriented perspective and allows LAs to assess the effect of consumption-based actions upon the whole energy chain. The framework is entitled the Service-Driven Energy Demand Chain (SEDC) framework and links the social and technical aspects of the energy system together through the concept of energy service demands (ESDs) meaning that technical energy efficiency measures can be considered and modelled beside avoid and shift options from the avoid-shift-improve (ASI) framework. The SEDC framework is used in subsequent chapters of the thesis, particularly, Chapter 6, to define different energy demand reduction (EDR) strategies and identify which stage of the energy chain that household EDR actions at a LA-level affect.

As stated in Chapter 1, devolving powers to enact EDR to a LA-level may have benefits for EDR as LAs and households tend to be more ambitious in climate targets than the national-level government. Additionally, the options used by LAs to reduce energy demand go beyond energy efficiency measures due to their lack of direct control over energy policy. Chapter 4 will therefore build upon the analysis of LAs, ESDs and the energy system frameworks in Chapter 2.

In Section 4.1, the findings of the literature review will be quickly recapped, and the gaps which were identified in Section 2.2 and 2.3 will be discussed alongside how services-oriented framing of the energy system from a LA-level could build upon these gaps. Secondly, a framework for analysing the whole energy chain, from primary energy to household wellbeing, which begins at the ESD stage of the framework – i.e. the point of consumption which LAs can affect - will be set out in Section 4.2. Section 4.2.1 with consider the framework's design requirements, and the framework itself will be set out in Section 4.2.2. The application of the framework will then be considered in Section 4.3, while the insights provided by the framework will be considered in Section 4.4. Finally, Section 4.5 will set out how the SEDC framework will be used in subsequent chapters of the thesis to examine the energy system, and model EDR, at a LA-level using the services perspective.

4.1 Insights from Literature Review

In Section 2.3 and Section 2.4, the frameworks and models which utilise the concept of energy services were analysed. In Section 2.3, it was found that energy system frameworks often included the concept of energy services as the end result of the energy system, rather than the drivers of the energy system itself. (Hafele, 1977; Kahane, 1991; Cullen and Allwood, 2010; Heun, *et al*., 2018). Additionally, many of these frameworks did not extend energy services to human wellbeing, thus neglecting wellbeing as a factor in energy consumption for ESDs, however, some frameworks are beginning to consider the link between ESDs and human wellbeing, but do not consider the full energy chain (Brand-Correa *et al*., 2018).

Within energy system frameworks and models which simulate ESDs, ESDs are often considered as the end point of the energy system and only focus upon energy service categories associated with direct energy consumption (Fell, 2017; Hardt *et al.*, 2019). Additionally, ESDs are sometimes modelled exogenously meaning that the effects of a model do not feedback and impact upon ESD levels, thus reinforcing the discourse of ESDs as a result of the energy system, rather than a driver of it in the model results (Fouquet, 2010; Fell, 2017; Hardt *et al.*, 2019). Models in Section 2.4 also tend to focus upon only those ESDs provided by direct energy, such as heating. The design of the frameworks, categories and models in Section 2.3 and Section 2.4 therefore tend to favour the current discourse surrounding energy demand and EDR – i.e. energy efficiency measures as the primary form of EDR – as the technical energy supply system tends to be prioritised in each of these areas (Morley, 2018).

LAs are areas of household consumption of ESDs, which are geographically separated from production due to the nature of the energy supply system in Great Britain (GB), and the globalised nature of the economy (Schulze and Ursprung, 1999; Tingey and Webb, 2020). Therefore, EDR should be framed around consumption when considering EDR at this level, rather than reducing the level of energy production for the same level of service through energy efficiency, as the means of production may be situated outside a LA's jurisdiction (Tingey and Webb, 2020). A focus upon household consumption rather than just household energy demand also broadens out the scope of EDR options to those which address the indirect energy associated with household consumption (Vringer and Blok, 1995; Min and Rao, 2018).

The insights from Section 2.2, Section 2.3 and Section 2.4 suggest that a new framing of the energy system is required to analyse EDR at a LA-level. LAs are situated at the point of consumption, therefore beginning a demand-side analysis from a LA perspective should begin with the underlying reasons that energy is demanded from the energy system – household ESDs. Focusing upon ESDs rather than energy demand at this level directly relates energy consumption to meet ESDs within a LA to household needs and wellbeing, thereby linking the social and technical aspects of the energy system (Nørgård, 2000; Brand-Correa *et al*., 2018). Additionally, a focus on households ESDs allows LAs to consider EDR which addresses energy consumption, but does not rely upon only energy efficiency to deliver EDR (Creutzig *et al.*, 2018; Ivanova *et al.*, 2020).

With these considerations in mind, Section 4.2 will set out the proposed framework for examining the energy system from a LA-level, and some examples of the potential EDR options available when considering EDR for ESDs at the point of consumption in a LA. Section 4.2.1 will first set out the design requirements of the framework, while Section 4.2.2 will subsequently set out the SEDC framework itself.

4.2 The Service-Driven Energy Demand Chain Framework

4.2.1 Energy Service Framework: Design Requirements

The SEDC framework is being used to examine energy consumption and EDR from a LA perspective, meaning that the area of the energy system which is governed by a LA must be placed at the beginning of the framework – energy consumption of household ESDs rather than production of energy in the direct energy supply system. The framework must also consider the full energy chain, from 'ultimate ends' – ESDs which drive household energy demand and are required by households to achieve wellbeing – to 'ultimate means' – the direct energy supply system (Nørgård, 2000). Therefore, the SEDC framework must reverse the traditional direction of energy system analysis (Jonsson *et al.*, 2011) in order to prioritise ESDs, and consumption, at a LA-level in this approach.

Placing ESDs at the beginning of the energy chain, rather than the end, is important for EDR at a LA-level as LAs have greater control over energy consumption within their boundaries than production elsewhere in GB or beyond (Tingey and Webb, 2020). Additionally, placing ESDs at the beginning of the SEDC framework means that the drivers of energy consumption are considered before other elements of the energy system, such as the fuels used to generate primary energy (Nørgård, 2000).

The ESD stage of the SEDC framework links household consumption of ESDs with wellbeing, and therefore the reasons underpinning household energy demand for ESDs (Nørgård, 2000). Understanding the initial levels of household energy demand, and the ESDs that the energy system is providing, can also be used to consider whether the EDR options implemented by LAs, which reduce the level of energy service consumption affect the ability of households to satisfy their needs and achieve wellbeing (Brand-Correa *et al*., 2018).

The SEDC framework is designed to examine household consumption, with a focus on energy and ESDs, within a LA. Therefore, the SEDC framework must also be able to consider the indirect energy that contributes towards household energy consumption and ESDs (Haas *et al.*, 2008). As stated in Chapter 2, ESDs categories can go beyond categories which focus only upon direct energy – e.g. heating and lighting – and focus upon all aspects of household consumption by considering embodied energy (Haas *et al.*, 2008; Owen and Barrett, 2020). Embodied energy is required to manufacture and transport each product to households, and represents an important area of EDR potential which is neglected by frameworks and models which only consider the direct energy supply system (Ivanova *et al.*, 2016; CREDS, 2022). Including a 'production system' stage in the SEDC framework will also allow EDR options which utilise avoid and shift measures from the ASI to be assessed by LAs, alongside the potential of EDR options which improve the technical energy efficiency of the direct energy supply system (Creutzig *et al.*, 2018).

The SEDC framework therefore offers LAs the opportunity to actively consider the entire energy system in an EDR strategy by using an energy services framing. Considering ESDs beyond those provided by direct energy by drawing in embodied energy into the SEDC framework also broadens the number of EDR options available to LAs, therefore allowing LAs to consider all the EDR options available for demand-side mitigation across the energy system in an overarching framework (Creutzig *et al.*, 2018; Ivanova *et al.*, 2020). The SEDC framework is set out in Section 4.2.2.

4.2.2 Framework

The SEDC framework is outlined in Figure 4.1. The SEDC framework recognises that households within a LA are consuming 'ESDs' in an attempt to satisfy their 'human needs', and achieve wellbeing. Delivering 'ESDs' requires energy from the energy system, ESDs are quantified by the amount of 'final energy' required to deliver ESDs to households. Delivering 'final energy' to households places a requirement upon the 'production system' to deliver energy to the household and to develop devices which convert final energy into the desired energy service.

The 'production system' requires energy supply to function, which can be generated from fossil-fuel sources of energy, at a geographically separate location to the examined LA, thus releasing emissions into the atmosphere and contributing towards climate change (Edenhofer *et al.*, 2014). Energy supply for ESDs can come from the 'direct energy supply system' which accounts for energy supplied directly to households for their 'ESDs' – e.g. heating and lighting. Or energy supply can come from the 'indirect energy' requirement which accounts for the level of energy required to manufacture the products and services purchased by households – e.g. food for nutrition ESDs.

Analyses begin at the 'ESDs' stage of the SEDC framework, and the effect of consumption-based EDR options, implemented in a LA, can be traced up the SEDC framework, to assess which stage of the SEDC framework EDR will affect. Household energy demand of a LA at the ESDs stage of the SEDC framework, and the upstream effects of EDR options are quantifiable as the energy services demanded by households require final energy to be delivered. For example, the energy service of mobility can be quantified in terms of passenger kilometres, and a specific level of passenger kilometres driven requires a certain amount of 'final energy' which can be quantified in energy units, such as joules, kilowatt-hours or tonnes of oil equivalent.

The direct energy required from the 'direct energy supply system' to produce the level of final energy required to deliver household ESDs, can also be quantified in energy units (Haas *et al.*, 2008). Direct energy is produced by a mix of different energy sources including both fossil-fuel powered energy sources and renewable energy sources, and is transformed into the final energy required by households to fulfil their ESDs. The 'direct energy supply system' is included as ultimately the aim of EDR in LAs is to reduce pressure upon the 'production system' to reduce the greenhouse gas (GHG) emissions associated with energy demand and to reduce the pressure on energy supply in order for it to be decarbonised faster (Grubler *et al.*, 2018).

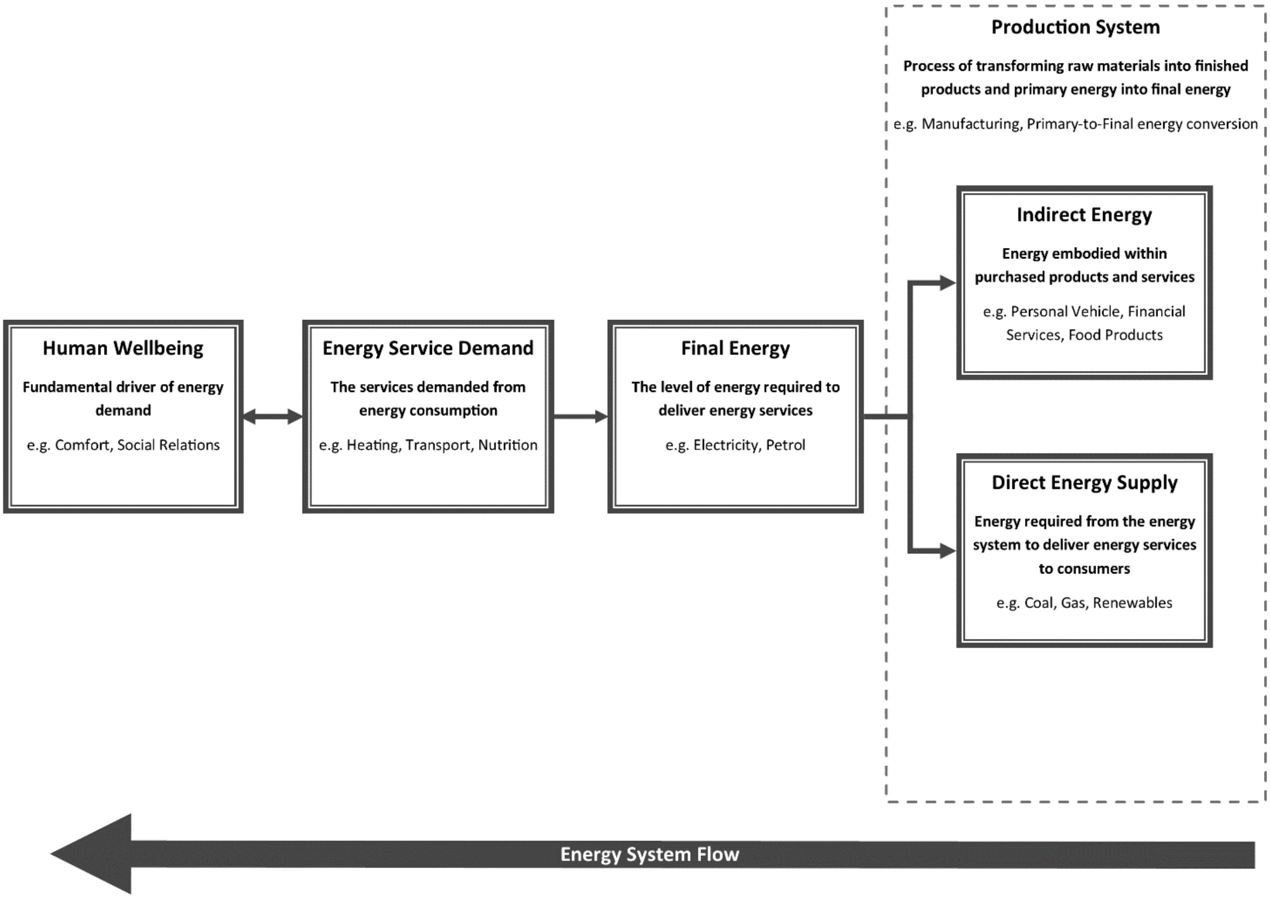

Figure 4.1 The 'Service-driven Energy Demand Chain' (SEDC) framework. Each stage of the chain includes a definition and an example of what that stage of the framework is representing.

However, due to the increasing globalisation of the production system, quantifying the energy required to deliver ESDs to households in LAs needs to go beyond quantifying direct energy (Kitzes, 2013). Quantifying the indirect energy embodied in the products and services purchased by households is an important aspect of EDR at a LA-level – due to the geographical separation of production and consumption – and can be reduced by consumption-based policy options implemented by LAs. An indirect energy stage of the SEDC framework is therefore included within the 'production system' alongside the 'direct energy supply system'. The indirect energy demanded from the production system to fulfil household can also be quantified in energy units through the use of multi-regional input-output modelling (MRIO) (Leontief, 1951; Lenzen, 1998; Miller and Blair, 2009; Kitzes, 2013).

Including a 'production system' stage in the SEDC framework broadens the scope of EDR options for LAs beyond direct energy considerations. Consumption-based options in Ivanova *et al.*, (2020) address both direct and indirect energy consumption, therefore allowing Chapter 6 to utilise the full range of options in Ivanova *et al.*, (2020). Providing that numerical consistency is maintained throughout the SEDC framework, to avoid double counting indirect energy, both ESD footprints and the EDR potential of strategies to reduce household demand for energy services in LAs can be modelled using this framing of the energy system.

The focus of the SEDC framework is to provide LAs with a method of viewing the full energy system from a services perspective – i.e. the point of consumption – and link local-level decisions with the globalised production system. The SEDC framework broadens the scope of EDR options to those which address indirect energy, therefore allowing the full range of consumption-based EDR options in Ivanova *et al.*, (2020) to be modelled in Chapter 6. EDR using the SEDC framework is therefore reframed away from energy efficiency, however with the inclusion of 'final energy' and 'direct energy supply system' stages of the SEDC framework, energy efficiency options can be implemented alongside EDR options which utilise the shift and avoid columns of the ASI framework.

Considering EDR using the SEDC framework therefore allows more complete EDR strategies, which encompass the whole energy system, to be devised, in order to help bring about the necessary reduction in energy demand for a 1.5°C future. The application of the SEDC framework will be considered in Section 4.3.

4.3 Framework Application

The SEDC framework is able to consider all options for EDR from the ASI framework at a LA-level. A full example of the SEDC framework being used to consider EDR for personal transport at a LA-level is considered in Section 4.3.1 using an illustrative example, while Section 4.3.2 considers the use of the SEDC framework in practice.

4.3.1 Framework example

A summary of how the SEDC framework could be used in practice can be seen below in Figure 4.2. The example used in this chapter sets out how a LA-level policymaker could use the SEDC framework to reduce household ESDs for personal transport by utilising measures implemented at a LA-level, but affecting the upstream stages of the energy system. The EDR options outlined in this chapter are not exhaustive and will be used to illustrate how the SEDC framework could be used in practice.

Beginning with the first stage of the SEDC framework, 'ESDs', the ESD of personal transport is considered. In this example, personal transport is demanded to fulfil the human need of subsistence as defined by Max-Neef (1991), which is achieved through employment. Personal transport is demanded by households to journey to their place of employment and is achieved through the use of a privately owned vehicle which runs using an internal combustion engine. The energy required to deliver the level of ESD is therefore a product of the amount of fuel a vehicle requires to deliver the energy service, as well as the indirect energy associated with the production of the vehicle itself. Having calculated the energy required to deliver this specific ESD, using MRIO (Leontief, 1936, 1951; Miller and Blair, 2009; Kitzes, 2013; Owen, 2018), methods of reducing the level of energy associated with the energy service of personal transport can be considered at a LA-level.

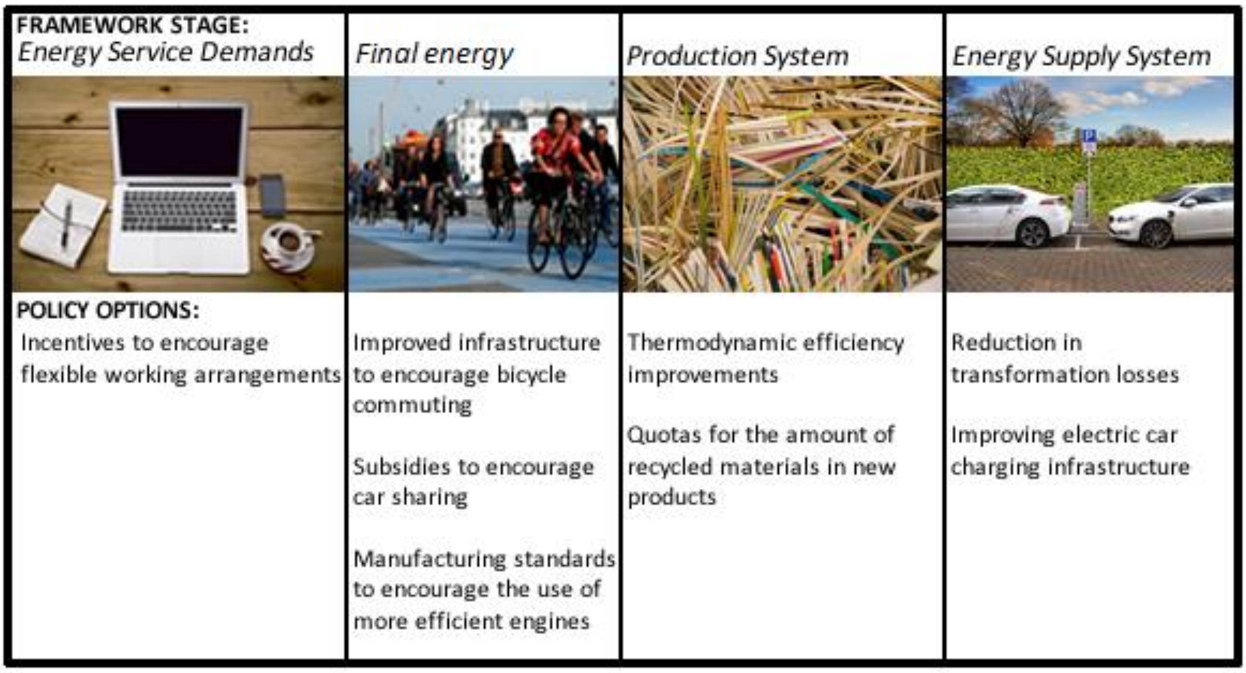

Figure 4.2 A non-exhaustive summary of the EDR options that could be implemented within a LA but affect each stage of the SEDC framework to bring about EDR for personal transport. Energy efficiency and EDR measures which 'avoid' and 'shift' household ESDs are considered side-by-side in the framework.

At the first stage of the SEDC framework, the amount of energy required to deliver the ESD of personal transport is calculated. At this stage, measures that negate the need for mobility to achieve subsistence, through employment, could be outlined by a LA. For example, LAs could focus upon telecommuting through incentivising companies to adopt flexible working arrangements for employees (Figure 4.2) (Creutzig *et al.*, 2018; Ivanova *et al.*, 2020). This would allow members of a household to work from home and therefore reduce the level of personal transport ESDs required to undertake employment and fulfil their need of subsistence ('avoid') (Creutzig *et al.*, 2018). The change in the need to travel every day for work would reduce the number of passenger kilometres travelled by household, which would reduce the level of energy required for this need to be fulfilled, therefore reducing energy demand without the need for energy efficiency.

LA-level EDR strategies aiming to reduce the level of energy consumption associated with personal transport ESDs can also consider measures which affect other stages of the energy chain displayed in the SEDC framework (Figure 4.1). As stated in Section 4.2, EDR options from all columns of the ASI framework can be considered using the SEDC framework and can be implemented alongside each other to allow EDR to be undertaken in a more complete way (Creutzig *et al.*, 2018). For example, at the 'final energy' stage of the SEDC framework, an option to reduce energy demand for personal transport is the mandating that households within a LA cannot purchase a new personal vehicle with an energy efficiency standard below a set level ('improve') (Creutzig *et al.*, 2018). Alternatively, LAs could introduce EDR options which encourage a reduction in the number of cars on the road through incentives designed to increase the use of public transport or car sharing schemes ('shift') (Creutzig *et al.*, 2018). By implementing these EDR measures, households achieve the same level of personal transport ESDs to get to work and achieve the need of subsistence, but for a smaller requirement of final energy.

Continuing the example of analysing EDR options, implemented by LAs, which affect different stages of the energy chain for personal transport for subsistence through employment using the SEDC framework: at the 'indirect energy' stage of the SEDC framework, LAs could offer incentives for households replacing a broken car to buy a second-hand vehicle, rather than a new one. Finally, within the 'direct energy supply system', the final stage of the SEDC framework, it would be possible to reduce the energy demand for personal transport through the improvement of electric vehicle charging infrastructure within a LA to encourage the uptake of electric vehicles, as opposed to the continued use of vehicles with internal combustion engines ('improve') (Creutzig *et al.*, 2018).

The illustrative example demonstrates that the SEDC framework encourages policymakers to consider every stage of the energy chain when considering EDR options at a LA-level to reduce high energy consumption of households for ESDs. Considering EDR from a services perspective at a LA-level offers a new outlook on the energy system and broadens the scope of EDR beyond the technical 'direct energy supply system'. While the example discussed here is hypothetical, the SEDC framework can be used in a similar way in practice (Section 4.3.2).

4.3.2 Framework in practice

The previous section sets out an example of how to utilise the SEDC framework to consider EDR options at a LA-level which affect different stages of the energy chain to deliver ESDs to households. However, while the example presented in Section 4.3.1 considers a single household ESD (personal transport), and describes potential interventions a LA could make based upon this, the example did not demonstrate that all household ESDs can be considered using the SEDC framework.

The SEDC framework is primarily a policy framework for LAs. If applied in a local setting, the framework, as shown in the example, has the potential for LA-level policymakers to consider household ESDs at all points of the energy demand chain from consumption to production. At present, the frameworks and models used by policymakers (Section 2.3 and Section 2.4) tend to focus upon direct energy, and the technical energy system.

However, the SEDC framework also adds value beyond policy simply as a method for examining the energy system. As stated previously, “energy is not consumed for itself, but as a means to supply a demand of useful services” (Le Gallic *et al*., 2017, p2619) to households. Therefore, while household ESDs are the end goal of the energy system, they are also the drivers behind it in order to achieve wellbeing. By placing ESDs at the forefront of energy system considerations, studies, reports and plans for EDR could offer new and different insights for future work (Nørgård, 2000).

Additionally, the SEDC framework is not limited to specific EDR options. Non-energy policies can affect household consumption patterns which affects ESDs levels within a LA (Cox *et al*., 2019). For example, the decision by a LA to cancel a bus route to a rural village would mean that commuters residing in the village may have to begin driving, instead of taking public transport, to reach their place of employment and satisfy their human need of subsistence. In this instance, the needs required by the village’s households would remain the same, but the amount of energy required to deliver this need would increase as a greater number of vehicles would be used to achieve household personal transport ESDs. Alternatively, cancelling a rural bus service could decrease transport ESDs as households in this rural area may be low income or elderly households who do not own their own personal vehicle. The SEDC framework therefore offers opportunities for the non-energy policies of LAs to contribute towards EDR across the whole energy system, and provides a case for the careful design of non-energy policies to always consider the positive and negative energy implications of policy (Royston *et al*., 2018).

4.4 Framework Insights

The SEDC framework offers theoretical insights, as well as practical insights into how the energy system functions and can be used to consider options designed to reduce energy demand for the transition to a net-zero society at a LA-level. Section 4.4.1 focuses on the theoretical insights, while Section 4.4.2 focuses on the practical insights.

4.4.1 Theoretical Insights

From a theoretical perspective, the SEDC framework offers a fresh perspective of the energy system to LA-level policymakers, which has been rarely adopted by other studies in the past (Nørgård, 2000). ESDs are commonly noted as the end point of the energy system, as energy is not produced in and of itself for no reason, therefore implying that any analysis of EDR strategies must be undertaken in the context of both services and wellbeing – as wellbeing is the underlying reason as to why energy services are consumed (Le Gallic *et al*., 2017; Brand-Correa *et al*., 2018). However, the energy system is often not examined in this way as stated in the literature review in Chapter 2 (Hafele, 1977; Kahane, 1991; Cullen and Allwood, 2010a).

The SEDC framework therefore reframes the conversation away from how energy is supplied to what energy is used for at a LA-level. From this, energy demand considerations can be centred on consumption, rather than making energy supply more efficient in the production system. Using the SEDC framework at a LA-level removes the geographical separation between consumption and production, and places an emphasis upon all the ability of actions undertaken by households in LAs across GB to reduce energy demand (Cox *et al.*, 2019; Ivanova *et al.*, 2020; Tingey and Webb, 2020).

Placing household ESDs at the forefront of EDR considerations can also help to ensure that wellbeing is not compromised in LA-level EDR strategies (Lamb and Steinberger, 2017). Considering energy demand from a services perspective using the SEDC framework ensures that LA policymakers can consider whether the same level of ESD is provided to households once a measure has been implemented. This reframes conversations of EDR away from energy efficiency at a LA-level as EDR can be implemented through improving energy efficiency, shifting energy demand to less energy intensive products and practices or avoiding energy use altogether by altering practices so that wellbeing can be achieved either without the use of an energy service or the consumption of a smaller level of household ESDs (Lamb and Steinberger, 2017; Brand-Correa *et al*., 2018; Creutzig *et al.*, 2018).

Additionally, the SEDC framework places LA-level EDR into a real-world context by focusing on services rather than just abstract numbers regarding how much energy is demanded from the energy system by households in LAs (Morley, 2018). Considering the energy system from a national perspective leads to policymakers focusing upon the amount of energy that is delivered to households, rather than focusing on the services themselves (Morley, 2018; Kalt *et al.*, 2019). Placing the focus on energy services rather than energy quantities in this context allows actors to see the real world impacts of energy consumption, and the benefits it brings (Morley, 2018; Kalt *et al.*, 2019). Considering the benefits of ESDs for wellbeing also draws in consideration of the overconsumption of energy and the benefits that reduced ESD levels may bring for households (Grubler *et al.*, 2018). For example, shifting household transport demand for personal transport to active transport reduces energy demand for ESDs and brings health benefits to households (Daioglou *et al*., 2012; Ürge-Vorsatz *et al.*, 2014). Placing the energy system in a real-world context is important, especially for EDR as the energy system is transitioned towards net-zero, to ensure that the implications of EDR are considered and that the ability of households to achieve wellbeing through energy consumption is not inadvertently compromised by EDR options at a LA-level (Lamb and Steinberger, 2017).

The SEDC framework links the energy system with human needs, wants and wellbeing (Brand-Correa *et al*., 2018). ESDs have previously been described as the ‘golden thread’ which links the technical energy system and human needs (Brand-Correa *et al*., 2018). While examining this link in detail at a LA-level is beyond the scope of this thesis, the SEDC framework could be used to examine the effect of changing needs and wants upon ESDs and the energy system rather than solely considering how changes in energy services affect wellbeing (Brand-Correa *et al*., 2018).

Finally, the SEDC framework diversifies the number of academic fields which can contribute to the development and implementation of EDR strategies beyond energy system modellers and engineers. Increasing the number of experts who can contribute towards a wicked problem, such as EDR, could provide innovative methods of reducing energy demand in an equitable manner at both a LA-level and national-level.

In addition to theoretical insights, the SEDC framework also offers practical insights. Practical insights will cover how the SEDC framework could be applied in a real-world context by policymakers and other stakeholders at a LA-level, and beyond, attempting to enact EDR in Section 4.4.2.

4.4.2 Practical Insights

As demonstrated in the framework example section of the thesis (Section 4.3.1), the SEDC framework broadens the scope of EDR options at a LA-level beyond the boundaries of both the LA itself and the direct energy supply system. Additionally, the impacts of LA-level behavioural changes upon both the ‘direct energy supply system’, and the ‘production system’, can be considered. However, the SEDC framework offers practical insights beyond its main application.

Beyond the SEDC framework’s main application, the framing of the energy system offers potential as a teaching tool for those in policymaking, at a LA-level, and beyond. The SEDC framework allows users to easily visualise different steps in the energy system and production system. Being able to visualise every step of the energy system is useful for those less familiar with how energy is produced (Nørgård, 2000). This could be advantageous to policymakers, although it should be assumed that policymakers have a certain level of familiarity with the policy area they are responsible for.

However, beyond policymakers, the SEDC framework presents the energy system in such a way that would be useful for any stakeholder, at a LA-level or beyond, who wishes to reduce the level of energy consumption associated with their ESDs. The SEDC framework presents the energy system in such a way that it is possible to easily visualise where a potential intervention could be made

(Figure 4.2). This is advantageous to all actors and stakeholders throughout society who may be looking to reduce energy demand using consumption-based options, but are unsure how to make reductions in energy demand beyond technological options, such as insulating an office building. Being able to easily visualise the energy system allows actors to easily understand which EDR options are available to them, as well as the stage of the energy system an option impacts further up the production chain in the 'direct energy supply system' or the 'production system'.

In addition to easier visualisation of the energy system, and where interventions could be made, the SEDC framework examines the energy system from the point of consumption, as stated previously (Section 4.2.2). By examining the energy system from the consumption end of the energy chain, EDR focuses upon energy consumption, rather than improving the efficiency of energy supply (Morley, 2018). In addition to providing methods of visualisation of the energy system from the point of consumption, the SEDC framework also allows other forms of modelling which focus on consumption of energy, rather than the production of energy to be used more prominently, such as input-output (IO) modelling (Miller and Blair, 2009; Kitzes, 2013).

As discussed in Section 2.4 of the thesis, IO modelling can be used to generate consumption-based accounts of energy demand across countries, regions and the world (Miller and Blair, 2009; Kitzes, 2013). Examining the energy system using the SEDC framework would therefore allow IO modelling to potentially take a more prominent role in EDR at a LA-level, and a national-level. The implications of IO modelling taking up a more prominent role in EDR strategies is that responsibility for EDR would be allocated differently throughout the world by assigning energy demand to the end consumer rather than producers (Miller and Blair, 2009; Kitzes, 2013).

The SEDC framework actively places the 'production system' within its boundaries, therefore encouraging LAs to consider the role of the production system in household ESDs and EDR. Drawing the production system into considerations of household EDR encourages LAs to implement EDR options that go beyond focusing upon energy efficiency and reducing the amount of direct energy supply required by households. Household EDR generally focuses upon energy efficiency measures to reduce the level of energy consumption associated with energy services (Shove, 2018). For example, reducing personal transport ESDs focuses upon switching to a BEV – i.e. Shifting energy demand to a less intensive product – rather than using an older vehicle for longer in order to reduce the energy demand associated with the production of a new vehicle (Creutzig *et al.*, 2018).

By drawing in the focus on the production system as well as the direct energy supply system into LA-level EDR considerations the number of options for EDR are increased, while the EDR options available to households are also increased (Kalt *et al.*, 2019). Additionally, it is possible that changes in household consumption patterns by adopting EDR measures which affect the 'production system' may also have knock-on effects within the production system as household demand for products and services drives production in the same way that ESDs drive the direct energy supply system (Fell, 2017; Le Gallic *et al*., 2017). This could therefore bring about even greater levels of EDR throughout society as well as at a LA-level.

The SEDC framework offers many practical insights into the energy system, and how EDR could be implemented. This is also true for its application in this thesis which will be examined in Section 4.5.

4.5 Application of the SEDC Framework in this thesis

In this thesis, the SEDC framework, and the LA-level services perspective of the energy system in GB, will form the underlying basis of the subsequent chapters of the thesis. There will be limited reference to the SEDC framework itself – with the exception of Chapter 6 – however, the framework will guide the flow of the thesis in Chapter 5 and Chapter 6, while Chapter 7 will draw the elements of the thesis together to assess whether a LA-level approach to EDR would be effective in GB.

Chapter 5 will focus primarily upon the ESDs stage of the SEDC framework. The LA-level ESDs of households, examined in Chapter 5, are considered the starting point of the SEDC framework, and therefore must be known before LA-level EDR can be considered. The modelling of LA-level household ESDs is undertaken in Chapter 5.

The SEDC framework is then referenced directly in Chapter 6 of the thesis to set out which stages of the SEDC framework are affected by the consumption-based EDR options, drawn from Ivanova *et al.*, (2020) and implemented by LAs. Utilising the SEDC framework in Chapter 6, allows an insight into the range of LA-level options under different service-oriented strategies for EDR, and also showcases which stages of the energy system that LAs can affect using different EDR options. The EDR strategies in Chapter 6 are then modelled to show the potential effect that LAs across GB could have upon the demand-side of the energy system using consumption-based EDR options. Additionally, Chapter 6 will compare the service-oriented strategies and the full consideration (FC) strategy with the energy efficiency strategy modelled in Chapter 6 to demonstrate the potential of going beyond the direct energy supply system in a policy framework for EDR.

In Chapter 7, the work of Chapter 5 and Chapter 6 is drawn together, alongside a capacity index (CI) analysis, to assess whether a disaggregated, LA-level approach to EDR, using the SEDC framework, would be more appropriate than a nationally-led approach. Finally, in Chapter 8, the insights gathered across the research chapters will be discussed in the context of wider literature. The discussion in Chapter 8 will focus on the benefits of using the SEDC framework to analyse the energy system and assess the level of EDR that could be achieved through adopting a services-oriented, consumption-based approach to EDR at a LA-level.

4.6 Summary

The SEDC framework offers both theoretical insights and practical applications for LAs, and stakeholders wishing to reduce energy demand for ESDs. The SEDC framework reverses the traditional direction of analysis when considering the energy system and places ESDs at the forefront of analyses undertaken with the SEDC framework (Nørgård, 2000).

The SEDC framework is primarily a policy framework designed to be used at a LA-level. LAs can use the SEDC framework to consider different consumption-based EDR options and the stage of the energy chain that each option will affect (Creutzig *et al.*, 2018; Ivanova *et al.*, 2020). Considering the effect of consumption-based options in an overarching framework is important for LAs as even if funding were devolved to LAs to develop EDR policy, they are geographically separated from the production of energy, products and services demanded by households to fulfil ESDs and achieve wellbeing (Tingey and Webb, 2020).

The SEDC framework offers a fresh perspective of the energy system which draws in different forms of modelling – e.g. IO modelling – and also broadens the opportunities for LA-level EDR for households to the 'production system'. The SEDC framework will be used as an underlying guide for this thesis as it is set out how to examine the energy system from a LA-level using a services perspective. However, at present, beginning an analysis of the energy system from a services perspective requires knowledge of the level of ESDs of each LA which is being examined.

Chapter 5 will report model household ESD footprints at a LA-level across GB. Modelling LA-level ESD footprints of households will establish the current level of ESDs consumed in GB on an annual basis across different categories. Once this baseline level of ESDs has been established, EDR strategies utilising consumption-based EDR options to reduce demand for ESDs at a LA-level can be modelled.

5 Great Britain's energy service demands at a Local Authority-level

Chapter 5 focuses on the energy service demand (ESD) footprints of each Local Authority (LA) across Great Britain (GB). As stated in Chapter 3, the ESD footprints have an input-output (IO) modelling methodological basis and are generated from household-level expenditure micro-data collected in the Living Costs and Food survey (LCFS) (UK Data Service, 2023).

The ESD footprints have been spatially segmented to analyse the variation in the consumption-based account of household energy service consumption at a LA-level. The results in Chapter 5 will provide an insight into how energy services are utilised by households in GB, and their variation across space, thus addressing the lack of a LA-level account of household ESDs for GB.

In this chapter, the results will first be presented on a national level (Section 5.1), before examining the total ESDs (Section 5.2). In Section 5.3, the aggregate results from Section 5.2 will then be examined across each ESD category set out in Section 3.2.5.

Finally, Section 5.4 will examine the correlation coefficients and relationships between a LA's underlying socioeconomic factors and ESD levels, using correlation and regression analyses. Correlation and regression analyses will be undertaken across all LAs for all the ESD categories modelled in this chapter. Section 5.4.1 focuses upon socioeconomic variables – e.g. income, household size and number of vehicles per household – which have been identified by previous footprinting studies as having strong relationships with the size of an environmental footprint (Minx *et al.*, 2013; Salo *et al.*, 2021). Following this, Section 5.4.2 will focus upon socioeconomic variables which have not exhibited strong relationships with the size of an environmental footprint in previous footprinting studies – e.g. population density, household age (Minx *et al.*, 2013; Salo *et al.*, 2021). Determining the factors which exhibit the strongest relationship with ESDs across space, will establish whether the LA-level footprints exhibit the same pattern as the environmental footprints of individual households, or if other factors are greater determinants of ESD footprint size at a LA-level.

5.1 GB Energy Service Demands: National Average

The average annual ESD footprint for all households in GB, across all ESD categories, is 2.47 tonnes of oil equivalent (toe) per capita for April 2015 to March 2018. The average annual ESD footprint per capita is the result of the applying the method set out in Sections 3.2.2 and 3.2.3 to the expenditure data collected as part of the LCFS, described in Section 3.2.1. A diagram of the key steps undertaken as part of the method in Section 3.2.2 and 3.2.3 is shown in Appendix 8.

Figure 5.1 shows the breakdown of the national average household ESD footprint for GB by the energy service categories outlined in Section 3.2.4. Examining the breakdown of the national average ESD footprint shows that heating and personal transport ESDs contribute the greatest level of energy consumption towards the total per capita footprint across GB, making up 21.3% and 24.9% of the national average respectively (Figure 5.1). Other shelter ESDs (15.9%) and aerial transport ESDs (10.7%) also contribute energy consumption towards the national average total (Figure 5.1).

Personal transport, heating and other shelter ESDs likely contribute more towards GB's national average per capita ESD footprint as both direct and indirect energy, contribute towards the energy consumption within each of these ESD categories. The consumption-based account of energy consumption in Figure 2.9 is an average of 12.2% higher than the territorial-based account which only considers direct energy, therefore direct energy makes up a larger proportion of the ESD footprints (BEIS, 2021d; Defra, 2022).

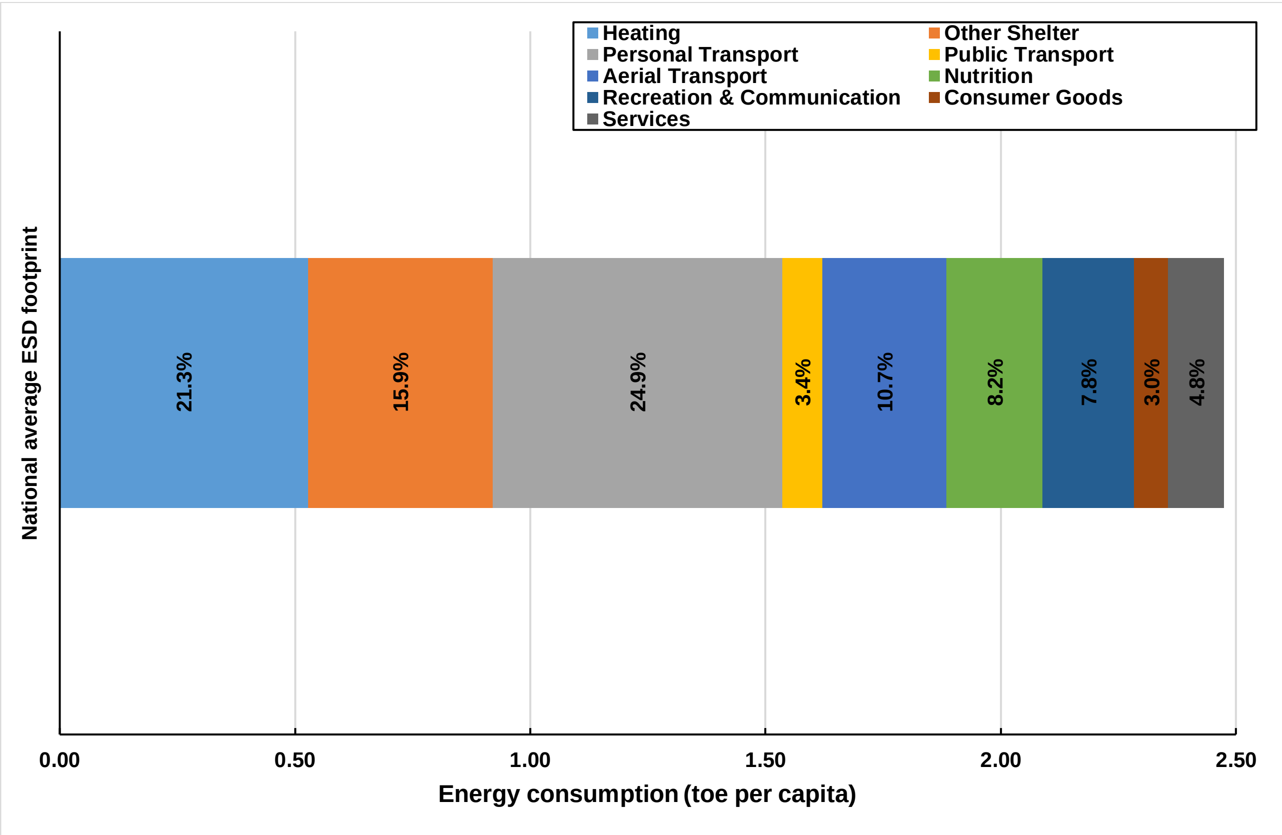

Figure 5.1 Make-up of the per capita national average energy service footprint. Percentage contribution of each energy service towards the total energy service footprint per capita is shown on the graph.

The national average results presented in this section will be used as a reference for comparison when considering the results for different LAs in the following sections. However, before examining each ESD in more depth, the variation in the total household ESD footprint, for all LAs, across GB will be considered.

5.2 Total Energy Service Demands

Having examined the national average for GB, Section 5.2 examines the LA-level variation in total ESD footprints, which represents the aggregate energy consumption by households across all the energy service categories considered in this study. Figure 5.2 shows the range of total energy consumption by households in all LAs in GB across all ESD categories modelled in this chapter. The range of total ESD footprints at a LA-level is 1.81 toe per capita.

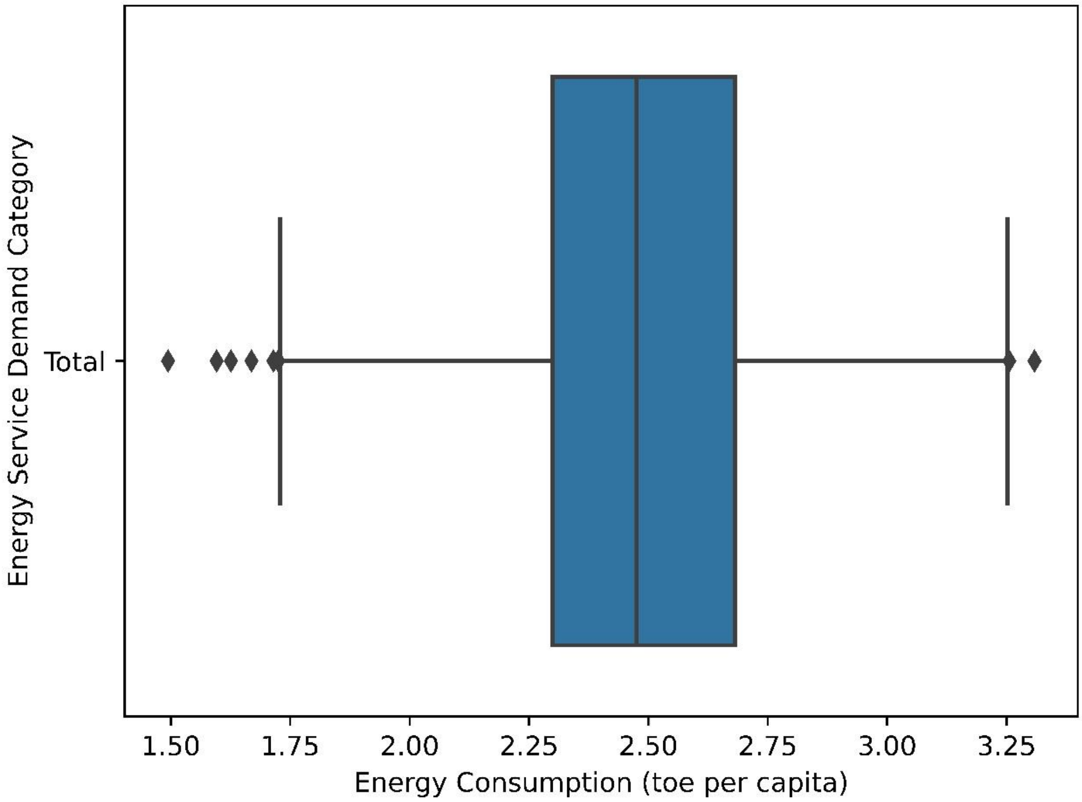

Figure 5.2 The range of total ESD footprints for each LA across GB. The whiskers in the box plot represent 1.5 times the interquartile range from the upper and lower quartiles. Individual points beyond the whiskers are outliers.

The centre line of the box in Figure 5.2 represents the median value of the GB's LA-level ESD footprint results (2.48 toe per capita per annum). The outer edges of the box section of the boxplot in Figure 5.2 represents the interquartile range of LA-level ESD footprint values, showing that the majority of total ESD footprints at a LA-level fall between 2.30 and 2.68 toe per capita per annum. The whiskers in Figure 5.2 represent data points which fall within 1.5 times the interquartile range of the upper and lower quartile values. The box and whiskers demonstrate the variability of the data both within, and beyond the dataset's interquartile range. Individual data values beyond the whiskers of the boxplot in Figure 5.2 are outliers, meaning that the annual total ESD footprint per capita differs significantly from the rest of the data. All boxplots in the remainder of the thesis can be interpreted in the same manner as Figure 5.2.

Figure 5.3(a) expands upon Figure 5.2 by demonstrating how total ESD footprints vary across all LAs in GB. As shown in Figure 5.2, the range in LA-level household ESD footprints is 1.81 toe per capita which varies between 1.49 toe per capita in Tower Hamlets, a LA in central London, and 3.31 toe per capita in Bromley, a LA in outer London (Figure 5.3(a)).

LAs within London therefore exhibit both the highest and the lowest total ESD footprint levels per capita at a LA-level. London as a region, experiences an average total ESD footprint of 2.26 toe per capita across its LA, which is lower than the national average (2.47 toe per capita). Similar footprint analysis studies have previously revealed similar consumption patterns in London. Minx *et al.*, (2013) noted a similar pattern in London, whereby this region contained both the highest and lowest footprint, with Central London having comparatively low footprints compared to Outer London.

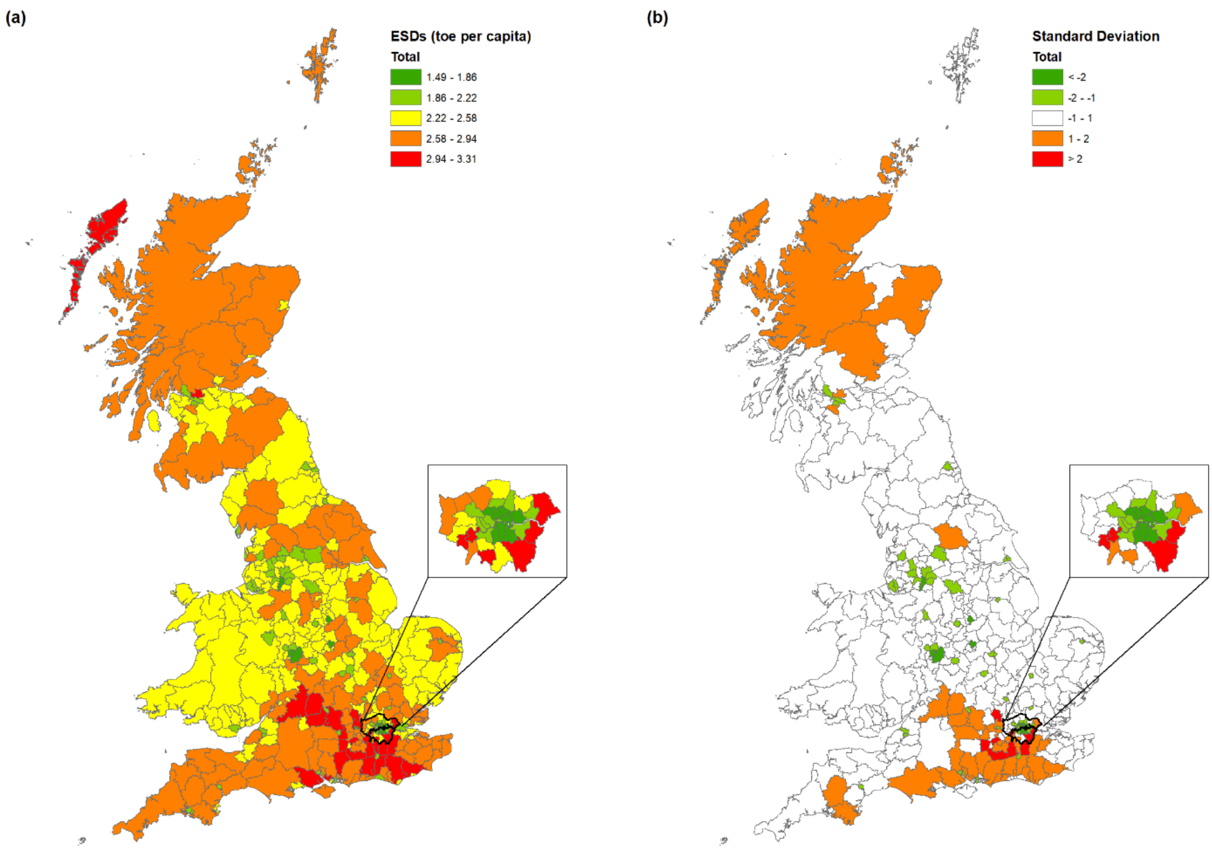

Figure 5.3 (a) Total, aggregate annual ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's aggregate annual energy service footprint per capita.

Beyond London, Figure 5.3(b) highlights both the positive and negative standard deviation anomalies from the GB national average. The greatest anomalies above the GB national average are predominantly located in the southern regions of England, and northern Scotland, while the areas of low standard deviation anomalies are generally located in densely populated areas, such as Manchester, Liverpool, Glasgow City and Birmingham. These findings are consistent with Ivanova & Büchs (2020) who find that across the majority of EU (including the UK, as the UK was still a member of the EU when these analyses were undertaken) households in urban areas tend to have a lower energy footprint than rural households.

However, Figure 5.3(b) suggests that many of the LA-level footprints modelled in this chapter do not vary greatly from the mean. Areas exhibiting high standard deviation anomalies are not consistent too, with a spatial autocorrelation analysis of the results in Figure 5.3 generating a Moran's I value of 0.35 indicating weak clustering. Therefore, despite the appearance of clusters of LAs with high ESD footprints in Scotland and the south of England, and low ESD footprints in London (Figure 5.3), there are not specific regions of GB with higher or lower ESD footprints. Therefore, while there total ESD footprints at a LA-level, the majority of LAs consumption energy within one standard deviation of the GB national average (Section 5.1).

Further analysis will be undertaken on total energy service footprint per capita in Section 5.4. However, in order to fully assess whether household ESD levels vary greatly at a LA-level across GB, the total energy service footprint examined in this section will be broken down by each energy service category in Section 5.3.

5.3 Energy Service Demands

As shown in Section 5.1, the total ESD footprint for each LA in Section 5.2 is made-up of different energy services, each of which contribute different totals towards the total. Figure 5.4 shows the range of results for each ESD across all LAs in GB.

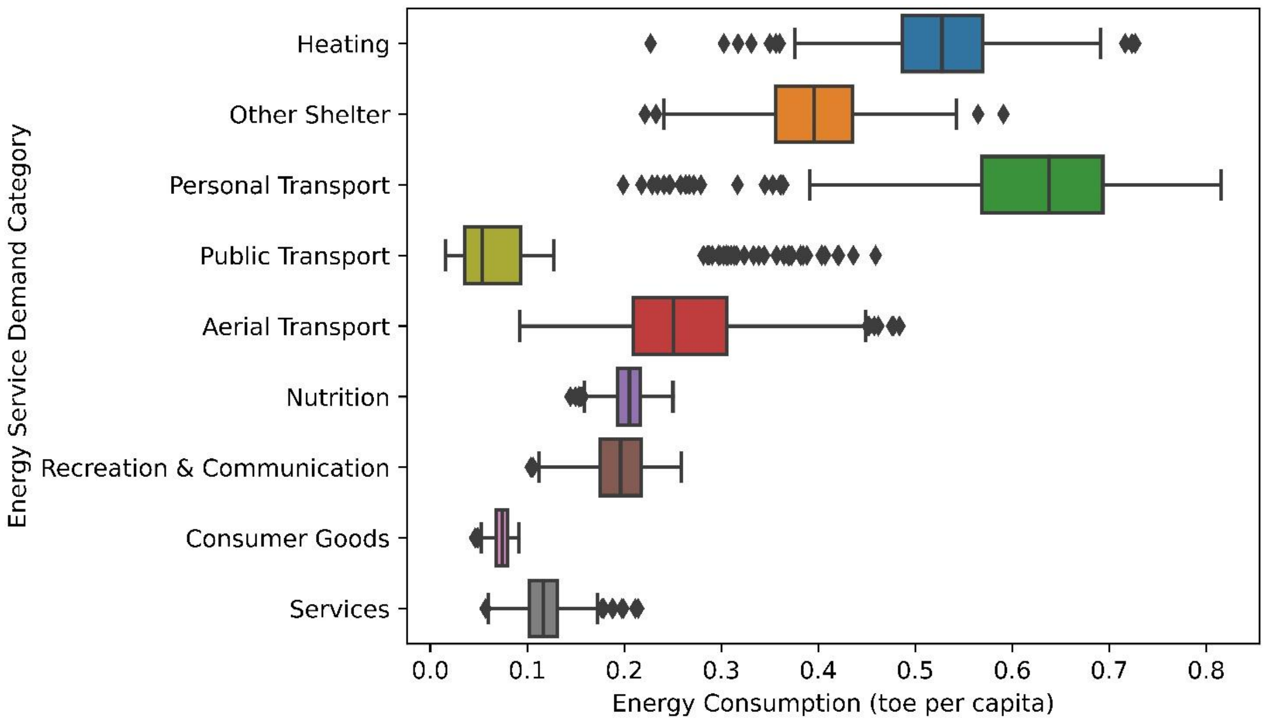

Figure 5.4 The range of ESD footprints for each LA across GB broken down by ESD category modelled in Chapter 5.

The results in Figure 5.4 reflect the national average results with personal transport ESDs and heating ESDs being the ESD categories with the highest level of energy consumption, however the range across these two ESD categories varies significantly. As with the national average (Section 5.1), other shelter ESDs and aerial transport ESDs have large footprints, and also exhibit a large range (Figure 5.4). Beyond ESDs which require direct energy, categories which are supplied only through indirect energy represent a smaller part of the footprint, and also exhibit smaller ranges across all LAs in GB (Figure 5.4).

Analysis of the variation in each ESD category will be undertaken in Section 5.3. Section 5.3.1 will begin by examining the variation in heating ESDs across LAs in GB.

5.3.1 Heating

Heating ESDs represent the amount of energy consumed to heat space, water and repair the central heating system within households in GB. As stated in Section 5.1, heating ESDs form a large proportion of the national average energy service footprint per capita for GB and is driven by gas consumption, which forms 87.1% of the household heating ESD footprint across GB (BEIS, 2021d).

Figure 5.5(a) shows the heating ESDs for each LA across GB. Figure 5.5(a) suggests that many of the LAs in GB exhibit high or very high levels of heating ESDs, with areas of moderate (yellow) heating ESDs being predominantly located in the south-west England, and the east of England regions.

The range of annual heating ESDs across LAs in 0.50 toe per capita, which varies from 0.23 toe per capita in the Tower Hamlets LA, to 0.73 toe per capita in Chiltern in south-east England. LAs in London likely contain exhibit lower levels of energy consumption associated with heating ESDs due lower use of natural gas as a heating source in these areas, with households relying upon electricity, a less carbon intensive energy source, to provide heating ESDs (Minx *et al.*, 2013). Conversely, Chiltern is an affluent LA whereby heating is primarily supplied by the gas grid, thus indicating that overconsumption of energy may be driving the level of heating ESDs in this area.

Figure 5.5(b) again shows that Central London exhibits low standard deviation anomalies when compared to the national average for GB, while rural areas in Scotland and Wales exhibit high standard deviation anomalies. The driver of the high heating ESDs in Scotland and Wales is likely the low levels of gas grid connectivity, and the use of petroleum products – such as oil – as the main source of fuel for heating ESDs in these areas (Naumann and Rudolph, 2020). Low levels of gas grid connectivity lead to the use of carbon intensive fuels such as coal, oil and paraffin to provide household heating, therefore driving up the energy consumption related to heating ESDs per capita in these areas (Naumann and Rudolph, 2020).

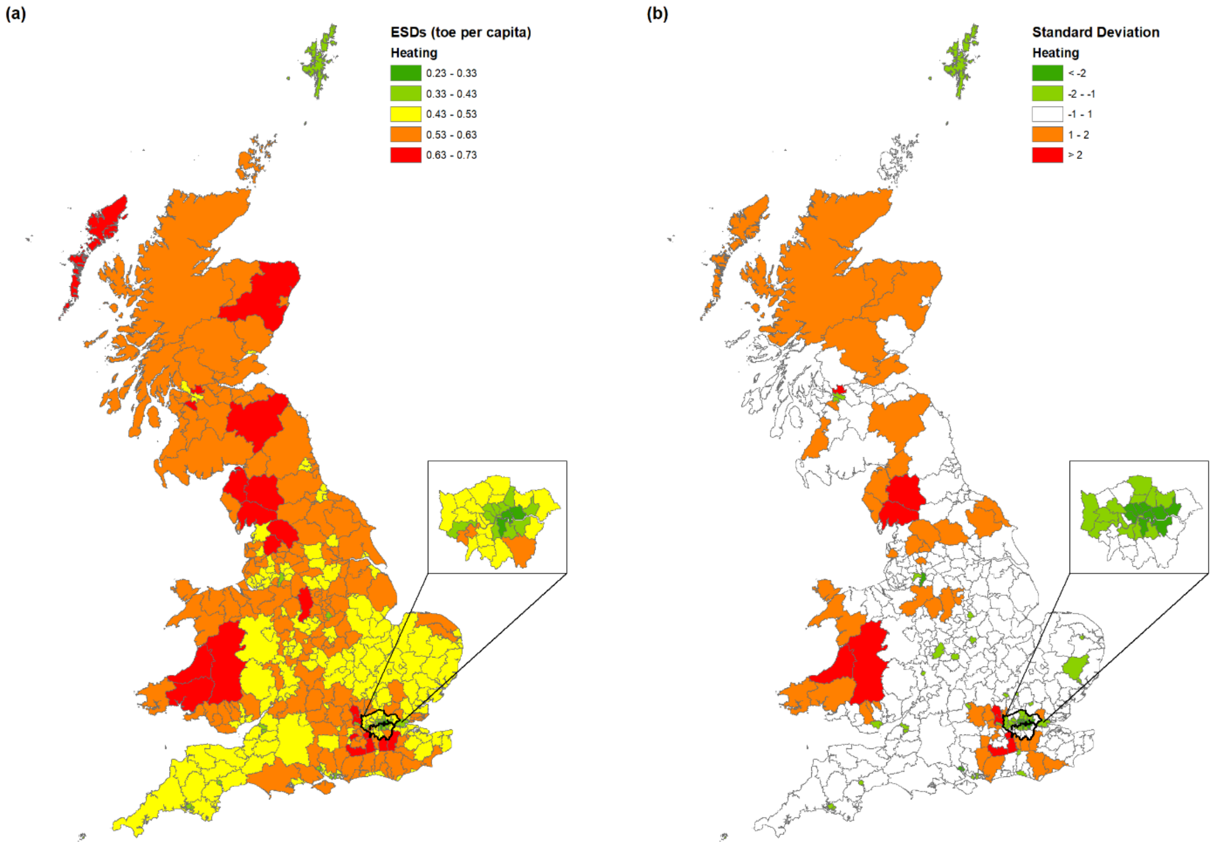

Figure 5.5 (a) Heating ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's heating energy service footprint per capita.

However, as with total ESDs (Figure 5.3), Figure 5.5(b) also suggests that much of the LAs in GB exhibit levels of energy consumption associated with heating ESDs within one standard deviation of the national average. A spatial autocorrelation analysis of the heating ESD footprints in Figure 5.5(a) shows that the heating ESD footprints across GB are moderately clustered, with a Moran's I value of 0.41, therefore implying that areas of standard deviation anomalies are more clustered than for total ESDs.

The higher level of clustering in heating ESDs than total ESD footprint in Section 5.1, is driven by rural areas in Wales, northern England and Scotland, which use more carbon intensive fuels for heating, being clustered together. However, gas-powered heating remains the main driver of heating ESDs across GB, therefore leading to only moderate clustering of LAs with high heating ESDs. The range of heating ESDs across space and moderate clustering of areas with higher and lower energy consumption associated with heating ESDs suggests that a disaggregated policy approach to addressing heating ESDs may be more appropriate than a national-level approach due to the diversity of fuels used for heating ESDs in these areas.

However, while rural LAs in GB seem to exhibit higher levels of heating ESDs in Figure 5.5, the exception to this are the results of the Shetland Islands LA. The Shetland Islands are one of the few areas outside of central London which are classed as having low heating ESDs (Figure 5.5(a)), which goes against the results of most of the LAs in Scotland north of the central belt (Glasgow and Edinburgh).

The Shetland Islands have similar characteristics to other LAs in the north of Scotland (low population density and poor gas grid connectivity). However, it is possible that this may be an anomaly due to the methodology used to calculate heating ESDs for LAs across GB. Heating ESDs in chapter are calculated from a combination of indirect energy calculated from the LCFS, and LA-level direct energy data compiled by the UK Government (Section 3.2). The direct energy data is apportioned to different ESDs using UK Government compiled information on the use of different fuels for different purposes – e.g. space heating, water heating, cooking, lighting and appliances. However, this data is set out at a national-level, and therefore may underestimate the level of non-national grid fuels (e.g. coal or paraffin) used for heating in rural areas of the country, instead apportioning it to another energy service, such as other shelter. Other shelter ESDs will be examined in Section 5.3.2.

5.3.2 Other shelter

Similarly with heating ESDs, other shelter ESDs contain elements of both direct and indirect energy in the footprint results. Figure 5.6(a) shows that the number of LAs exhibiting low (light green) energy service footprints for other shelter ESDs is greater than for heating (Figure 5.5(a)). However, as with heating ESDs, an area of lower other shelter ESDs is concentrated in London. Although low levels of energy consumption associated with other shelter ESDs are not limited to London, as with heating ESDs.

Areas of lower other shelter ESDs can be seen throughout England, Scotland and Wales, but a visual analysis of Figure 5.6(a) does not reveal any large clusters of low other shelter ESDs. Additionally, a spatial autocorrelation analysis of the other shelter ESDs generates a Moran's I value of 0.32, indicating weak clustering. Figure 5.6(b) also shows however that despite many areas having low ESDs for other shelter, many of these areas are within one standard deviation of the national average mean, thus suggesting they are not anomalies.

The range of other shelter ESD LA between the LA with the lowest other shelter ESDs (Tower Hamlets in London with a total of 0.22 toe per capita for other shelter ESD), and the highest (the Shetland Islands in Scotland with a total of 0.59 toe per capita for other shelter ESDs) is 0.37 toe per capita. The range for other shelter ESDs is smaller, however only four LAs in GB are classed as having very high other shelter ESDs.

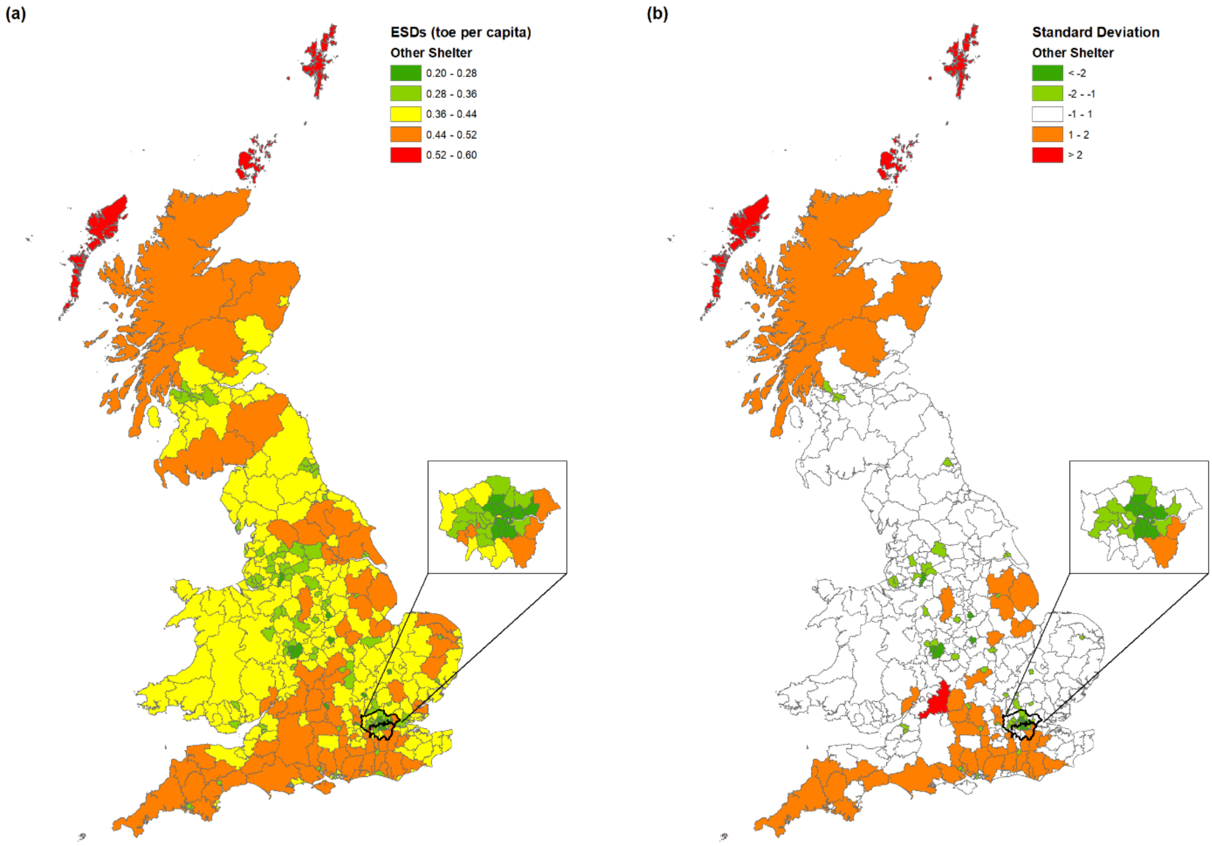

Figure 5.6 (a) Other shelter ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's other shelter energy service footprint per capita.

The small number of LAs in this category, and the small number of both high and low standard deviation anomalies in Figure 5.6(b) suggests that the while the range of other shelter ESDs remains large across GB, this is driven by a small number of outliers, rather than all LA being spread across the full range of values. This would suggest that a national-level approach to reducing other shelter ESDs would be appropriate across much of GB, with only a small number of LAs requiring a more bespoke approach to reducing energy demand for other shelter.

5.3.3 Personal transport

Personal transport ESDs has been separated from public transport ESDs and aerial transport ESDs in this study as aggregating the three ESD categories into one overarching transport ESDs category would lose the nuance of the results of energy consumption for different types of transport. Figure 5.7(a) shows that 76% of LAs across GB exhibit high levels of personal transport ESDs. This aligns with the national average results for GB in Section 5.1, whereby personal transport made up the largest proportion of the total national average ESD footprint.

As with heating, and other shelter ESDs, Tower Hamlets has the lowest annual personal transport ESDs per capita of 0.20 toe. In Tower Hamlets, the personal transport ESD footprint per capita makes up 12% of Tower Hamlets' total ESD footprint, whereas in Fareham, in south-east England, the area with the highest annual personal transport ESDs (0.82 toe per capita), personal transport ESDs make-up 25.5% of the LA's total ESD footprint. The range of 0.62 toe per capita exhibited by personal transport ESDs is the largest across the ESD categories modelled in this chapter.

As well as Tower Hamlets, Figure 5.7(b) shows that other LAs within London demonstrate low anomalies of personal transport ESDs, particularly in Central London. This is due to the high density of public transport infrastructure in this area reducing the need to rely on a private vehicle for personal mobility. However, while Figure 5.7(a) shows high levels of personal transport ESDs across 76% of LAs in GB, Figure 5.7(b) shows that no LA exhibits very high anomalies (>2 standard deviations from the mean).

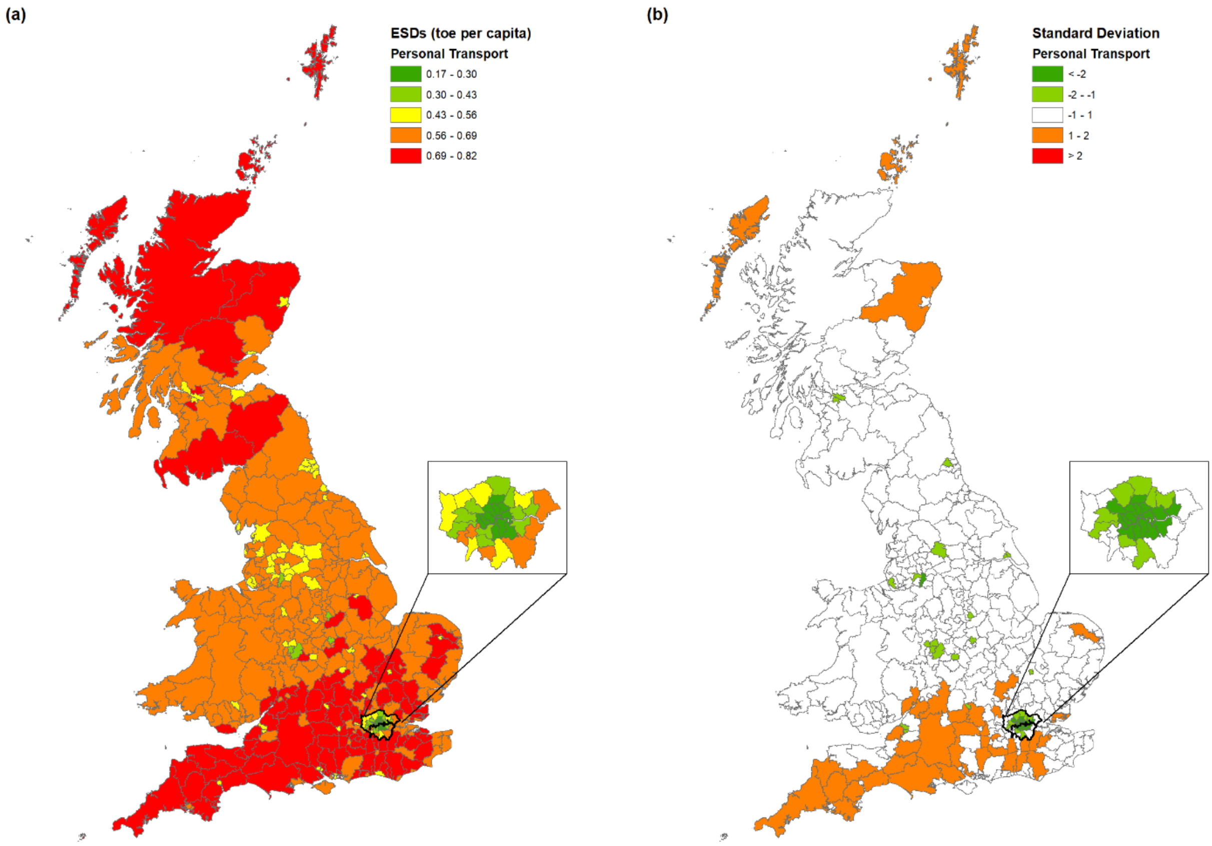

Figure 5.7 (a) Personal transport ESDs per capita by LA throughout Great Britain. (b) Standard deviation of each LA's Personal transport energy service footprint per capita.

The lack of very high anomalies for personal transport is due to the number of LAs (76%) exhibiting high levels of personal transport ESDs. High personal transport ESDs across much of GB has skewed the mean, meaning that despite many areas of GB needing to significantly reduce energy for personal transport, significant reductions are needed for almost all LAs across GB.

A spatial autocorrelation analysis of personal transport ESD footprints generates a Moran’s I value of 0.62, indicating high levels of clustering of LAs with similar ESD footprints. This is evident within Figure 5.7(a), whereby a cluster of low personal transport ESDs is evident in London, while in south-west England and Scotland, household ESDs for personal transport are much higher.

The high level of personal transport ESD across much of GB suggests that disaggregated, LA-level approaches to energy demand reduction (EDR) for the energy consumption associated with personal transport ESDs, may be less relevant than other ESD categories. However, the high levels of clustering of LAs with similar personal transport ESD levels suggests that LAs in certain areas of GB – e.g. south-west England, Scotland and London – may be high due to the underlying geographical factors of the area, thus implying that a more bespoke approach could benefit these areas when considering EDR for personal transport ESDs.

5.3.4 Public Transport

Public transport accounts for household use of shared transport provided as a public good or through a private company. Flying could fall under this description, however, it is excluded from this ESD category as it requires far greater energy demand than other forms of public transport such as buses and trains.

Figure 5.8(a) shows that LAs throughout much of GB (87.6% of LAs) exhibit low household demand for public transport ESDs. Public transport ESDs are a lot lower than the previously examined ESDs in Section 5.3.1, Section 5.3.2 and Section 5.3.3. Figure 5.8(a) also shows a concentrated area of high public transport ESD levels in the London region of GB, with residents of Harrow having the highest annual public transport ESD footprint of 0.46 toe per capita. Conversely, the area with the lowest annual public transport ESDs per capita is Eden is north-west England, with residents in this area only requiring 0.02 toe per capita per capita to fulfil their present level of public transport ESDs, thus giving a range of 0.44 toe per capita between highest and lowest consuming area.

A spatial autocorrelation of the data aligns with the maps in Figure 5.8. The analysis generates a Moran’s I value of 0.85, indicating very high clustering of areas with similar public transport ESD levels.

Figure 5.8(b) highlights that the ESD footprint for public transport is significantly higher than the national average in London than the rest of GB, with anomalies of >2 standard deviations present across the whole London region. London has the densest public transport network throughout GB, meaning residents often rely on public transport rather than a private vehicle to fulfil their transport ESDs. However, as with personal transport ESDs, due to the large number of LAs across Scotland, Wales and the majority of England exhibiting low levels of public transport ESD, the mean has been skewed downwards and therefore the LAs outside of London do not exhibit standard deviation anomalies in Figure 5.8(b).

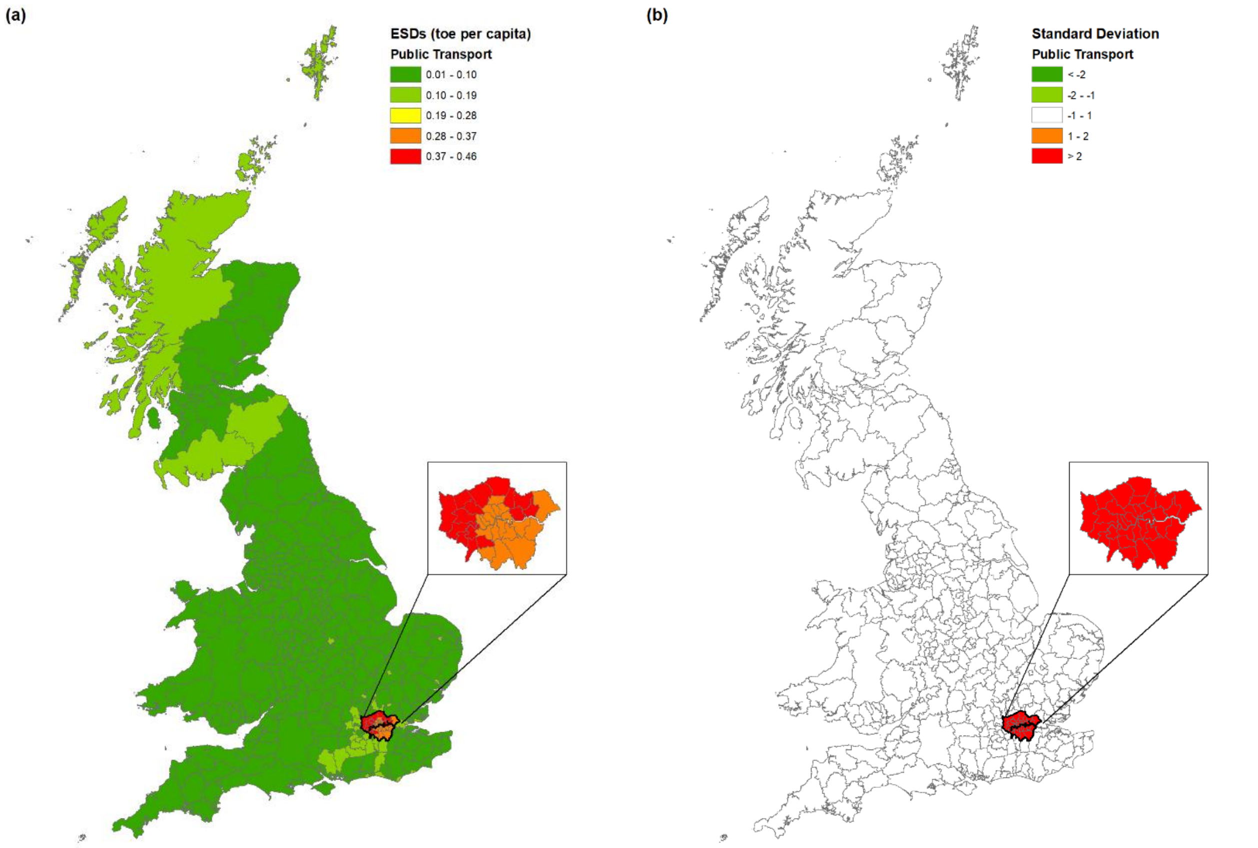

Figure 5.8 (a) Public Transport ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's Personal Transport energy service footprint per capita.

Considering Figure 5.8(a) and Figure 5.8(b) without context implies that limited intervention is needed for public transport ESDs, with the exception of London. However, a significant element of transitioning to a low energy demand society requires the increased use of public transport by shifting transport to a less energy intensive option – i.e. private vehicle use to public transport use (Ivanova *et al.*, 2020). Therefore, London should be used as an example for public transport use, rather than treated as an area where high ESDs need to be addressed.

Many of the LAs throughout GB exhibit low levels of public transport use by households. Therefore, increasing the level of public transport is necessary across much of GB. The results in Section 5.3.4 therefore suggest that a national-level approach to increasing public transport ESDs would be appropriate for GB.

5.3.5 Aerial Transport

Aerial transport is the final transport ESD to be examined in this study. Aerial transport includes flights taken by individuals for holidays or business trips, as well as freight.

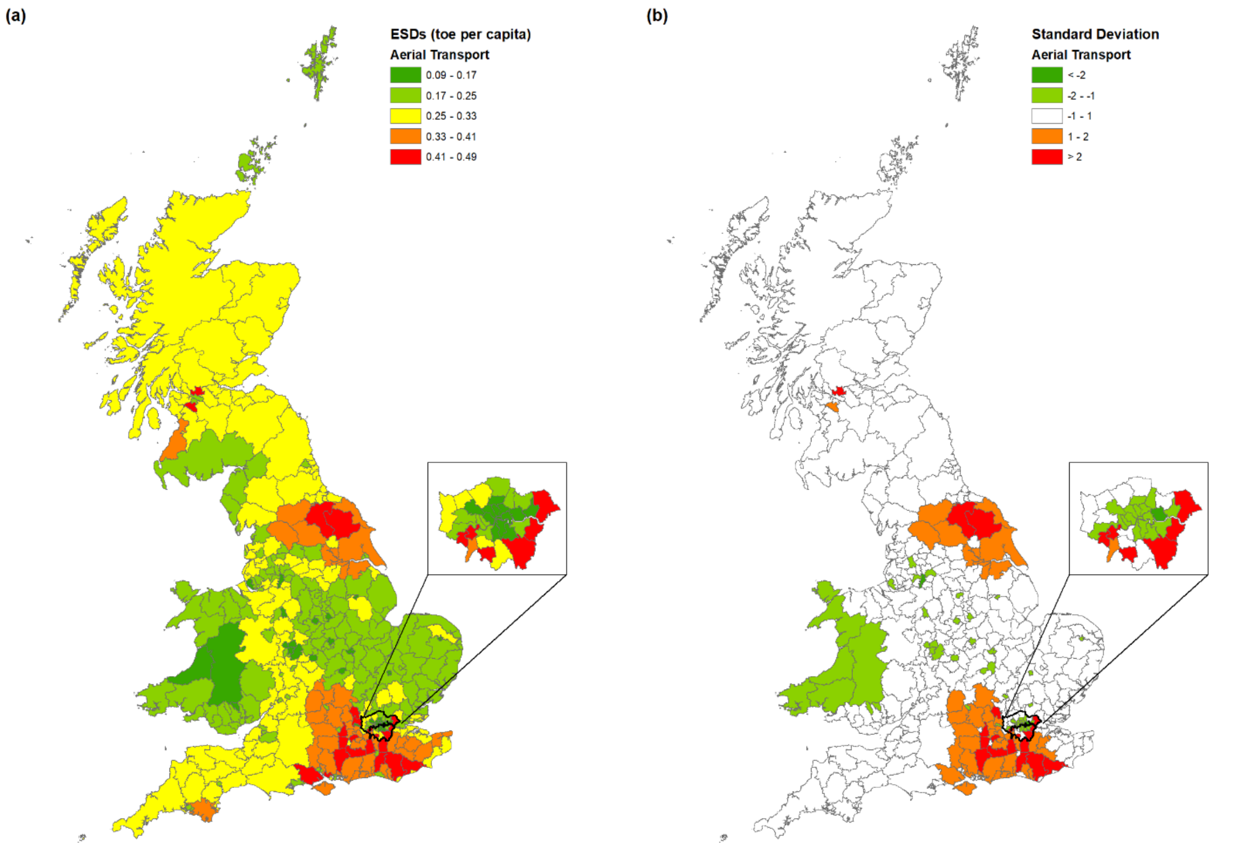

Figure 5.9 (a) Aerial Transport ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's Aerial Transport energy service footprint per capita.

A spatial autocorrelation analysis of the modelling results of household aerial transport ESDs by LA generates a Moran's I value of 0.50 indicating moderate clustering (Figure 5.9). Figure 5.9(a) shows that ESDs for aerial transport are lowest in Manchester (0.09 toe per capita), while Waverley, in south-east England, exhibits the largest demand for aerial transport (0.48 toe per capita). The range for household aerial transport ESDs across LAs in GB (0.39 toe per capita) is therefore lower than the other two transport ESD categories examined in this chapter (0.62 for personal transport ESDs and 0.42 for public transport ESDs). The smaller range therefore suggests marginally less variation in the number of flights taken by households across GB than the number of personal vehicle journeys, and the number of journeys on public transport.

Areas of high and very high demand for aerial transport ESDs seem to be predominantly located in south-east England, which have much greater proximity to large airports such as Heathrow and Gatwick, compared to other areas of the country (Figure 5.9(a)). In addition to south-east England, Figure 5.9(b) shows that LAs within Yorkshire and the Humber, and two LAs near to Glasgow exhibit high and very high standard deviation anomalies for aerial transport ESDs. All of these areas have proximity to large airports – Leeds-Bradford and Glasgow airports respectively.

However, residents of Manchester live in close proximity to Manchester airport, yet exhibit the lowest ESDs for aerial transport in GB, therefore suggesting that distance from an airport is not a driving factor of aerial transport ESDs, meaning that other socioeconomic factors must be driving aerial transport ESDs in these areas. Additionally, Wales exhibits low and very low demand for aerial transport ESDs across many of its LAs, while the East Midlands, and the east of England regions seem to also predominantly exhibit low demand for aerial transport ESDs (Figure 5.9(a)).

The LA-level results across GB show that aerial transport ESDs are more regionally specific than has been observed in the results for heating, other shelter, personal transport and public transport ESDs. This is evident in in Figure 5.9(b) where the map highlights areas of high consumption. The regional clustering suggests that a regional, rather than a national or LA specific approach may therefore be appropriate for reducing aerial transport ESDs. However, regions of GB are administrative and do not possess any form of governmental capability in GB, therefore a national-level approach would be most appropriate for aerial transport ESDs.

5.3.6 Nutrition

In this study, nutrition ESD results for each LA are generated from both direct and indirect energy consumption. Direct energy for nutrition relates to the energy required from the energy system to cook food in each area, while indirect energy is embodied within food products consumed by households in each LA. Nutrition ESDs have been included in this study as it is expected that large shifts in diet will be necessary in order to reach the UK's net-zero climate target and achieve the 1.5°C temperature goal in the Paris Agreement (Masson-Delmotte *et al.*, 2018; Garvey *et al.*, 2021).

Figure 5.10(a) shows that areas of high and low energy consumption for nutrition at a LA-level is weakly clustered, with a spatial autocorrelation analysis generating a Moran's I value of 0.37. Therefore, while the majority of households in LAs across GB exhibit moderate to very high levels of energy consumption for nutrition ESDs, there is limited patterning in the results.

The range of results for nutrition ESDs is much smaller than the results for the ESD categories previously examined in Section 5.3. The range of results varies from 0.14 toe per capita in Tower Hamlets to 0.25 toe per capita in Bromley, thus giving a range of 0.11 across GB, and the region of London, which contains the highest and lowest consuming LAs. The small range of Nutrition ESDs and limited clustering of areas with similar results suggests that while Figure 5.10(b) shows that areas of Scotland and south-west England exhibit high standard deviations about the national average there are no areas of excessively high consumption in GB which would require a LA-specific approach to EDR.

Dietary shifts are expected to play an important role in EDR for households in the future (Garvey *et al.*, 2021). However, shifts to plant-based diets, rather than meat-based diets, in households would be a relevant policy option across GB.

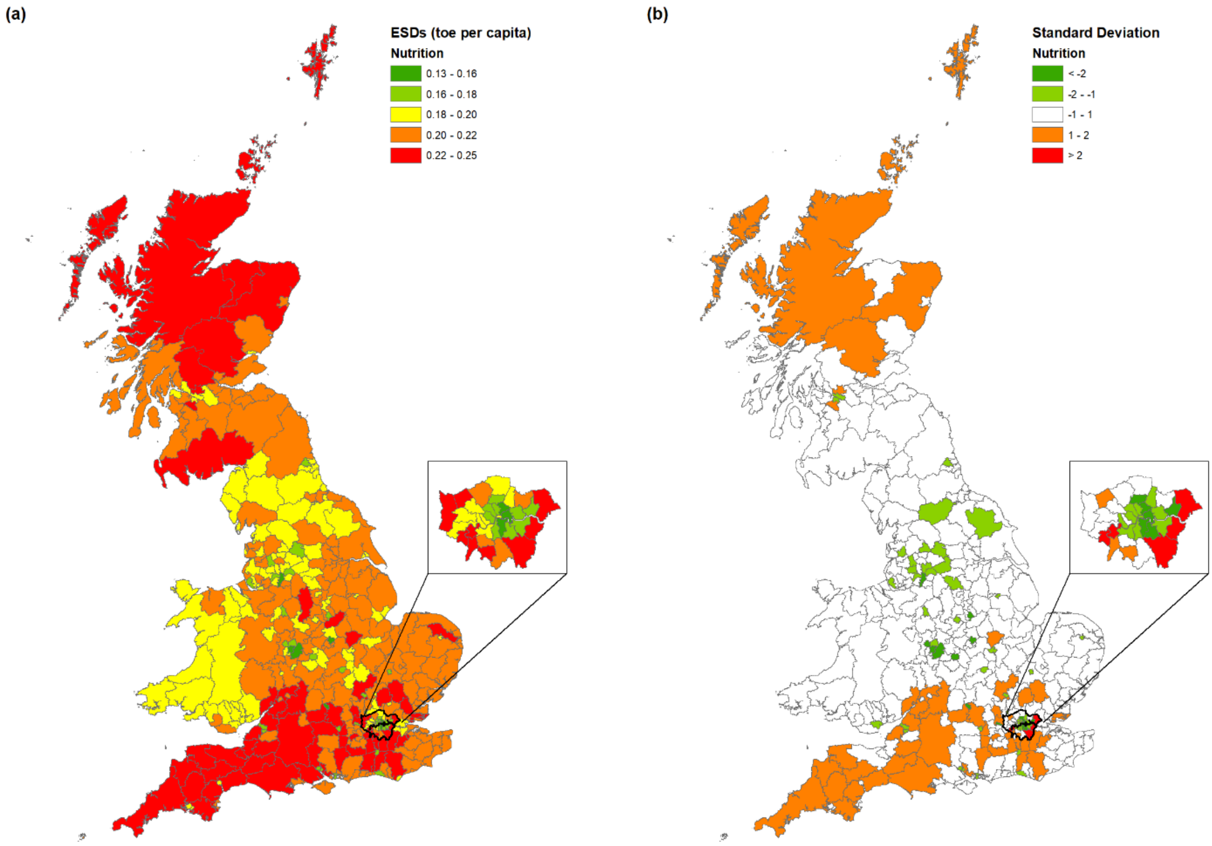

Figure 5.10 (a) Nutrition ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's Nutrition energy service footprint per capita.

5.3.7 Recreation & communication

Recreation & communication ESDs are supplied to households in LAs across GB through indirect ESD embodied in the products and services purchased for recreation & communication. The range of energy consumption for recreation & communication ESDs is 0.16 toe per capita, ranging from 0.10 toe per capita in Tower Hamlets (London) to 0.26 toe per capita in Wealden (south-east England). As with nutrition ESDs, the range in recreation & communication ESDs is smaller than buildings and transport-related ESDs due to the lack of direct energy modelled for this category.

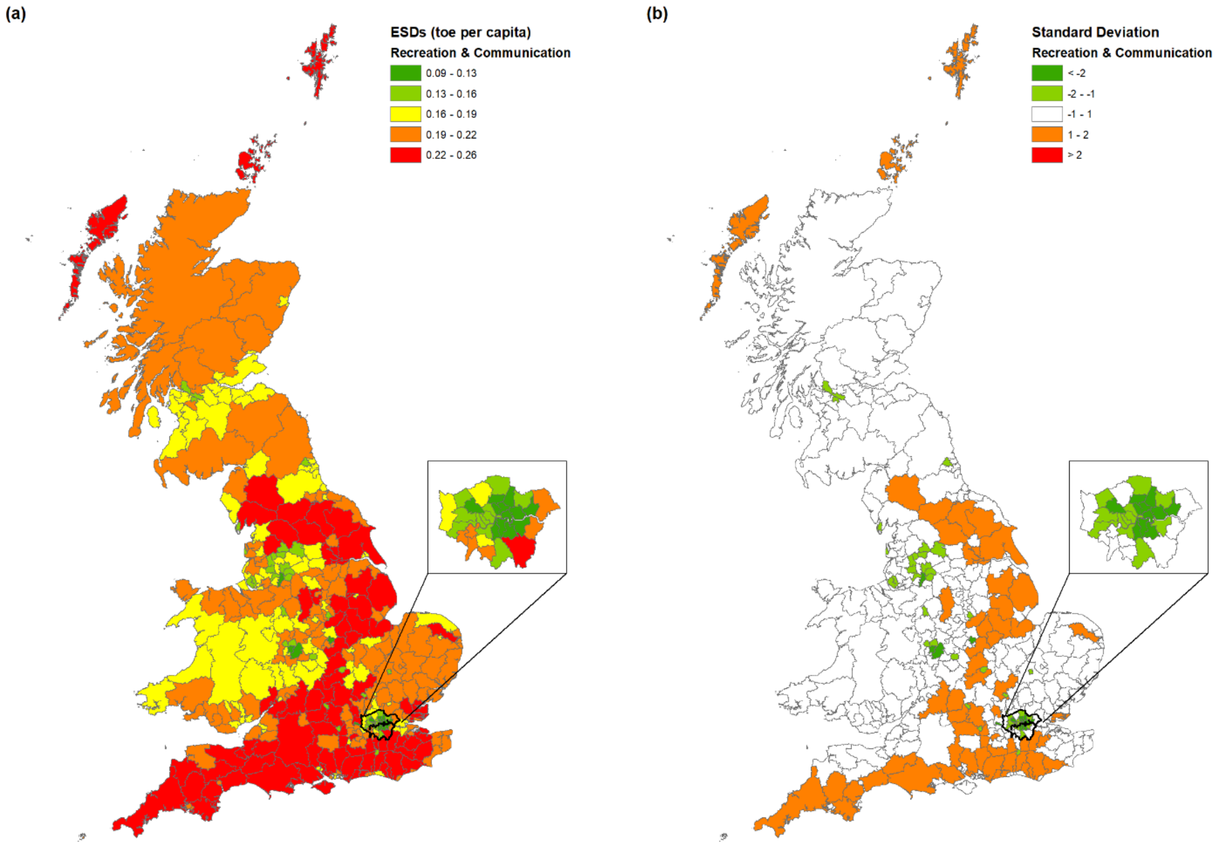

Figure 5.11 (a) Recreation & Communication ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's Recreation & Communication energy service footprint per capita.

Figure 5.11(a) shows the different levels of recreation & communication ESDs across LAs within GB, while Figure 5.11(b) shows areas which exhibit high and low standard deviations about the national average for this ESD. Much of GB exhibits moderate to very high levels of recreation & communication ESDs (Figure 5.11(a)). However, Figure 5.11(b) shows that there are no areas of very high anomalies for this ESD category in GB.

A spatial autocorrelation analysis of the results in Figure 5.11 generates a Moran's I value of 0.39, indicating weak clustering of LAs with similar levels of recreation & communication ESDs. The small range and weak clustering of LAs with similar recreation & communication ESDs suggests that a LA-specific approach to EDR for this ESD category would not add any value to the current, nationally-led approach. Any LA-specific approach would likely be applicable to multiple LAs, therefore creating and implementing EDR policy at a local-level for recreation & communication would be very time-consuming and costly to generate a similar result across many areas of GB.

5.3.8 Consumer goods

Consumer goods represent a small proportion of the total ESD footprint of each LA, an average of 3% for GB (Figure 5.1). However, through less consumption and material efficiency, reducing the level of energy demand associated with consumer goods provides opportunities for household EDR in GB.

Figure 5.12(a) shows that few LAs in GB exhibit very high levels of household consumer goods ESDs. Additionally, Figure 5.4 and Figure 5.12(a) shows that the range of consumer goods ESD across GB is low. As with other ESD categories, the Tower Hamlets LA in London exhibits the lowest level of households ESDs for consumer goods in GB – 0.05 toe per capita – while another London LA, Richmond upon Thames, exhibits the highest level of household consumer goods ESDs of 0.09 toe per capita.

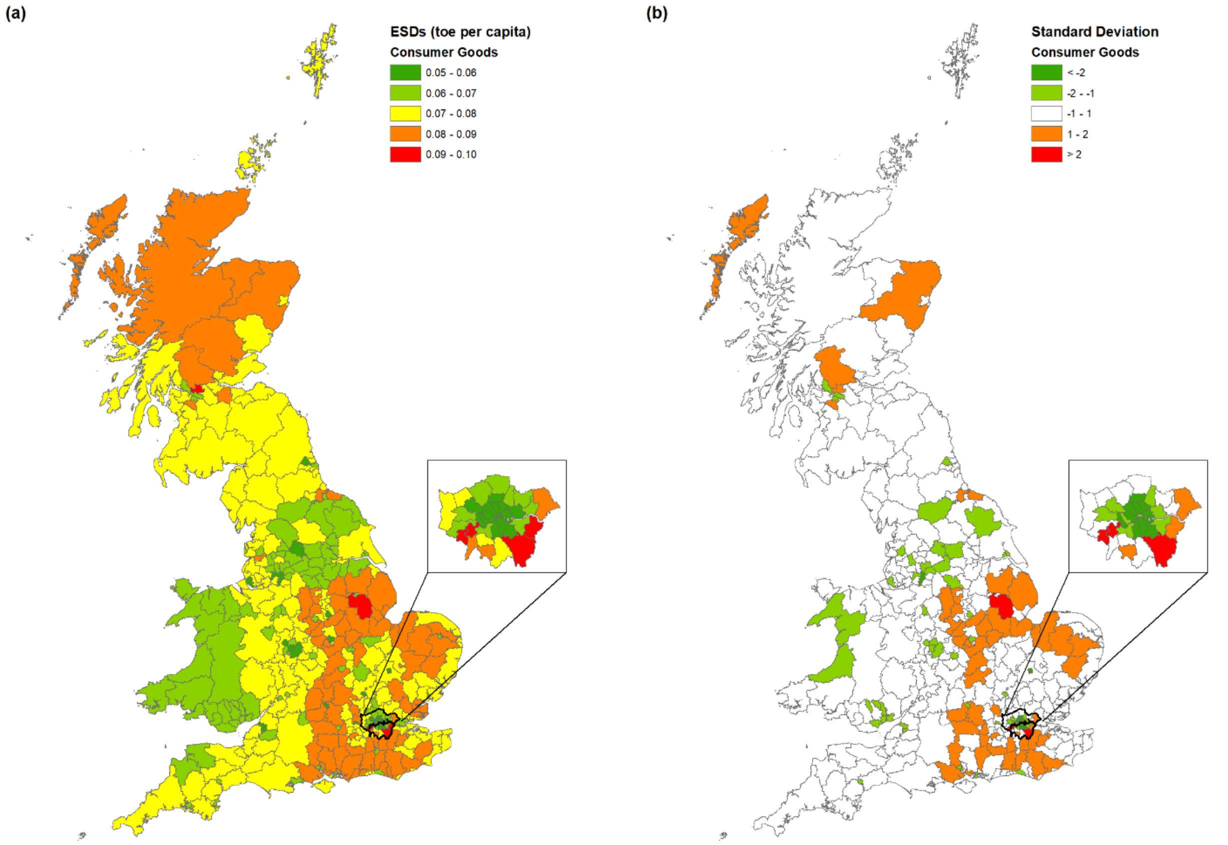

Figure 5.12 (a) Consumer Goods ESDs per capita by LA throughout Great Britain. (b) Standard deviation of each LA's Consumer Goods energy service footprint per capita.

Figure 5.12(a) shows that much of GB, with the exception of Central London, Wales and a large cluster within Yorkshire and The Humber, exhibits moderate to high consumer goods ESDs on an annual basis. However, an analysis of the results using a spatial autocorrelation analysis generates a Moran's I value of 0.41, indicating moderate clustering, therefore implying that while clusters can be identified visually, there is a very limited pattern to household consumer goods ESDs across GB.

Additionally, few of the low consumption LAs in Figure 5.12(b) produce low standard deviation anomalies. This indicates that even though Figure 5.12(a) suggests that the modelling results indicate low levels of energy consumption associated with consumer goods ESDs, they are within one standard deviations of the national average, and are not anomalously low areas of consumption.

The consumer goods ESD results in this section suggest that a disaggregated approach to EDR for this ESD category may be better suited to a nationally-led approach. While some LAs in GB exhibit high standard deviation anomalies, very few very high standard deviation anomalies have been modelled for the consumer goods ESD category (Figure 5.12(b)). Additionally, the Moran's I value of 0.41 does not suggest that LAs in different areas of GB exhibiting low or high levels of consumer goods ESDs are clustered. Finally, the small range of consumer goods ESDs suggests that consumer goods ESDs does not vary significantly across different LAs in GB (Figure 5.4).

5.3.9 Services

The final ESD category examined in Section 5.3 is services ESDs. Services ESDs account for the energy demand associated with utilising public and private service industries. Service industries included in this total includes financial, health and education services. Services ESDs do not utilise direct energy but have indirect energy embodied within the service an industry provides.

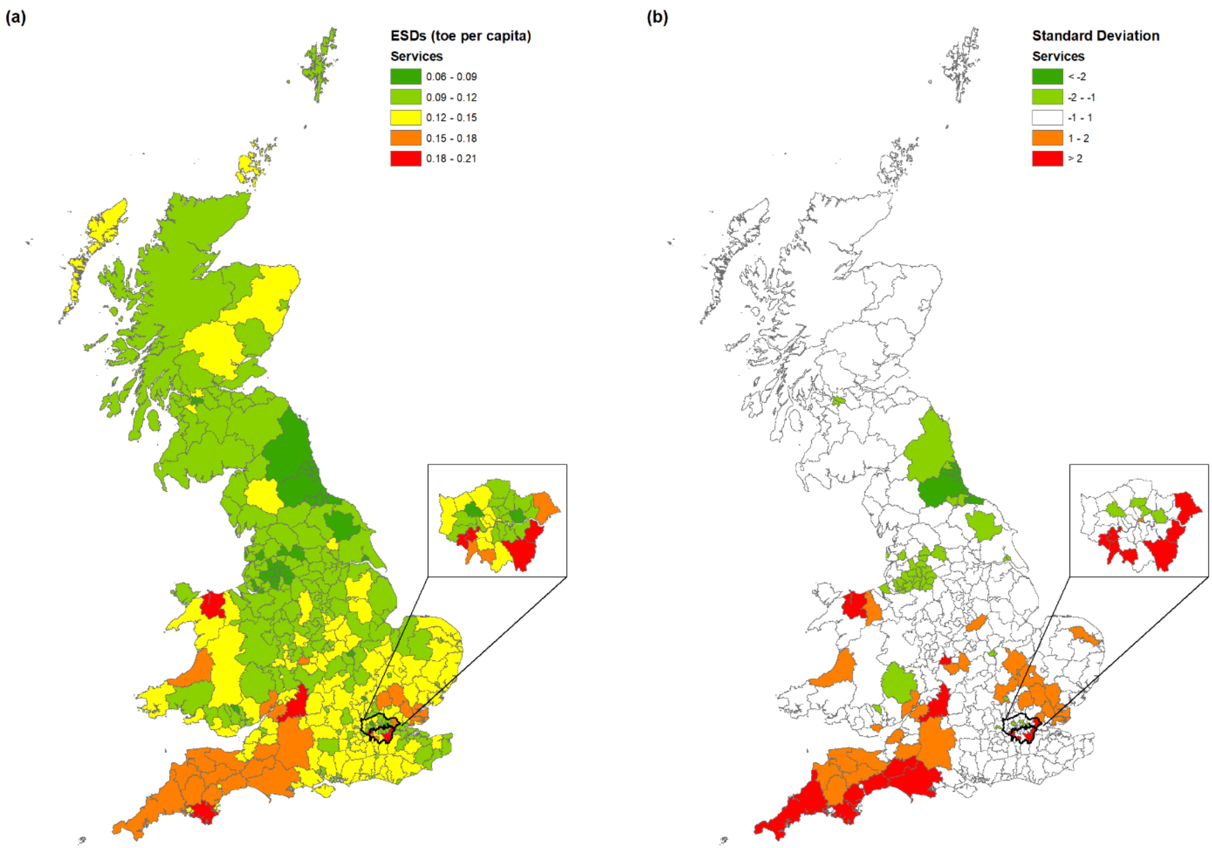

Figure 5.13 (a) Services ESDs per capita by LAs throughout Great Britain. (b) Standard deviation of each LA's Services energy service footprint per capita.

Figure 5.13(a) shows that households within the majority of LAs across GB have low to moderate ESDs for services. However, a cluster of LAs with high ESD footprints for services, are located in the south-west England region (Figure 5.13(a)). South Tyneside in the north-east of England has the lowest annual Services ESDs of 0.06 toe per capita, while the highest consuming LA is the Isles of Scilly, with an annual energy service footprint of 0.21 toe per capita, thus meaning that the range of energy consumption for services ESDs across GB is 0.16 toe per capita.

Figure 5.13(b) shows that the cluster of high services consumption, identified in Figure 5.13(a), exhibit high to very high standard deviation anomalies. Figure 5.13(b) also shows an area of low and very low standard deviation anomalies in north-east England, as well as in Lancashire and Cheshire in north-west England. The low anomalies are also identifiable in Figure 5.13.

The clusters visible in Figure 5.13 generate a Moran's I value of 0.48 when undertaking a spatial autocorrelation analysis, thus indicating moderate clustering of areas with higher and lower consumption of energy for services ESDs. The low range of services ESDs and moderate clustering suggests that there are no LAs GB which exhibit significantly different levels of services ESDs in GB that would warrant a disaggregated approach to EDR.

5.3.10 Summary

Section 5.3 breaks down the total ESD footprints examined for LAs across GB in Section 5.2. Heating ESDs and personal transport ESDs make-up the largest proportions of the national energy footprint in Section 5.1, however, across GB, the range of aerial transport and other shelter ESDs overlaps with the lower end of the range of heating and personal transport ESDs (Figure 5.4). Nutrition ESDs, recreation & communication ESDs, consumer goods ESDs and services ESDs exhibit smaller ranges than the ESD categories related to buildings and transport.

From a clustering perspective, transport ESDs are more strongly clustered than the other ESD categories. However, the only ESD exhibiting strong clustering is public transport, whereby public transport ESDs are high in London, but lower elsewhere in GB. The clustering results suggest that for most ESDs, a disaggregated approach to reducing ESD levels would be unnecessary as many LAs exhibit similar ESD levels across much of GB. The exceptions to this are personal transport, public transport and heating ESDs. The large range for heating ESDs across GB suggests that more emphasis needs placed upon reducing heating ESDs in different areas of GB, while the large range and high levels of clustering for personal transport ESDs and public transport ESDs suggests that a more bespoke approach to EDR in different areas of GB may necessary. Although, considering personal transport ESDs, there is a need to significantly reduce energy consumption associated with this ESD category across GB, therefore any national-level EDR strategy may be effective across most LAs.

While, the ESD footprints in Section 5.3 give an insight into the variation of household ESDs across space in GB, there is no universal pattern which emerges across GB for all ESD categories, thus suggesting that household ESDs are driven by factors other than geography – with the exception of public transport ESDs in London. Section 5.4 will examine the underlying socioeconomic characteristics of each LA in relation to each LA's ESD levels to better understand the relationship between a LA's underlying geographic and socioeconomic and LA ESD levels per capita.

5.4 Analysis & discussion

Section 5.3 analyses the per capita ESD footprint results presented in Section 5.1 and Section 5.2 against the geographic and socioeconomic characteristics of each LA using correlation (Spearman's Rank) and regression analyses. The analyses undertaken in Section 5.3 will be used to identify insights into the relationship between ESDs and the underlying geographic and socioeconomic factors of LAs.

As stated previously, past studies have identified socioeconomic drivers of household-level footprints – including household income, household size, and the number of vehicles per household – as indicators of households with higher environmental footprints (Minx *et al.*, 2013; Owen and Barrett, 2020; Salo *et al.*, 2021). Undertaking analyses to identify the socioeconomic factors which share the strongest relationship with LA-level ESDs in GB will demonstrate whether the same trends exhibited by individual household energy footprints are replicated at a LA-level.

Section 5.4.1 will perform analyses upon the ESD footprints of each LA, and the socioeconomic factors which have been identified as drivers of high consumption in the past. Following this, Section 5.4.2 will examine other socioeconomic factors – including population density, median age of the population, unemployment rate – which have exhibited limited relationships with household footprint size in the past.

5.4.1 Analysis of previously identified consumption drivers

The socioeconomic factors analysed in Section 5.4.1 are average household income, average household size and the number of vehicles per household in each LA. These factors have been identified by previous studies as drivers of household consumption, and should therefore indicate areas of higher ESD footprints in GB (Minx *et al.*, 2013; Salo *et al.*, 2021).

In Section 5.4.1, each ESD will be analysed against each socioeconomic factor, however it is not expected that each analyses will yield a significant result. For example, it is unlikely that the number of vehicles per household will affect the level of heating ESDs in a LA, however, analysing each ESD against each variable ensures that a potential connection between two variables is not overlooked.

The correlation analyses for the ESD categories and the previously identified socioeconomic drivers of household consumption can be seen in Table 5.1[18], while the regression analyses of the same ESD footprints and socioeconomic variables be seen in Table 5.2[18]. Figure 5.14,

Figure **5.15** and

Figure **5.16** show the scatterplot of average household income, average household size and number of vehicles per household respectively for each ESD footprint analysed in Section 5.2.

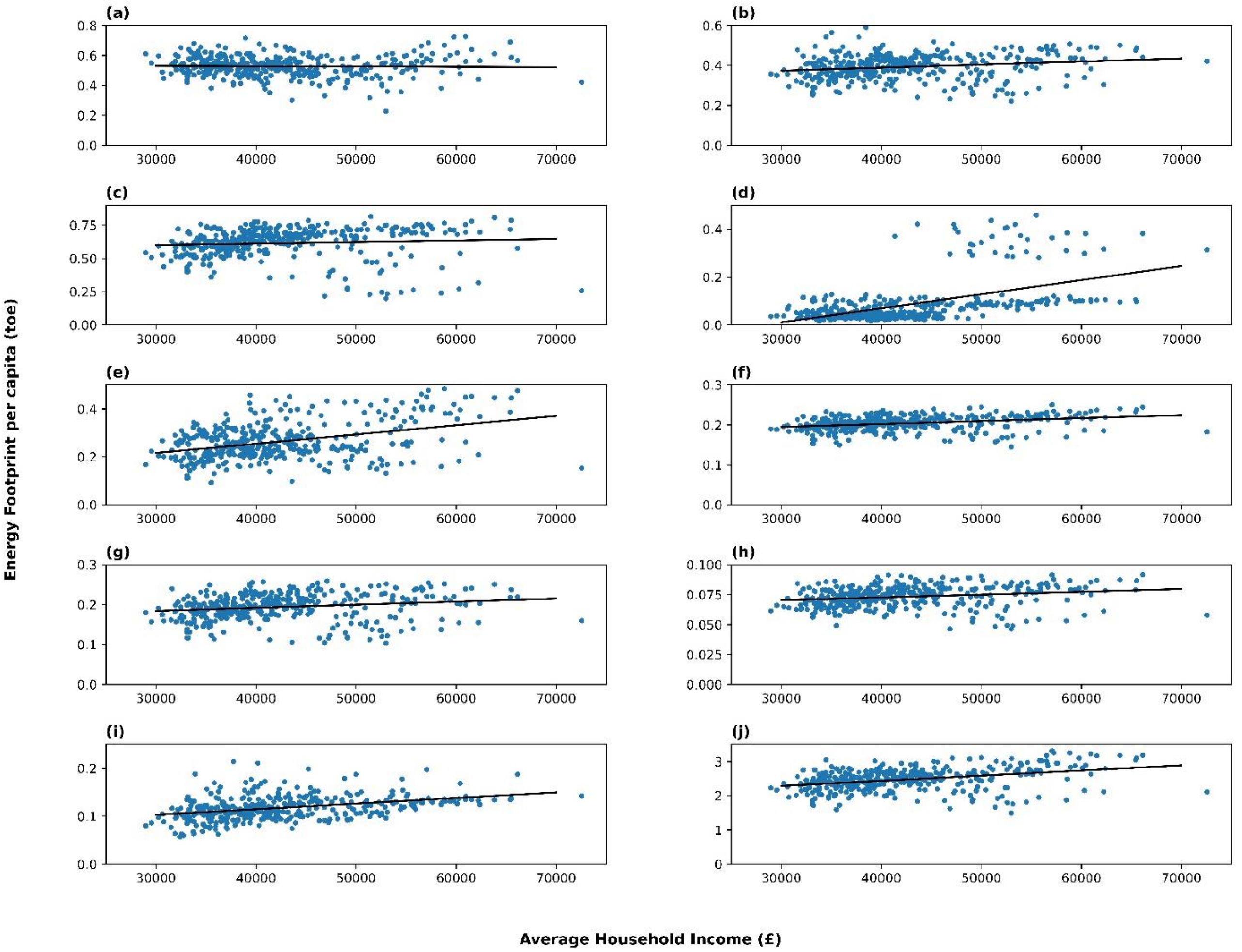

Figure 5.14 Scatterplots of the average household income of a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

[18] The correlation and regression results presented in Section 5.4 are based upon analyses of the untransformed socioeconomic variables and ESDs. The data was also logarithmically transformed and analysed using correlation and regression analyses, however the log transformed data presented weaker relationships between the ESDs and socioeconomic factors than the untransformed data.

Table 5.1 Correlation coefficients from the Spearman's Rank analyses between the different ESDs analysed in Chapter 5 and different socioeconomic indicators. Red cells highlight very weak correlation coefficients between variables, orange cells highlight weak correlation coefficients between variables, yellow cells highlight moderate correlation coefficients between variables, light green cells represent strong correlation coefficients between variables and dark green cells represent very strong correlation coefficients between variables.

Energy Service Demands	Heating	Other Shelter	Personal Transport	Aerial Transport	Public Transport	Nutrition	Recreation & Communication	Consumer Goods	Services	Total ESDs
Average Household Income	-0.06	0.26*	0.34*	0.30*	0.50*	0.37*	0.28*	0.30*	0.43*	0.39*
Number of Vehicles per Household	0.29*	0.63*	0.74*	0.38*	-0.15*	0.60*	0.65*	0.56*	0.43*	0.60*
Average Household Size	0.29*	-0.16*	0.01	0.02	0.44*	0.02	-0.10*	0.04	0.09	0.00

* Correlation coefficient is statistically significant to a 95% level (p<0.05).

Table 5.2 r-squared values from the regression analyses between the different ESDs analysed in Chapter 5 and different socioeconomic indicators. Red cells highlight very weak relationships between variables, orange cells highlight weak relationships between variables, yellow cells highlight moderate relationships between variables, light green cells represent strong relationships between variables and dark green cells represent very strong relationships between variables.

Energy Service Demands	Heating	Other Shelter	Personal Transport	Aerial Transport	Public Transport	Nutrition	Recreation & Communication	Consumer Goods	Services	Total ESDs
Average Household Income	0.00	0.04*	0.01	0.16*	0.27*	0.10*	0.04*	0.05*	0.14*	0.14*
Number of Vehicles per Household	0.08*	0.25*	0.41*	0.10*	0.10*	0.22*	0.25*	0.23*	0.06*	0.23*
Average Household Size	0.08*	0.06*	0.00	0.00	0.17*	0.00	0.04*	0.00	0.00	0.00

* r-squared value is statistically significant to a 95% level (p<0.05).

As has been identified in previous studies, average household income generally exhibits positive correlation with all the LA-level ESD footprints modelled in Section 5.3 (Figure 5.14) (Table 5.1). However, the regression analysis in Table 5.2 indicates that the relationship between the average household income variable and each ESD footprint is ‘very weak’, with the exception of public transport ESDs, whereby the relationship is merely ‘weak’.

The results in Table 5.1 and Table 5.2 therefore indicate that average household income is not an effective indicator of household ESD footprints when considering energy demand at a LA-level. Similarly, when considering average household size, the negative trend per capita exhibited in correlation and regression analyses undertaken by previous footprinting studies, between household size and energy footprint size is not present (Table 5.1 and Table 5.2).

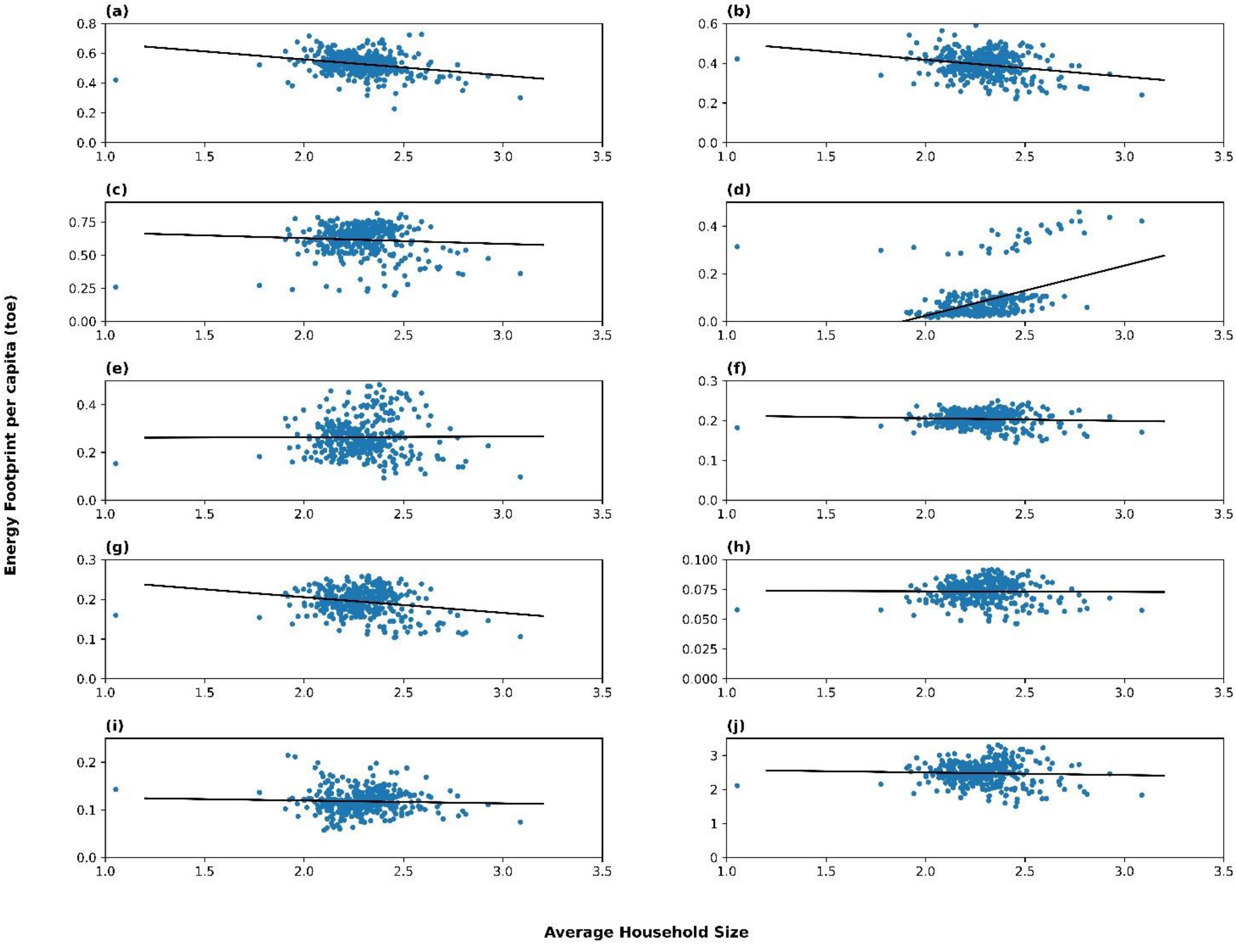

Figure 5.15 Scatterplots of the average household size of a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Public transport ESDs exhibits the strongest correlation between the ESD categories modelled in Section 5.2 and the three socioeconomic variables analysed in this section. However, the moderately positive correlation coefficient between public transport ESDs and average household size in Table 5.1 also demonstrates that average household size is a very weak determinant of public transport

ESDs. Figure 5.15 shows that there is no correlation, or a slight negative correlation between each ESD category and average household size (with the exception of public transport ESDs), therefore demonstrating that the previous trend between the two variables identified in footprinting studies is not present within the LA-level data. However, the regression analysis shows that as a predictor of ESD footprint size for all ESD categories, average household size is a weak determinant (Table 5.2).

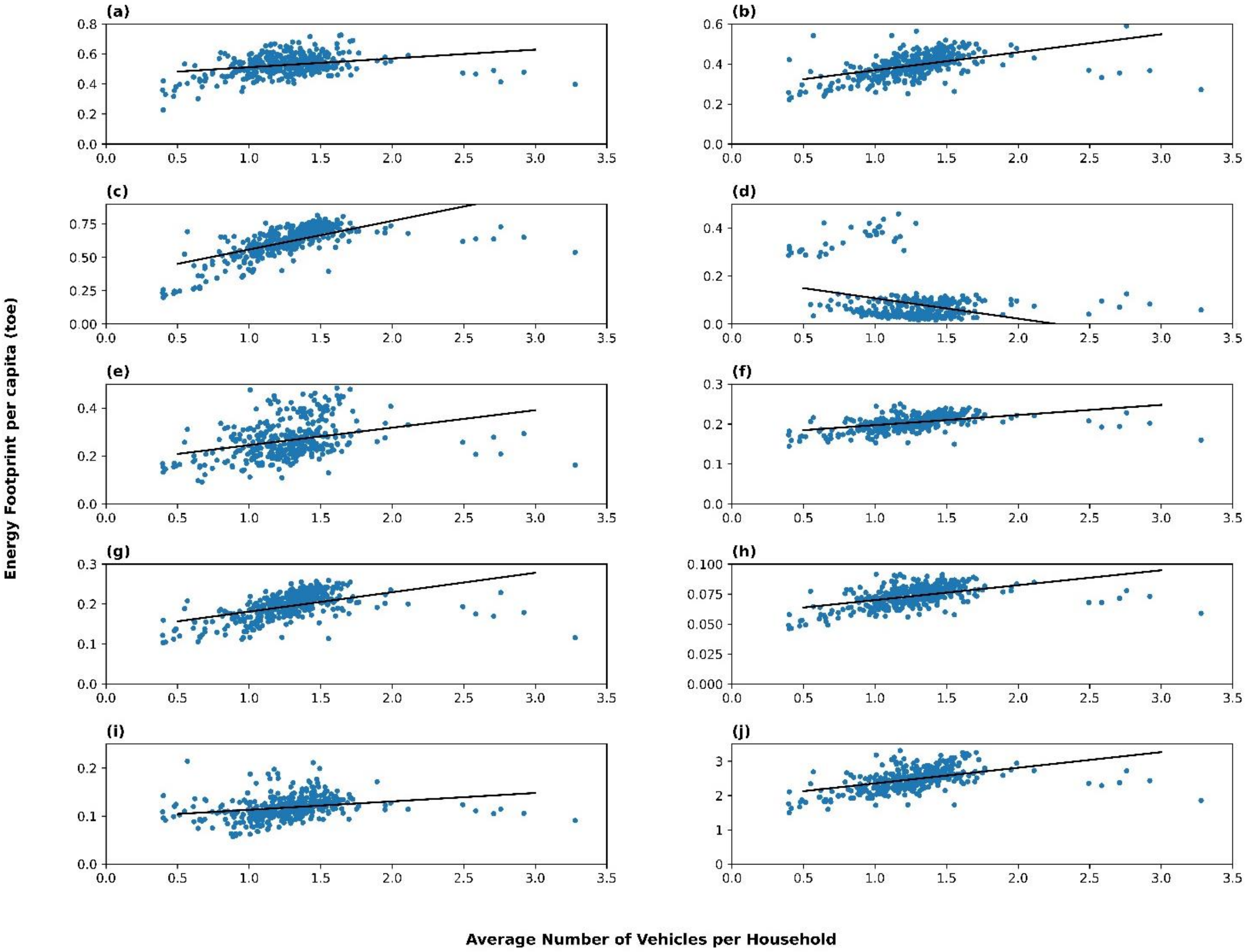

Figure 5.16 Scatterplots of the number of vehicles per household in a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Finally, the number of vehicles per household has previously been identified as a determinant of higher household footprints as transport-related consumption is often a large, energy intensive segment of a household's footprint (Minx *et al.*, 2013). Table 5.1 and Table 5.2 show that the number of vehicles per household for each LA has a stronger correlation and relationship with different ESDs than average household income and average household size.

The number of vehicles per household is expected to have the greatest effect upon personal transport, public transport and total ESDs as these directly relate to personal vehicle use. Table 5.1 shows positive correlation between personal transport and total ESDs, with personal transport ESD footprints of each LA having strong positive correlation and total ESD footprints of each LA having moderate positive correlation with the number of vehicles per household. However, the regression analysis in Table 5.2 suggests that the use of the number of vehicles per household variable as a determinant of personal transport and total ESD footprint size at a LA-level is weaker, with a moderate relationship for personal transport ESDs, and a weak relationship for total ESDs.

Beyond personal transport and total ESDs, the relationship between public transport ESDs and the number of vehicles per household is negative, rather than positive (Figure 5.16(d)). The difference in the direction of the correlation coefficient is logical as more available vehicles per household mean that public transport is less necessary for households. However, both the correlation coefficient in Table 5.1 and the r^2 value generated by the regression analysis in Table 5.2 suggests a weak relationship between the two variables, and that the number of vehicles per household does not indicate the level of public transport ESDs of a LA.

The analysis in this section suggests that previously identified drivers of household footprints are still present, but less significant when household footprints are considered at a LA-level, despite the socioeconomic variables and ESD footprints exhibiting similar trends to previous studies (Minx *et al.*, 2013; Owen and Barrett, 2020; Salo *et al.*, 2021). Therefore, analysis of the LA-level ESD footprints and different determinants of footprint size in this section, must go beyond traditional determinants of household footprint size and consider a wider variety of socioeconomic and geographic variables. Section 5.4.2 will consider more variables and their effect upon the ESD footprints modelled in Section 5.3.

5.4.2 Other socioeconomic determinants of consumption

The LA-level socioeconomic factors analysed in Section 5.4.2 are unemployment rate (%), population density (per km^2), proportion of population with degree-level qualifications (%), median age of the population, proportion of households not on the gas grid (%) and median household EPC rating. As with Section 5.4.1, each ESD will be analysed against each socioeconomic factor, to ensure that a potential connection between two variables is not overlooked. The correlation analyses for the ESD categories and the socioeconomic variables can be seen in Table 5.3[19], while the regression analyses can then be seen in Table 5.4[19]. Figure 5.17, Figure 5.18 and Figure 5.19 show the scatterplots for each LA-level ESD footprint and unemployment rate, population density and median age of the population respectively.

[19] The correlation and regression results presented in Section 5.4 are based upon analyses of the untransformed socioeconomic variables and ESDs. The data was also logarithmically transformed and analysed using correlation and regression analyses, however the log transformed data presented weaker relationships between the ESDs and socioeconomic factors than the untransformed data.

Table 5.3 Correlation coefficients from the Spearman's Rank analyses between the different ESDs analysed in Chapter 5 and different socioeconomic indicators. Red cells highlight very weak correlation coefficients between variables, orange cells highlight weak correlation coefficients between variables, yellow cells highlight moderate correlation coefficients between variables, light green cells represent strong correlation coefficients between variables and dark green cells represent very strong correlation coefficients between variables.

Energy Service Demands	Heating	Other Shelter	Personal Transport	Aerial Transport	Public Transport	Nutrition	Recreation & Communication	Consumer Goods	Services	Total ESDs
Unemployment Rate (%)	-0.40*	-0.71*	-0.75*	-0.44*	0.11*	-0.66*	-0.71*	-0.59*	-0.52*	-0.70*
Population Density (per km^2)	-0.56*	-0.71*	-0.59*	-0.34*	0.46*	-0.49*	-0.62*	-0.47*	-0.26*	-0.57*
Households not on the Gas Grid (%)	0.00	0.51*	0.36*	0.11*	0.02	0.30*	0.40*	0.15*	0.40*	0.36*
Median Household EPC Rating	-0.04	0.08	0.08	0.17*	-0.06	0.07	0.07	0.01	0.06	0.10*
Median Age of the Population	0.58*	0.75*	0.62*	0.43*	-0.46*	0.57*	0.67*	0.52*	0.29*	0.63*
Degree Level Qualifications (%)	0.11*	0.26*	0.18*	0.25*	0.37*	0.25*	0.19*	0.12*	0.36*	0.33*

* Correlation coefficient is statistically significant to a 95% level (p<0.05).

Table 5.4 r-squared values from the regression analyses between the different ESDs analysed in Chapter 5 and different socioeconomic indicators. Red cells highlight very weak relationships between variables, orange cells highlight weak relationships between variables, yellow cells highlight moderate relationships between variables, light green cells represent strong relationships between variables and dark green cells represent very strong relationships between variables.

Energy Service Demands	Heating	Other Shelter	Personal Transport	Aerial Transport	Public Transport	Nutrition	Recreation & Communication	Consumer Goods	Services	Total ESDs
Unemployment Rate (%)	0.19*	0.47*	0.49*	0.19*	0.05*	0.42*	0.49*	0.33*	0.24*	0.45*
Population Density (per km^2)	0.41*	0.43*	0.63*	0.14*	0.48*	0.30*	0.44*	0.38*	0.03*	0.33*
Households not on the Gas Grid (%)	0.00*	0.24*	0.04*	0.00	0.00	0.04*	0.07*	0.00	0.11*	0.05*
Median Household EPC Rating	0.01	0.01	0.01	0.02*	0.00	0.01*	0.01	0.00	0.02*	0.01*
Median Age of the Population	0.40*	0.59*	0.47*	0.19*	0.22*	0.40*	0.52*	0.36*	0.09*	0.43*
Degree Level Qualifications (%)	0.00*	0.01	0.04	0.04*	0.25*	0.00	0.00	0.00	0.09*	0.03

* r-squared value is statistically significant to a 95% level (p<0.05).

Unemployment rate is the percentage of the population of a LA which is unemployed. Considering unemployment rate and the aggregated energy service footprint of all LAs across GB shows a strong correlation Figure 5.17(j) of -0.70 ($p<0.05$) (Table 5.3). The relationship exhibited for the aggregated energy service footprint per capita is similar across all ESDs in Figure 5.17 with the exception of public transport ESDs (Figure 5.17(d)).

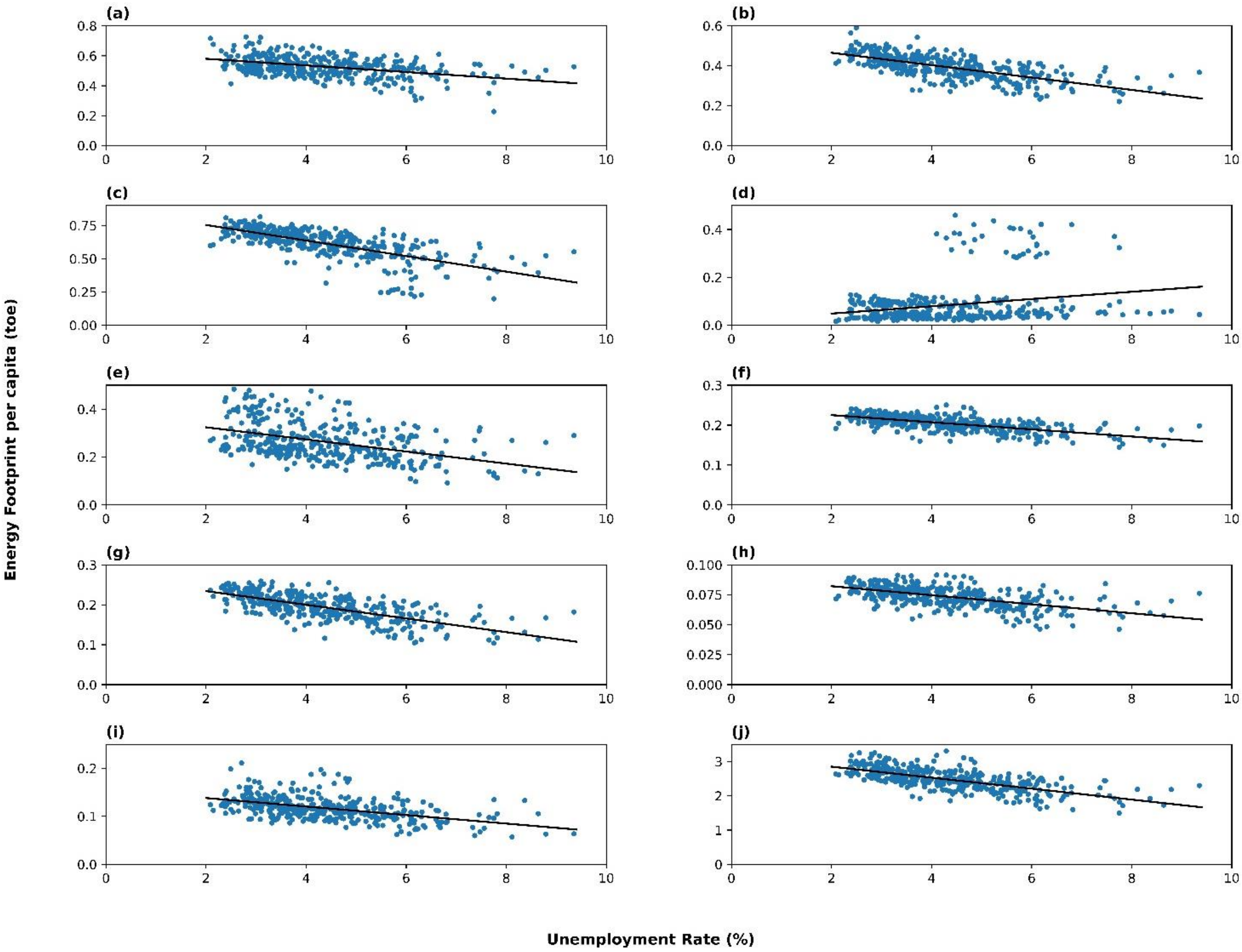

Figure 5.17 Scatterplots of the unemployment rate of a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Figure 5.17 suggests that as the unemployment rate of a LA increases, the ESDs per capita within a LA will decrease. The strongest correlation between unemployment rate and an ESD is with personal transport (Figure 5.17(c)) which has a very strong negative correlation of -0.75 ($p<0.05$) (Table 5.3) and an r^2 value of 0.49 suggesting a moderate relationship between the two variables (Table 5.4). Additionally, other shelter, nutrition and recreation & communication ESDs all exhibit statistically significant strong correlations with the unemployment rates of LAs throughout GB or -0.71, -0.66 and -0.71 respectively (Table 5.3). However a regression analyses suggests a moderate relationship between unemployment rate and these LA-level ESD footprints (Table 5.4).

Conversely, public transport ESDs are the only disaggregated ESD category to show a positive correlation with unemployment rate (Figure 5.17(d)). However, the correlation coefficient (Table 5.3) and the r^2 value between the two variables is very weak (Table 5.4). Therefore, it is unlikely that the unemployment rate of a LA is driving the level of public transport ESDs in that area.

The negative correlation exhibited between unemployment rate and both the aggregated and disaggregated ESD categories in Figure 5.17, with the exception of public transport ESDs, is due to unemployment rate acting as a LA-level proxy for household income. Table 5.3 and Table 5.4 show moderate to very weak correlation coefficients, and weak to very weak relationships between household income and different ESD categories, whereas, the correlations and relationships with unemployment rate are much stronger.

The relationship between household income and energy consumption has been noted by many studies (Goldstein *et al.*, 2020; Oswald *et al.*, 2020; Owen & Barrett, 2020). However, a relationship between unemployment rate and ESDs is less documented.

The data in Figure 5.17 suggests that increasing unemployment rate leads to lower LA ESDs, with the exception of public transport. However, increasing the unemployment rate of a LA is not a viable policy option, and would also not be a just transition to a low energy demand society, as it could impact upon the ability of households to meet their basic needs. However, the implication that higher average household income (through a lower unemployment rate) backs-up previous studies that show that higher income leads to higher ESDs (Goldstein *et al.*, 2020; Oswald *et al.*, 2020).

Population density per km^2 of a LA is calculated by dividing the population of a LA by its area. Urbanised areas have a greater population density compared to rural areas, therefore population density represents a gauge of the rurality of a LA.

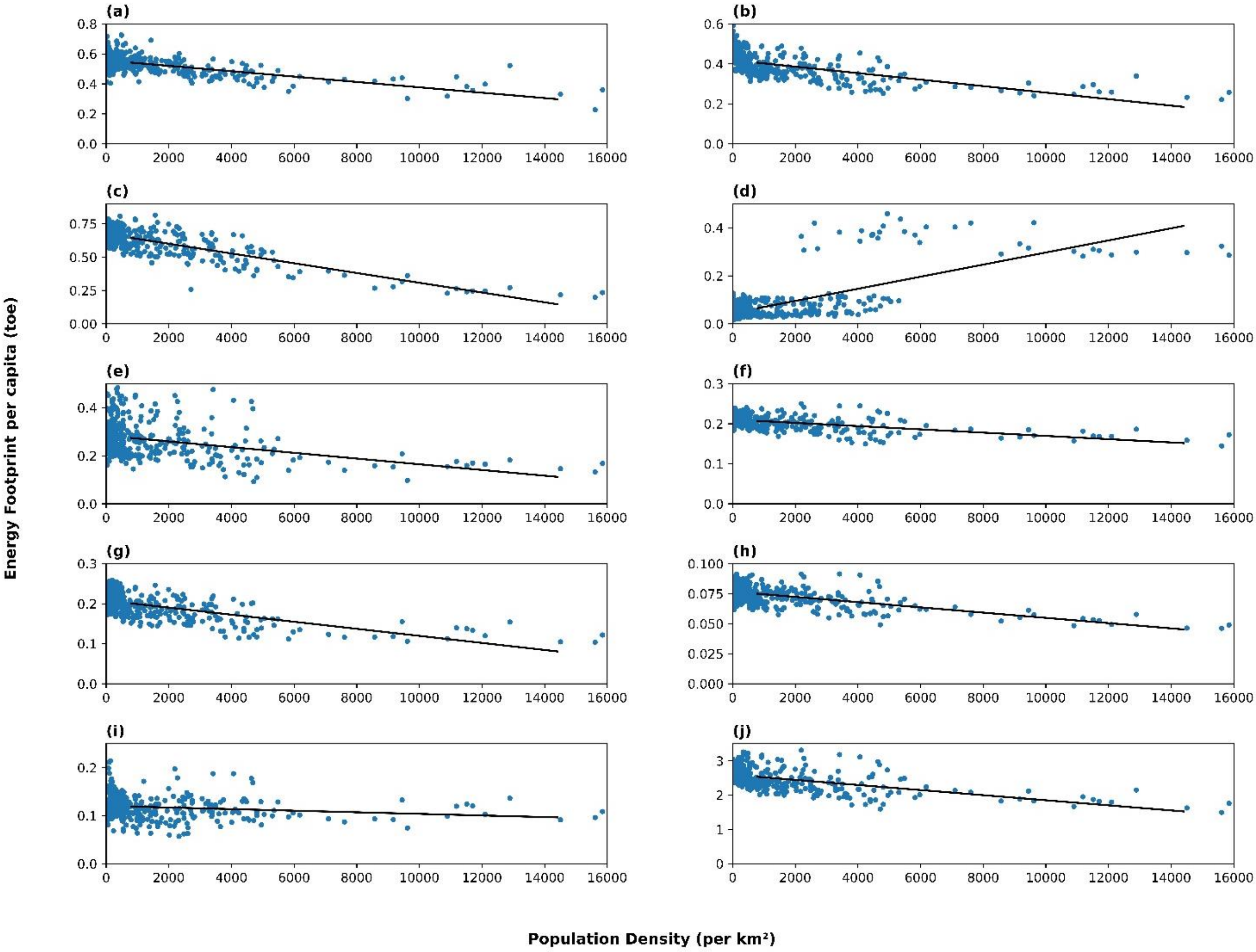

Figure 5.18 Scatterplots of the Population density (per km^2) of a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Figure 5.18 shows that population density (per km^2) has a negative correlation with the ESDs of a LA, with the exception of public transport ESDs (Figure 5.18(d)). Figure 5.18 therefore suggests that as the population density of a LA increases, the per capita ESDs of a LA decrease, meaning that the more urbanised LAs have lower ESDs than their rural counterparts. Figure 5.18(j) shows that this is the case for the aggregated per capita ESD footprints for LAs, suggesting that rural households require more energy to meet their ESDs than urban households. However, the distribution of the data in Figure 5.18 must be considered. The range of population densities is 15,836, however 62% of LAs in GB have a population density of <1000 per km^2, while there are very few very densely populated LAs with population densities above 4,000 people per km^2, meaning population density values in GB are concentrated under 1000 people per km^2, and that other values are outliers. However, taking logarithms of the dataset did not generate greater correlation coefficients or r^2 values when considering population density.

Table 5.3 shows that the strongest correlation between population density and the different LA-level ESD variables is for the other shelter ESDs which exhibits a strong negative correlation of -0.71

($p<0.05$), while personal transport and heating ESDs also exhibit moderate correlation coefficients of -0.59 and -0.56 respectively ($p<0.05$). However, undertaking regression analyses shows that the strongest relationship between population density and a LA-level ESD variable is for personal transport ESDs (Table 5.4) with heating and other shelter ESDs only exhibiting a moderate relationship with population density (Table 5.4).

The strong relationship between personal transport ESDs and population density has been explored in previous studies (Hutchinson *et al.*, 2014). By their very nature, rural, less densely populated LAs are not as compact as urban areas, meaning that rural households have to travel longer distances to reach places of work, education and recreation with limited public transport options available to them. Therefore, private vehicle use is generally higher in less densely populated LAs.

Based on the data in Figure 5.18, EDR for personal transport, other shelter and heating ESDs has greater potential in rural LAs. This is due to the nature of rural LAs in GB, and the need for direct energy to deliver heating, other shelter and personal transport ESDs. Rural LAs are less compact than urbanised areas, with a lower level of public transport infrastructure, therefore requiring households to rely upon personal transport instead of public transport or walking (Naumann and Rudolph, 2020). While for heating and other shelter ESDs, more polluting and energy intensive fuels – e.g. paraffin – are required to deliver direct energy to households, which makes up a large proportion of the heating and other shelter ESD footprints (Naumann and Rudolph, 2020). Insights, such as this may be beneficial for policymakers trying to assess EDR in different LAs across GB.

Public transport ESDs are the exception when considering a LA's population density, exhibiting a positive correlation (Table 5.3). Urbanised LAs (i.e. towns and cities) generally have a denser, more frequent public transport network than rural areas. Better access to public transport increases the likelihood of public transport use, therefore leading to higher public transport ESDs.

The median age of the population represents the mid-point of a LA's age structure. Half the population of a LA will be younger than the median age, while the other half will be older.

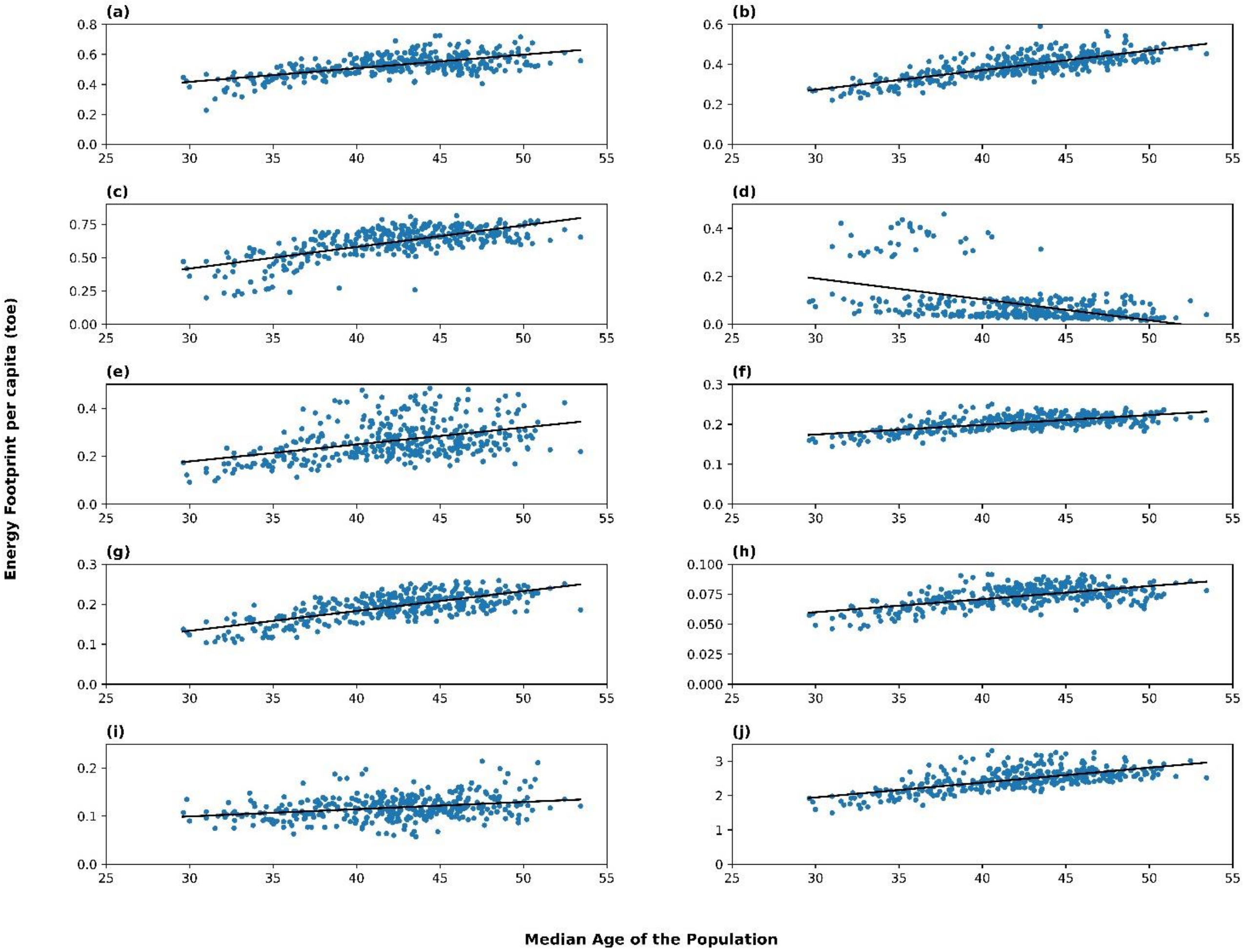

Figure 5.19 Scatterplots of the median age of the population of a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Figure 5.19 shows that all aggregated and disaggregated ESDs, again with the exception of public transport ESDs (Figure 5.19(d)), exhibit a positive correlation with the median age of a LA's population, which therefore suggests that the older a LA's population is, the more ESDs they will use. Table 5.1 shows that other shelter ESDs (Figure 5.19(b)) has the strongest correlation with the median age of a population across GB, with other shelter (Figure 5.19(b)), personal transport (Figure 5.19(c)), nutrition (Figure 5.19(f)), recreation & communication (Figure 5.19(g)) and total ESDs (Figure 5.19(j)) also strongly correlating with this particular socioeconomic variable. However, the regression analyses results in Table 5.4 show that median age of a LA's population only has a moderate effect on the increase in ESDs in the other shelter, personal transport, nutrition and total ESDs categories.

The increase in residential energy usage as a population ages has been observed in previous studies in the US (Estiri & Zagheni, 2019). However, the relationship between an older population and increased energy demand is also affected by other underlying factors (Salo *et al.*, 2021). For example, as people age, they often require or can afford larger homes with greater floor space which can lead to an increase in energy consumption (Estiri & Zagheni, 2019). It is therefore likely that increasing age rises alongside other factors, such as household's floor space and income which affect ESDs (Salo *et al.*, 2021). However, this can provide insights in its own way, allowing policymakers to identify LAs of potentially higher ESDs, before analysing such areas in greater detail to identify potential areas of energy demand reduction.

The exception to the positive correlation between the median age of a population and ESDs, can be seen in Figure 5.19(d) for public transport ESDs. Public transport ESDs have a moderate correlation (Table 5.3) and a weak relationship with the median age of the population of a LA (Table 5.4). As with all the other energy service categories the median age of a LA is driving other factors such as car ownership and disposable income (Salo *et al.*, 2021). A younger population is less likely to own a car, or have the disposable income to buy a car, and therefore must rely on public transport for commuting and leisure activities which causes increased ESDs in this category (Salo *et al.*, 2021).

Median household energy performance certificate (EPC) rating and the percentage of households not on the gas grid have also been examined against all variables, however as it is unlikely that they will affect all ESD categories, such as personal transport ESDs, these socioeconomic variables will only be discussed in the context of specific energy service categories.

Median household EPC rating refers to the mid-rating of the energy efficiency of households (Department for Levelling Up, 2017) within a LA, while the percentage of households not on the gas grid refers to the proportion of households within a LA which are not connected to the GB gas network. In its net-zero strategy, the UK government has made the insulation of households a priority to reduce domestic ESDs for heating (Figure 5.20(a)) (BEIS, 2021). However, the energy efficiency of households – identified through the EPC Rating of households – does not drive heating ESDs. Additionally, considering households which use more polluting fuels, such as paraffin – using households not on the gas grid as a proxy – also shows a low-level of correlation between the two variables (Figure 5.20(b)).

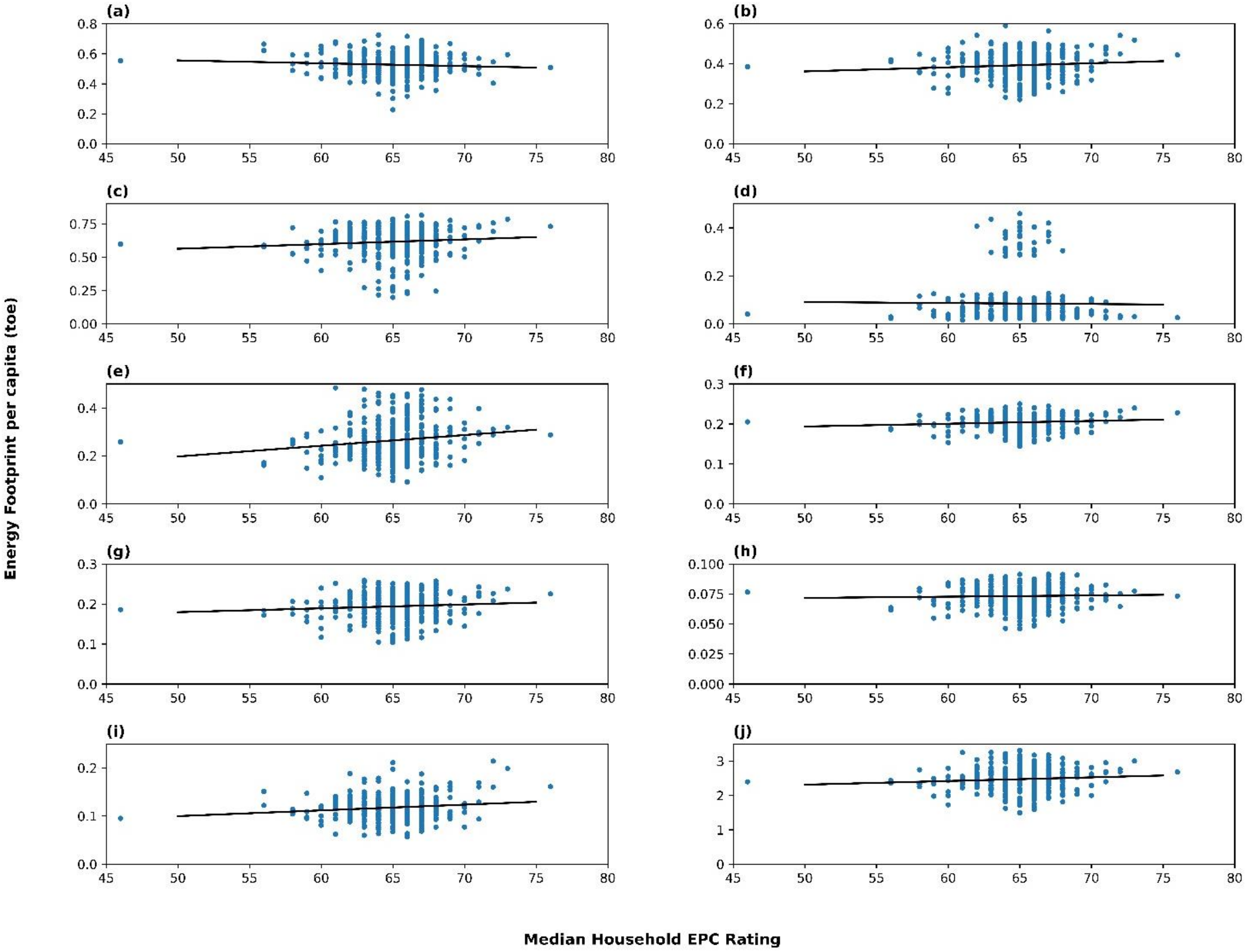

Figure 5.20 Scatterplots of the median household EPC rating of LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Figure 5.20(a) and Figure 5.21(a) shows that there is a very weak correlation between heating ESDs and the median household EPC rating of a LA (0.09, $p<0.05$) and the percentage of households in a LA not on the gas grid (0.05, $p<0.05$). Table 5.4 also shows that a regression analysis suggests a very weak relationship between heating ESDs and the two variables.

The lack of correlation and relationship between heating ESDs and the median household EPC rating in Figure 5.20(a) suggests that the energy efficiency of a dwelling does not determine the level of energy demanded by residents for heating. It is therefore likely that household ESDs for heating are driven by overconsumption. If policymakers simply try and address the energy efficiency of households, heating ESDs are unlikely to be reduced sufficiently in line with the EDR needed for a 1.5°C future.

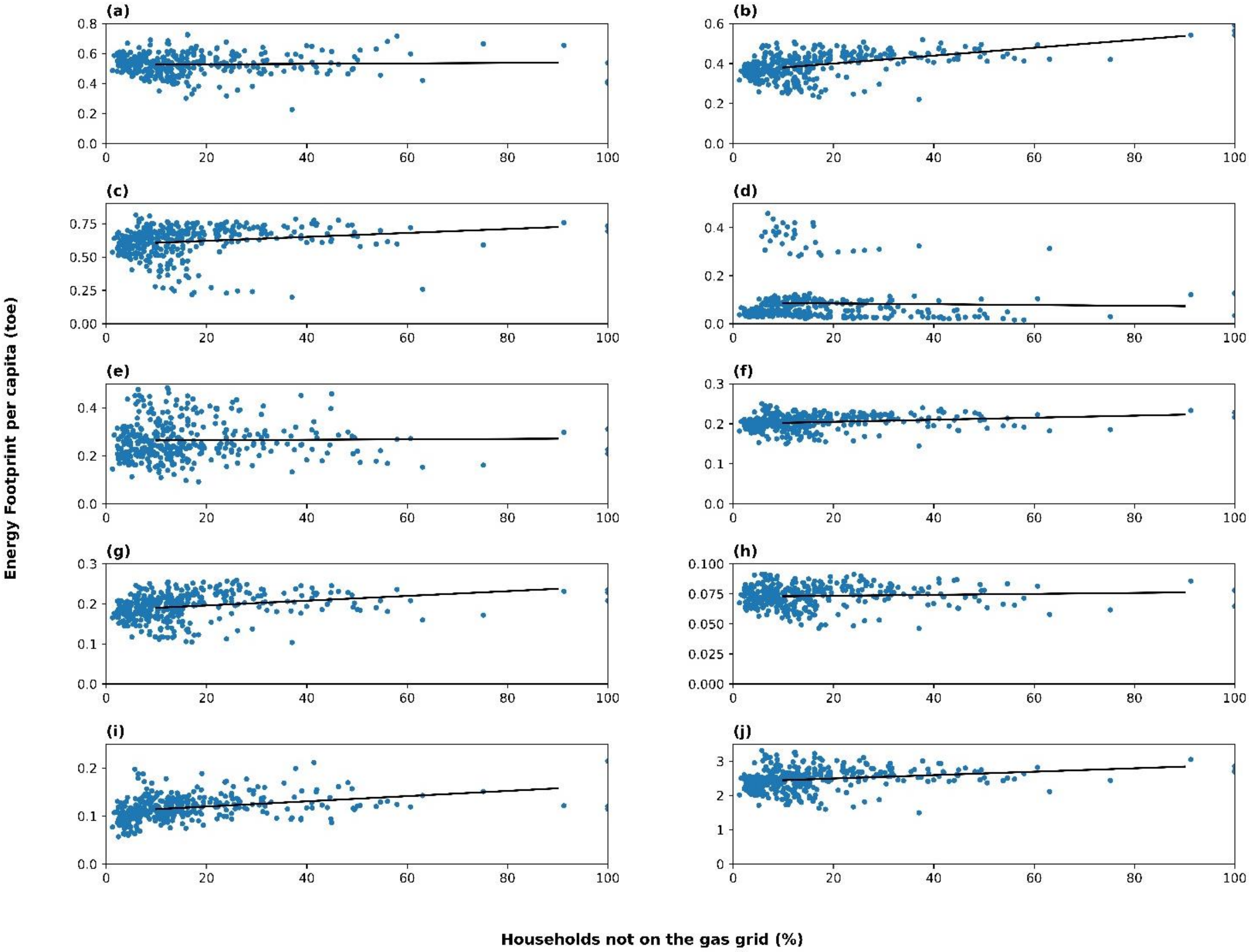

Figure 5.21 Scatterplots of the proportion of households not on the gas grid of a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Similarly, from examining Figure 5.5(a) and Figure 5.5(b) it might be expected that the greater the number of households not on the gas grid, the greater the level of heating ESDs in a LA. However, Figure 5.21(b) shows that the percentage of households not on the gas grid has, at best, a very weak correlation with heating ESDs. It is therefore unlikely fuel switching in rural areas, through adding households to the main gas grid across GB, will reduce heating ESDs in line with the level of reduction required for a 1.5°C future. The results from Figure 5.20 therefore suggest that policymakers need to go beyond considering energy efficiency options when addressing heating ESDs across GB.

Finally, the proportion of households with degree-level qualifications was considered. Table 5.3 and Table 5.4 show that a LA's proportion of households with degree-level qualifications does not determine LA-level ESDs (Figure 5.22). Table 5.3 shows that this variable has weak correlation with any LA-level ESD category, while Table 5.4 shows that all the relationships exhibited in Figure 5.22

are weak, with the exception of public transport ESDs. Degree-level qualifications are therefore not a good determinant of ESD footprint size at a LA-level.

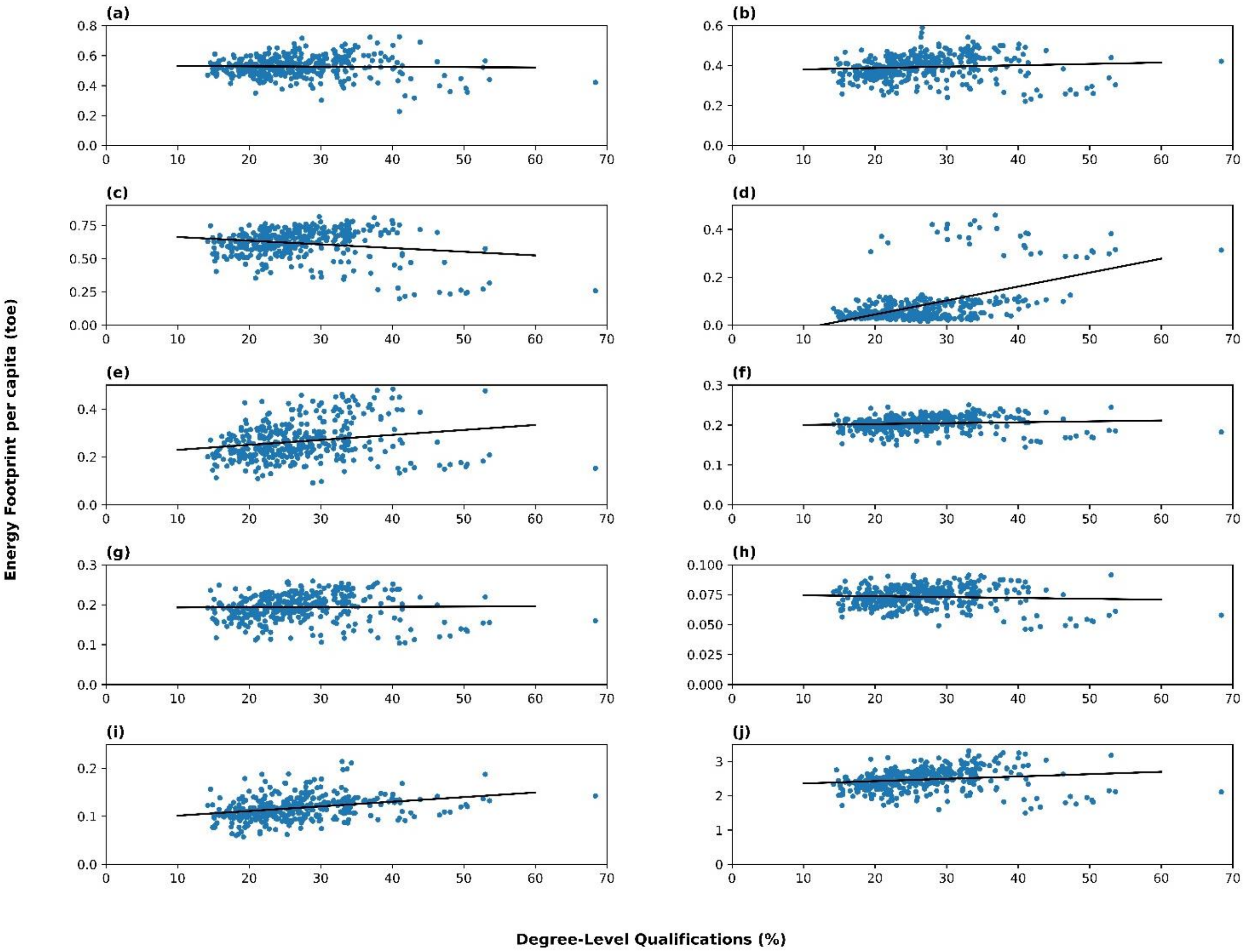

Figure 5.22 Scatterplots of the proportion of households with degree-level qualifications in a LA and the ESDs of the corresponding LA. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

5.5 Summary

GB's ESDs vary significantly across space. Chapter 5 of this thesis has quantified ESDs at a LA-level across GB and analysed the relationship between the underlying socioeconomic factors of a LA and a LA's energy service footprint. Personal transport and heating ESDs make up the greatest proportion of the GB national average footprint (Figure 5.1), however, other ESDs, including other shelter and aerial transport make a significant contribution towards LA energy service footprints.

LAs within Central London generally have the lowest ESDs per capita in GB, with the exception of public transport ESDs (Minx *et al.*, 2013). Conversely, Outer London and the regions of south-east England, south-west England and Scotland have much higher annual ESDs per capita across different ESD categories (Minx *et al.*, 2013).

However, as Section 5.3 shows, there are not large clusters of LAs across GB responsible for having significantly higher anomalies of ESDs than other areas of the country. These results therefore suggest that for the majority of ESD categories, variation of ESDs across GB is not high enough to disaggregate EDR policy to a LA-level. Although, heating, personal transport and public transport ESD categories are the exception to this. Results of the ESD modelling and spatial autocorrelation analysis suggest that regions of GB may benefit from bespoke approaches to EDR due to high levels of clustering of high and low areas of consumption, and large range of values generated across the ESD categories.

Analysing the effect of underlying socioeconomic factors of LAs on ESD footprints revealed that the unemployment rate, population density per km^2 and the median age of the population have a significant effect upon the ESDs of a LA's residents. However, other socioeconomic factors such as income and household size which would be expected to be correlated with ESDs exhibit a very weak relationship between the two variables. Unemployment rate, population density per km^2 and the median age of the population are therefore better determinants of LA-level ESD footprint size than income and household size. Although income does still exhibit the same relationship – albeit a weaker relationship – with ESD footprint size at a LA-level as it does for individual households.

The ESD footprints examined in Chapter 5 are therefore robust and will be used in Chapter 6. The ESD footprints of each LA will be used as a baseline for the EDR strategies which will be modelled upon household ESDs across all LAs to assess the EDR potential of four service-oriented strategies in GB.

6 Energy demand reduction strategy potentials at a Local Authority-level

Using the method described in Section 3.4.1, the data in Appendix 7, and the data assumptions in Appendix 6, Chapter 6 will build upon the modelled ESD footprints for each local authority (LA) throughout Great Britain (GB) in Chapter 5, by modelling the potential of the policy options in Ivanova *et al.*, (2020) to reduce GB's per capita energy service demands (ESDs). The policy options in Ivanova *et al.*, (2020) will be aggregated into different EDR strategies based upon the avoid-shift-improve framework (Appendix 5) (Creutzig *et al.*, 2018), and the effect each strategy upon all the ESDs analysed in Chapter 5 will be examined. Each ESD category is considered for each energy demand reduction (EDR) strategy to identify any potential rebound effect across household energy consumption if that strategy were to be implemented.

EDR strategies and policy mixes are complex, and their EDR potential and impact upon energy consumption across society can vary across each strategy (Kern *et al*., 2017). EDR strategies are therefore modelled using assumed policy penetration rates, rebound effects and are only applied to the population not undertaking the measures already to improve the accuracy of the results (Wood *et al.*, 2018).

The EDR strategies set out in Chapter 6 will be used to examine the effect of four universal EDR strategies upon households ESDs across LAs in GB. The four strategies are an energy efficiency strategy, a maintained service levels (MSL) strategy, a reduced service levels (RSL) strategy and a full consideration (FC) strategy. Modelling these four service-oriented strategies which utilise consumption-based EDR options will allow an assessment of the level of EDR achieved by an energy efficiency approach, alongside that of an approach which goes beyond technical energy and material efficiency, but does not compromise the level of energy service provided to households (MSL strategy). Additionally, the RSL strategy will assess the effect of reducing the levels of ESDs consumed by households, while the FC strategy will demonstrate the effect of a transformative EDR strategy upon GB, building upon the work of (Grubler *et al.*, 2018) and Barrett *et al.*, (2022).

Chapter 6 will be set out as follows. Section 6.1 will present and discuss the modelling results of the EDR strategies for GB at a national-level. Section 6.2 will then examine the variation in EDR potential across space at a LA-level and the implication of each strategy upon household energy consumption.

6.1 National-level EDR strategy potential

The EDR strategy potentials in this section are presented at a national-level using the median EDR potential of the measures from Ivanova *et al.*, (2020). The potential of each of the four strategies is set out in Table 6.1, Table 6.2 and Table 6.3, before Section 6.1.1, Section 6.1.2, Section 6.1.3 and Section 6.1.4 examine the energy efficiency, MSL, RSL and FC strategies respectively.

Table 6.1 National average EDR strategy potential by ESD category (tonnes of oil equivalent (toe)).

	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C	Consumer Goods	Services	Total
Energy Efficiency	0.07	0.01	0.27	-0.07	0.00	0.01	0.00	-0.01	-0.02	0.26
Maintained Service Levels	0.35	0.08	0.34	-0.11	0.00	0.08	0.00	-0.02	-0.03	0.70
Reduced Service Levels	0.06	0.03	0.17	-0.06	0.19	0.07	0.02	0.03	-0.01	0.49
Full Consideration	0.41	0.10	0.50	-0.18	0.19	0.11	0.03	0.01	-0.04	1.12

Table 6.2 National average ESD levels after each EDR strategy is applied to all LAs in GB (toe).

	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C	Consumer Goods	Services	Total
Energy Efficiency	0.46	0.39	0.35	0.15	0.26	0.19	0.20	0.08	0.13	2.21
Maintained Service Levels	0.18	0.32	0.27	0.20	0.26	0.13	0.19	0.09	0.14	1.77
Reduced Service Levels	0.47	0.37	0.44	0.15	0.07	0.14	0.17	0.05	0.13	1.99
Full Consideration	0.12	0.30	0.12	0.26	0.07	0.10	0.17	0.06	0.16	1.35

Table 6.3 National average percentage reduction of energy consumption for energy service demands by energy service.

	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C	Consumer Goods	Services	Total
Energy Efficiency	13.7%	1.5%	42.9%	-134.6%	-0.1%	6.1%	-1.6%	-10.7%	-13.9%	10.5%
Maintained Service Levels	66.6%	19.3%	55.8%	-226.0%	-0.1%	37.6%	2.3%	-20.9%	-22.8%	28.3%
Reduced Service Levels	11.1%	6.7%	27.7%	-124.1%	70.6%	32.2%	10.7%	34.8%	-9.8%	19.4%
Full Consideration	77.7%	24.0%	80.4%	-357.1%	70.6%	52.6%	12.9%	14.1%	-34.3%	45.0%

6.1.1 Energy efficiency strategy

As stated in the methodology, the energy efficiency EDR strategy focuses upon improving the technical and material efficiency of the energy consumed by households or the goods and conversion devices purchased to satisfy ESDs, as well as the efficiency of households to retain heat. Figure 6.1 shows the measures modelled in the energy efficiency strategy and the stage of the service-driven energy demand chain (SEDC) framework which they would affect if implemented by LAs. The absolute EDR potential of the energy efficiency strategy is presented in Table 6.1, the effect of the energy efficiency strategy upon all the ESDs modelled in Chapter 5 is presented in Table 6.2, while Table 6.3 shows the percentage reduction of the energy efficiency strategy upon each ESD.

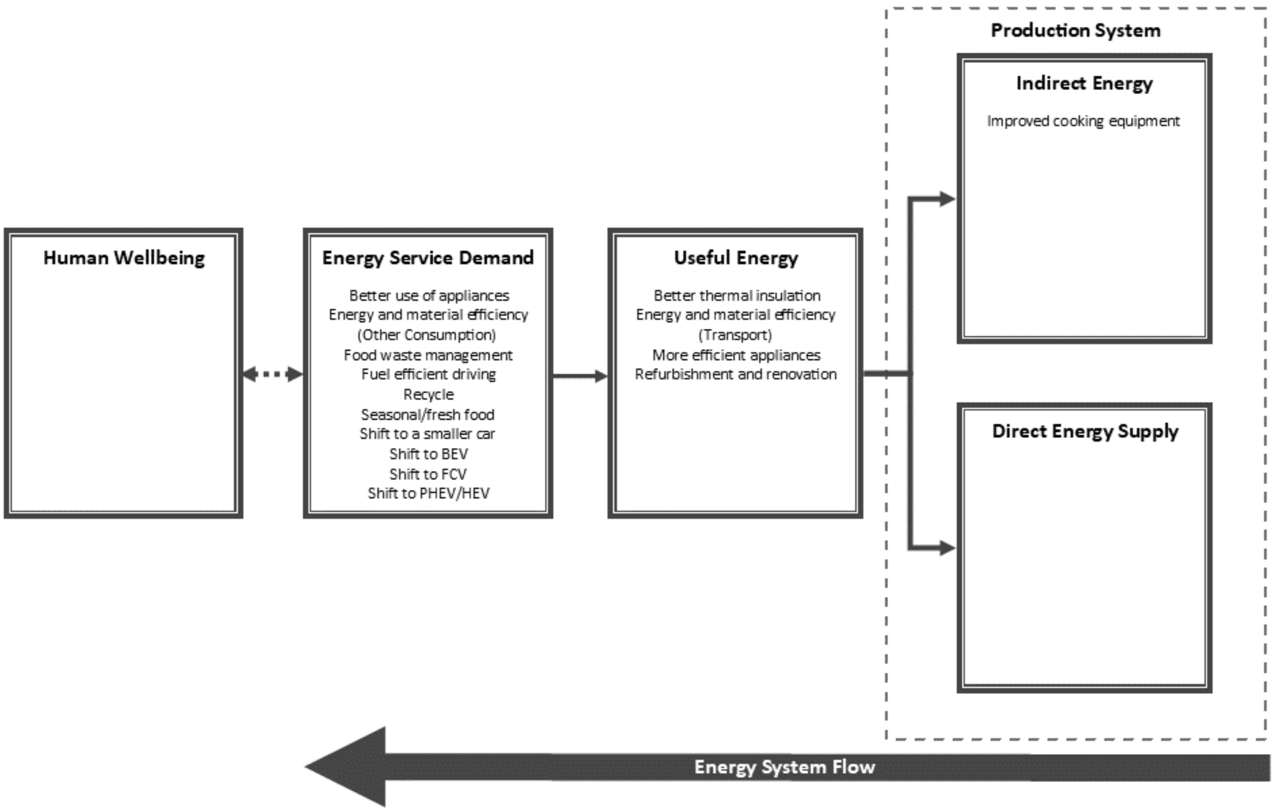

Figure 6.1 Measures modelled in the energy efficiency EDR strategy, and the stage of the SEDC framework which each measure would affect.

The national average of energy demanded to meet all household ESDs has been reduced from 2.47 tonnes of oil equivalent (toe) per capita to 2.21 toe per capita, a reduction of 10.5%. However, the reduction is not universal across all ESDs, with the reduction in the energy efficiency strategy being driven primarily by a reduction in personal transport ESDs (42.9%) and heating ESDs (13.7%) (Table 6.3). A reduction in the energy consumption associated with nutrition ESDs (6.1%) and other shelter ESDs (1.5%) also contributes to EDR in the energy efficiency strategy.

As stated previously in the thesis, academics have expressed concerns that focusing solely on energy efficiency may not deliver the level of EDR required for a net-zero society due to the rebound effect, and the limits of thermodynamic energy efficiency being reached (Brockway *et al.*, 2017; Shove, 2018). Table 6.3 show that in the energy efficiency strategy there is rebound – i.e. an increase in consumption – of five ESD categories (public transport, aerial transport, recreation & communication, consumer goods and services), thereby negating the impact of the reductions in previously mentioned ESD categories.

The rebound effect of the strategies presented in Section 6.1 and 6.2 was calculated using cross-price elasticity equations as set out in Section 3.4.1 (Equation 11). In this thesis, cross-price elasticities represent the amount of money that consumers would spend on another ESD, thereby increasing energy consumption, if they were to spend less on an ESD due to the implementation of an EDR measure or strategy (Chitnis and Sorrell, 2015). Therefore, under the energy efficiency strategy, consumers would spend money saved on heating, personal transport, other shelter and nutrition ESDs on public transport, aerial transport, recreation & communication, consumer goods and services instead, therefore reducing the impact of the EDR strategy.

However, despite the impact of the rebound effect, the modelled results of the energy efficiency strategy show that focusing solely upon energy efficiency would bring about a reduction in energy demand. However, the reduction does not reach the level of EDR required by scenario P1 in Masson-Delmotte *et al.*, (2018) to reach the emission levels necessary for a 1.5 °C future, meaning that greenhouse gas (GHG) removal would be relied upon to reach the UK's long-term climate goals.

Energy efficiency will therefore play an important role in reducing energy demand for ESDs across GB in the transition to a low energy demand society, however, the modelling results demonstrate that EDR strategies must go beyond energy efficiency to reduce energy demand to the levels estimated by Masson-Delmotte *et al.*, (2018) (Creutzig *et al.*, 2018; Grubler *et al.*, 2018; Barrett *et al.*, 2022). The following sections will examine strategies that go beyond energy efficiency.

6.1.2 Maintained service levels strategy

The MSL strategy requires households to undertake EDR measures that would alter their behaviour and technologies used to fulfil their ESDs, without reducing the level of ESDs demanded by households from the energy system. Table 6.1, Table 6.2 and Table 6.3 show the national-level potential of the MSL EDR strategy. Figure 6.2 shows the measures modelled in the MSL strategy and the stage of the SEDC framework which they would be implemented at.

If the MSL strategy were to be implemented by the UK government, the national average total ESDs would decrease from 2.47 toe per capita to 1.77 toe per capita (Table 6.2), a reduction of 28.3%

(Table 6.3). As with the energy efficiency strategy, there is a large reduction in the level of personal transport ESDs across GB under the MSL strategy, with a national average reduction of 55.8%, however, the reduction in heating ESDs is higher than personal transport ESDs under the MSL strategy than the energy efficiency strategy (66.6%). As with the energy efficiency strategy, a reduction in the level of energy consumption associated with nutrition ESDs and other shelter ESDs (37.6% and 19.3% respectively) is also modelled under the MSL strategy, as is a reduction in recreation & communication ESDs (2.3%). However, as with the energy efficiency strategy, the rebound effect is also evident in the MSL strategy, with public transport, aerial transport, consumer goods and services ESDs all expected to rise under the MSL strategy (Table 6.3).

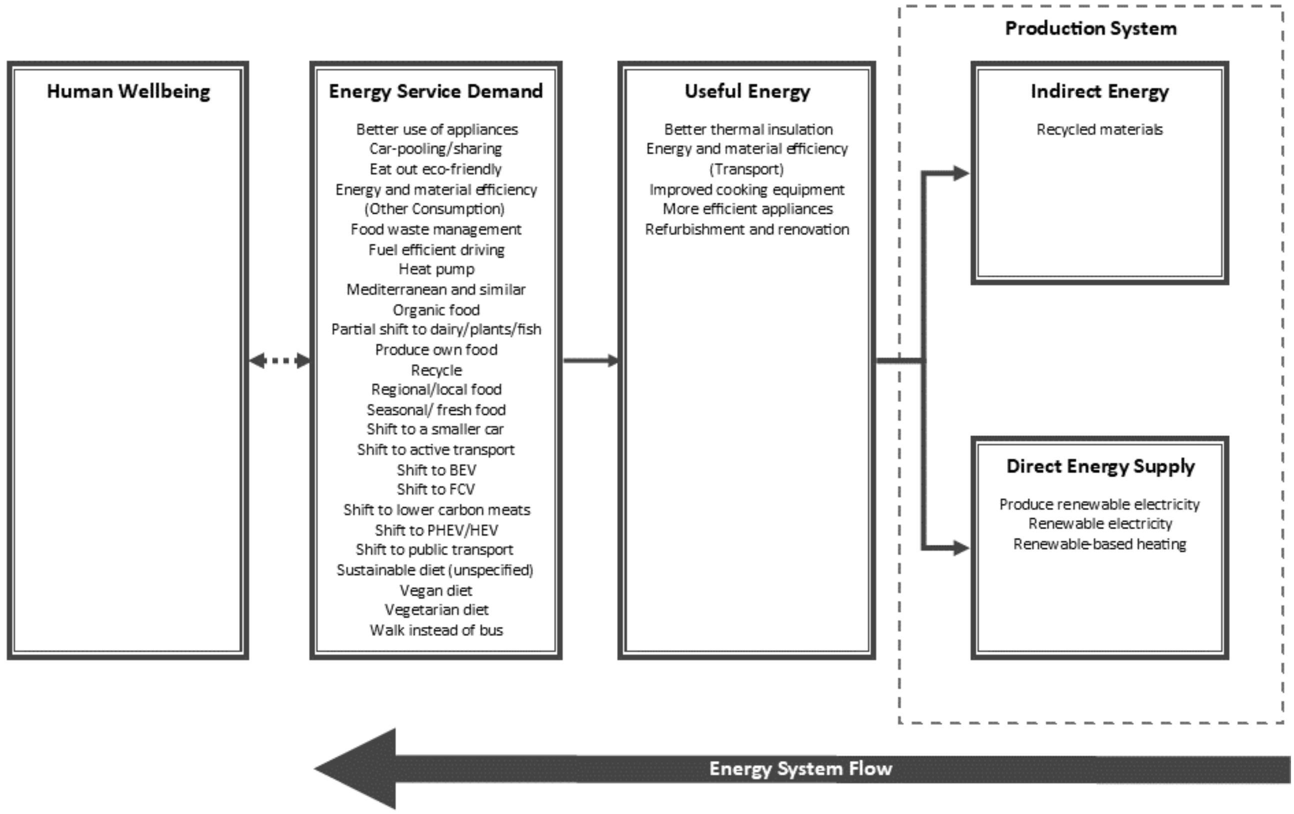

Figure 6.2 Measures modelled in the MSL EDR strategy, and the stage of the SEDC framework which each measure would affect.

The MSL strategy demonstrates that significant reductions can be made to the national-level of energy consumption for ESDs across GB whilst maintaining energy service levels to households. Modelling the MSL strategy demonstrates that the government must go beyond energy efficiency measures when considering EDR in GB. However, as with the energy efficiency strategy, the MSL strategy does not reduce energy demand for households to a level compatible with the level of EDR expected for a 1.5°C future (Masson-Delmotte *et al.*, 2018). Therefore, reducing energy service levels must also be undertaken for a climate safe future (Creutzig *et al.*, 2018; Grubler *et al.*, 2018; Barrett *et al.*, 2022).

6.1.3 Reduced service level strategy

The RSL strategy requires households to undertake EDR measures that would reduce the level of energy services demanded by households from the energy system in order to reduce their energy demand. Table 6.1, Table 6.2 and Table 6.3 show the national-level EDR potential of the RSL EDR strategy, while Figure 6.3 shows the measures modelled in the RSL strategy and the stage of the SEDC framework which they would affect.

The RSL strategy reduces total ESDs to 1.99 toe per capita in GB, a reduction of 19.4%. Therefore as the reduction is less than the MSL strategy, it is unlikely that reducing service levels alone will deliver the modelled EDR for a 1.5°C future in Masson-Delmotte *et al.*, (2018). However the RSL strategy is more effective than the energy efficiency strategy in Section 6.1.1 and will contribute towards the FC strategy in Section 6.1.4.

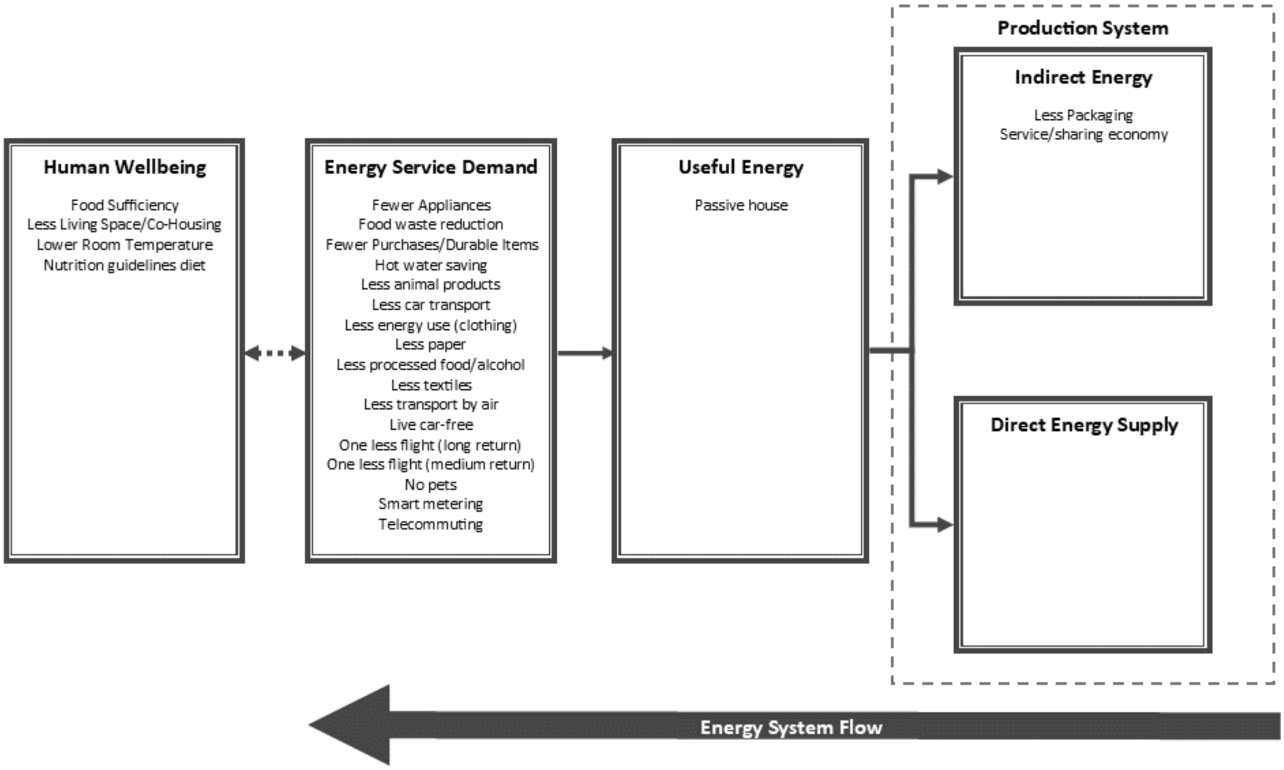

Figure 6.3 Measures modelled in the RSL EDR strategy, and the stage of the SEDC framework which each measure would affect.

Considering the modelled reduction of each ESD under the RSL strategy in Table 6.3, the driver of the reduction in the strategy is from the reduction in aerial transport ESDs (Table 6.3). Table 6.3 shows that the 70.6% reduction in aerial transport ESD category is the largest reduction under this strategy. However, while the reduction in aerial transport may be the largest reduction in a single ESD category, the RSL strategy has reductions across more ESD categories than under the energy efficiency and MSL strategies (Table 6.3).

Under the RSL strategy, there are reductions for heating, other shelter, personal transport, nutrition, recreation & communication and consumer goods ESDs, with rebounds only occurring in the public transport and services ESD categories (Table 6.3). While the reduction in heating, other shelter and personal transport ESDs is lower under the RSL strategy, the reduction in nutrition ESDs is comparable to the MSL strategy, while recreation & communication and consumer goods ESDs – ESDs which are supplied through indirect, embodied energy – have greater levels of reduction than in the energy efficiency or MSL strategies (Table 6.3).

Under the RSL strategy, EDR is modelled across a greater number of categories due to the wide variety of measures considered under this strategy (Figure 6.3) (Ivanova *et al.*, 2020). Going beyond an energy efficiency strategy is therefore important to reduce the embodied energy associated with the lifestyle of households in GB. However, to meet the UK's long-term net-zero climate goal for a 1.5°C future, the RSL strategy cannot meet the level of EDR required for a 1.5°C future alone, and must therefore be combined with the MSL strategy into a FC strategy (Masson-Delmotte *et al.*, 2018).

6.1.4 Full consideration

The final EDR strategy to be examined at a national-level is the FC strategy. The FC EDR strategy applies all the policy options set out in Ivanova *et al.*, (2020), with the exception of Green Roofs, Low Carbon Construction and Bio-Plastics/Chemicals, to the ESDs of each LA in GB. As stated in Section 3.4, the FC EDR strategy is expected to be the most effective EDR strategy considered in Chapter 6 due to the number of consumption-based policy options included in the strategy being greater than the number included in the energy efficiency, MSL and RSL strategies. The level of reduction under the FC strategy for each ESD can be seen in Table 6.1, and the strategy's effect upon GB's national average per capita ESDs in Table 6.2, while Table 6.3 shows the percentage reduction the FC strategy has upon each ESD. Figure 6.4 shows the measures modelled in the FC strategy and the stage of the SEDC framework which they would affect.

Table 6.1 shows that total ESDs are reduced by an average of 1.12 toe per capita across GB, with the national average total ESD levels for GB being reduced to 1.35 toe per capita (Table 6.2), which is a 45% reduction in total ESDs across GB (Table 6.3). The level of reduction modelled under the FC strategy is greater than the level modelled by Masson-Delmotte *et al.*, (2018) for a 1.5°C future, therefore, meaning that for households in GB to reduce their energy consumption for ESDs to a level which can achieve the net-zero target, all the measures in Ivanova *et al.*, (2020) must be considered by the government.

The level of reduction in energy demand under the FC EDR strategy varies for different ESDs, with heating, personal transport, aerial transport and nutrition ESDs all being reduced by a value greater than the national average for total ESDs (Table 6.3). The higher levels of reduction for these ESD categories is due to the measures in Ivanova *et al.*, (2020) being predominantly centred around buildings, transport and nutrition.

The results show that personal transport ESDs have the greatest modelled reduction (80.4%), with heating ESDs also experiencing a 77.7% reduction in energy consumption (Table 6.3). Heating and personal transport ESDs were the two highest consumption ESD categories in Chapter 5, therefore large reductions under the FC strategy are beneficial for households in GB to reduce their energy demand in line with the national net-zero climate target.

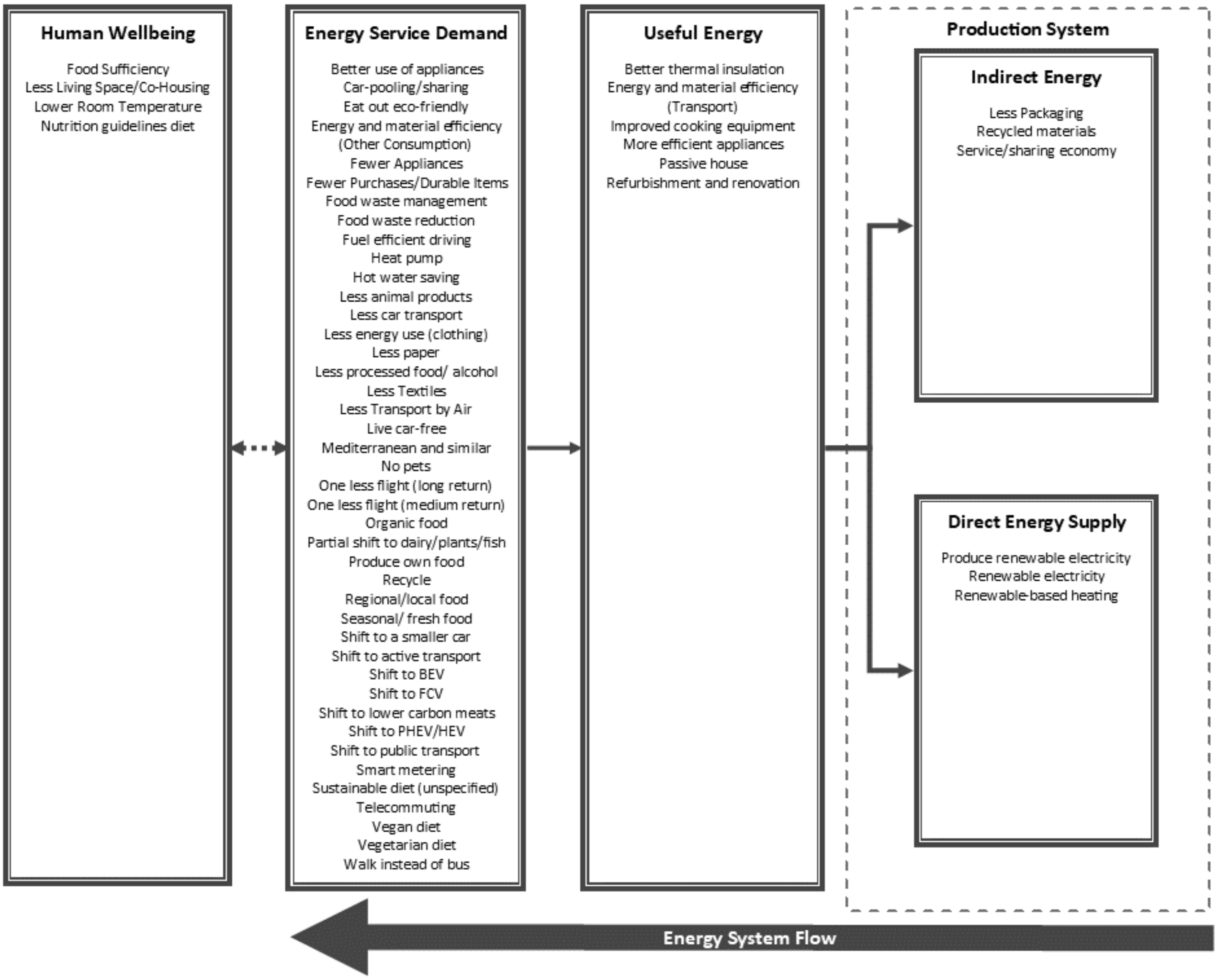

Figure 6.4 Measures modelled in the FC EDR strategy, and the stage of the SEDC framework which each measure would affect.

However, as with the RSL strategy, there is an overall rebound effect for the public transport and services ESD categories under the FC strategy. However, the increase in public transport ESDs is not unexpected due to a reduction in personal transport ESDs, being, in part, due to a shift from private to public transport (Appendix 5). While for services ESDs, the shift to a service/sharing economy leads to households spending less money on ESD categories, such as consumer goods, and more on services ESDs (Appendix 5).

The level of EDR achieved in the FC strategy will require significant investment, upskilling, infrastructural projects and technology improvement across the entire economy in GB, and will address all aspect of household's lives and practices (Simpson *et al*., 2020). The costs and policies required to achieve this level of EDR will not be considered in this thesis, however the results are broadly comparable to previous studies on radical EDR, such as Grubler *et al.*, (2018) and Barrett *et al.*, (2022), and will be discussed in more detail in Chapter 8.

6.1.5 Summary

Examining the energy efficiency, MSL and RSL EDR strategies shows that the three different strategies set out in Section 6.1 would all contribute to EDR in GB's efforts to transition to a net-zero society, however a transformative FC strategy is necessary for households in GB to reduce their energy consumption in line with the levels necessary for a 1.5°C future (Masson-Delmotte *et al.*, 2018). Across the strategies in Section 6.1, energy demand is reduced to differing extents. Each strategy is made up of different EDR options with differing levels of effectiveness. The energy efficiency strategy, which assumes the current, preferred framing of EDR, is the least ambitious and least effective strategy considered in Chapter 6. Focusing purely on technical improvements in efficiency would reduce energy demand in GB, but not at the levels required for a 1.5°C future (Masson-Delmotte *et al.*, 2018).

The MSL, RSL and FC strategies demonstrate the need to go beyond energy efficiency, and the potential reductions in energy demand that can be made with and without reducing energy service levels delivered to households (Table 6.3). However, as the energy efficiency, MSL and RSL strategies alone cannot deliver the level of EDR, estimated by Masson-Delmotte *et al.*, (2018), for a 1.5°C future without GHG removal, therefore a transformative FC strategy for EDR needs to be developed for households in GB (Grubler *et al.*, 2018; Barrett *et al.*, 2022).

The results in Section 6.1 demonstrate that the level of EDR required for a 1.5°C future in GB can be achieved. EDR strategies must go beyond energy efficiency to achieve this level of reduction by completely transforming the behaviours and technologies presently dominating household practices (Grubler *et al.*, 2018; Masson-Delmotte *et al.*, 2018; Barrett *et al.*, 2022).

However, while Section 6.1 reported national average levels of reduction in GB, the current level of ESDs vary across space, meaning that EDR potential will likely also vary across space in GB.

Section 6.2 will examine the modelled results of EDR for each LA in GB, and consider whether a disaggregated, LA-specific approach may be beneficial for EDR in GB.

6.2 EDR strategy potential across space in GB

Section 6.1 presented the national average EDR for each ESD category for each of the modelled EDR strategies. However, the model used to generate the national average levels of reduction was also used to model the level of EDR achieved by each EDR strategy for each LA in GB. The level of EDR in each strategy is not universal across GB. The model generated different EDR statistics for different LAs across GB, with some areas experiencing above national average levels of EDR, and others, below average levels of EDR. As with Section 6.1, Section 6.2 will examine each EDR strategy, however rather than considering the national average reduction, Section 6.2 will consider modelled EDR across space in GB. Section 6.2.1, Section 6.2.2, Section 6.2.3 and Section 6.2.4 examine the reduction of individual ESD categories under the energy efficiency, MSL, RSL and FC EDR strategies respectively, while Section 6.2.5 will consider the reduction in total ESDs for each strategy.

6.2.1 Energy efficiency strategy

Figure 6.5 demonstrates the variation in the modelled level of EDR potential for the energy efficiency strategy across all LAs in GB. Figure 6.5 shows that EDR in the personal transport ESD category is the largest contributor to EDR under this strategy across all LAs, with the EDR potential ranging from 31.1% in Southwark to 49.4% in Thurrock – a range of 18.3%. The level of reduction modelled for personal transport ESDs leads to a significant change in the level of energy consumption associated with personal transport ESDs across GB (Figure 6.6(b)). A spatial autocorrelation analysis indicates low levels of clustering for LAs with similar percentage reduction of energy consumption for personal transport ESDs across GB.

Similarly, measures aiming to reduce energy consumption associated with heating and nutrition ESDs, do not lead to rebound in these categories, under the efficiency strategy (Figure 6.5). The reduction of energy required to fulfil household heating ESDs has a smaller range of variation than personal transport ESDs, with a range of 7.5% from an 8.7% reduction in Newham to a 16.2% reduction in Cheshire East. The range of reduction in nutrition ESDs has a yet smaller range of reduction across GB, varying from 1.8% in Tower Hamlets to 10.1% for the City of London LA. Spatial autocorrelation results for LAs with similar levels of EDR under the efficiency strategy generates Moran’s I values of 0.11 for heating ESDs and 0.19 for nutrition ESDs.

However, considering the level of EDR for the other ESD categories modelled under the energy efficiency strategy, the rebound effect leads to an increase in other shelter, public transport, aerial transport, recreation & communication, consumer goods and services ESDs across some areas of

GB (Figure 6.5). An increase in energy consumption is present in 27.2% of LAs across GB for other shelter ESDs, 72.5% of LAs for aerial transport ESDs and 100% of LAs for public transport ESDs, recreation & communication ESDs, consumer goods ESDs and services ESDs (Figure 6.5).

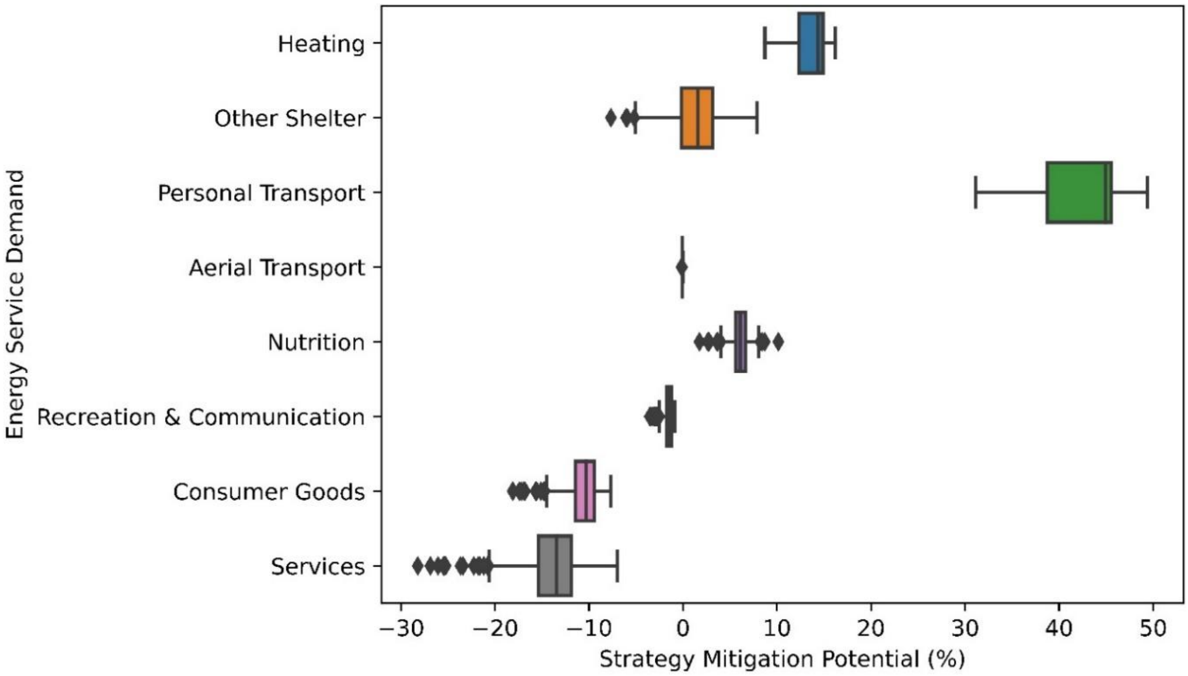

Figure 6.5 The EDR potential range for each LA under the energy efficiency strategy. Public transport ESDs have been omitted from this graph due to the large rebound effect modelled for public transport ESDs under the energy efficiency strategy. The effect of each EDR strategy upon public transport ESDs can be seen in Appendix 9.

Despite increases in six of the nine modelled ESDs under the efficiency strategy, these services make-up a smaller proportion of each LA's energy footprint than heating and personal transport ESDs (Chapter 5). Therefore, this means that the rebound effect in these ESD categories reduces the impact of the energy efficiency strategy, but, generally, does not lead to an overall increase in total energy consumption for ESDs, with the exception of two LAs – Southwark and Tower Hamlets in London. The large range of values generated for heating, other shelter and personal transport ESDs under the energy efficiency strategy suggests that a disaggregated approach to EDR may improve the effectiveness of EDR under an energy efficiency strategy. However, the low range of values for other ESD categories suggests that a national-level approach that the rebound effect would be similar across much of GB under the energy efficiency strategy. The effect of the energy efficiency strategy upon total ESDs, and the implications of these results for a disaggregated approach to EDR in GB will be discussed in more detail in Section 6.2.5.

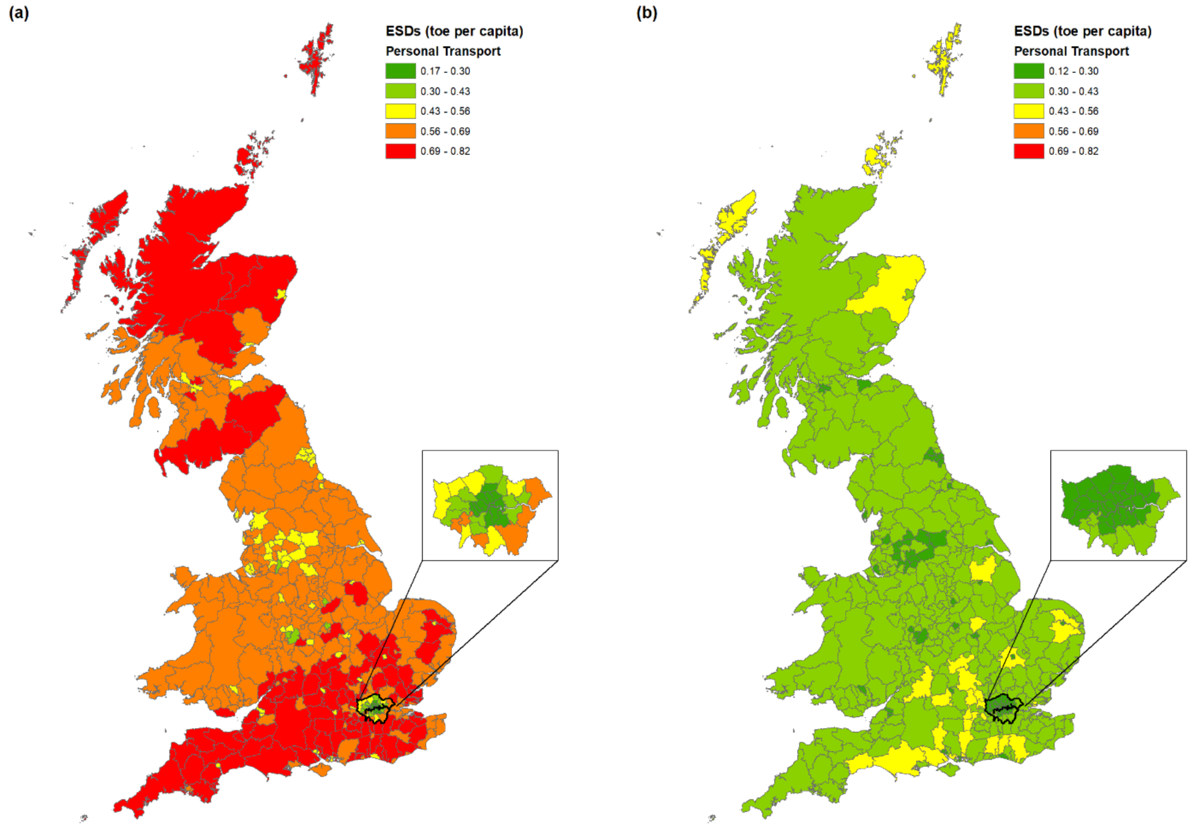

Figure 6.6 (a) Personal transport ESDs per capita by LA throughout GB. (b) Personal transport ESDs per capita LA throughout GB under the energy efficiency EDR strategy. The scale on each map is constant.

6.2.2 Maintained service levels strategy

Figure 6.7 demonstrates the variation in the modelled level of EDR potential for the MSL strategy across all LAs in GB. Unlike the energy efficiency strategy in Figure 6.5, Figure 6.7 shows that reduction in one ESD category is not greater across all LAs than reduction in another ESD category, as was the case with personal transport ESDs in the energy efficiency strategy. Under the MSL strategy, the range of EDR potentials by LA for the ESD category modelled to experience the greatest reduction in energy consumption under the MSL strategy (heating ESDs) over laps with the range for personal transport ESDs (Figure 6.7). Similarly, the range of values modelled for nutrition and other shelter ESDs overlap with the range of personal transport ESDs. The overlapping of EDR potential ranges for different ESDs suggests that EDR is not driven by a reduction in energy consumption for a single ESD category, as is the case for the energy efficiency strategy (Section 6.2.1).

As with the energy efficiency, all LAs experience increases in energy consumption associated with public transport, consumer goods and services ESDs under the MSL strategy (Figure 6.7). However, unlike the energy efficiency strategy, recreation & communication ESD are modelled to reduce across 95.5% of LAs under the MSL strategy (Figure 6.7).

The range of values for heating ESDs varies from 53.5% in Newham to 75.5% in South Somerset – a range of 22% across all LAs in GB – while the variation for personal transport ESDs ranges from 39% in Southwark to 65.1% in Thurrock – a range of 26.1%. Therefore, despite a higher level of reduction under the MSL strategy, the potential reduction in energy consumption for heating ESDs varies less than personal transport ESDs across GB.

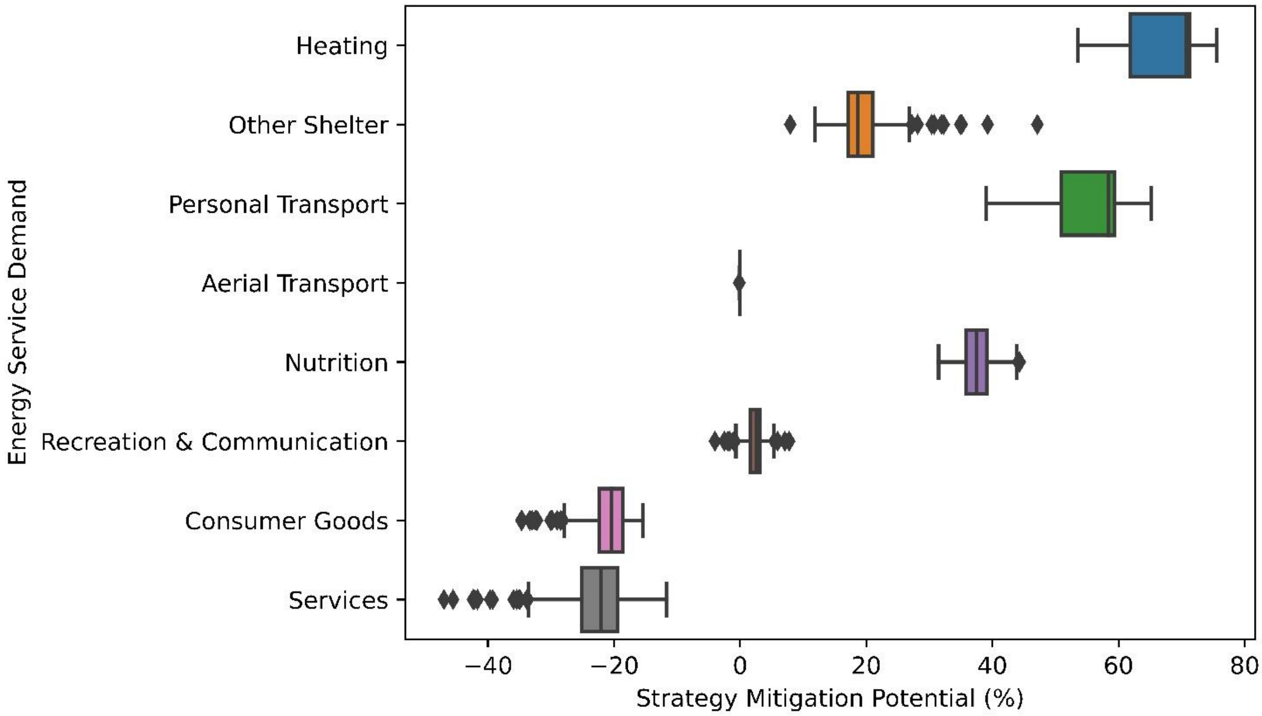

Figure 6.7 The EDR potential range for each LA under the MSL strategy. Public transport ESDs have been omitted from this graph due to the large rebound effect modelled for public transport ESDs under the MSL strategy. The effect of each EDR strategy upon public transport ESDs can be seen in Appendix 9.

A spatial autocorrelation analysis of the reduction results under the MSL strategy does not suggest that LAs in close proximity to each other have similar levels of reduction for the ESD categories which have been modelled to reduce energy consumption across all LAs under the MSL strategy. Very low levels of clustering are evident for heating ESDs (0.08) thus implying that the high and low levels of EDR for heating ESDs are almost randomly dispersed (a Moran's I value of 0 indicates random dispersion). Similarly, the level of spatial autocorrelation for other shelter ESDs (0.26), personal transport ESDs (0.22) and nutrition (0.38) ESDs also suggests low levels of clustering. Conversely, the spatial autocorrelation values for the ESD categories which only increase across all LAs - public transport ESDs (0.65), consumer goods ESDs and services ESDs (0.62) - suggest high levels of clustering, therefore implying that the rebound exhibited across these ESDs is larger in certain areas of GB.

The spatial autocorrelation values generated for the modelled MSL strategy results suggest that clusters of similar areas of reduction under the MSL strategy do not exist in GB. As with the energy efficiency strategy, the range of values and lack of clustering generated across heating and personal transport ESDs under the MSL strategy suggests that a disaggregated approach to EDR may be beneficial as areas of high and low EDR are almost randomly dispersed across GB. Additionally, the larger range of rebound for services ESDs also suggests that LA-specific measures to reduce the rebound effect for this ESD category may be required. However, the smaller range of nutrition values suggests that nutrition-related measures used in this strategy could be implemented nationally with a similar effect. Having modelled the effects of an EDR strategy which maintains service levels to households, the RSL strategy will be explored in Section 6.2.3.

6.2.3 Reduced service levels strategy

Figure 6.8 demonstrates the variation in the modelled level of EDR potential for the RSL strategy across all LAs in GB. Unlike the energy efficiency and MSL strategy in Figure 6.5 and Figure 6.7, Figure 6.8 shows that EDR under the RSL strategy reduces energy consumption across a wider number of ESD categories, with the exception of services ESDs[20].

As shown in Table 6.3, Figure 6.8 shows that demand reduction for aerial transport ESDs drives EDR under the RSL strategy, however the range is significant for this ESD category, with the EDR potential for aerial transport ESDs varying between 14.6% and 100%, depending upon the LA the strategy is modelled for – a range of 85.4%. The range in EDR for aerial transport ESDs can be attributed to the proportion of households in each LA taking flights. LAs where the majority of households take a single return flight each year will have a larger reduction in aerial transport ESDs, by taking one fewer flight per year than LAs where fewer households take greater numbers of flights.

The level of reduction in the two largest ESD footprints – heating and personal transport ESDs – is less than in the MSL strategy for both ESD categories, however the range is also much smaller. The smaller range, particularly for heating (4.2%), suggests that measures, such as lower room temperature, would have a similar effect across much of GB. The reduction in nutrition ESDs under the RSL strategy is similar for the RSL and MSL strategies, thus implying that shifting to dietary habits offers a similar level of EDR as reducing the level of calorie intake by households in GB.

[20] Public transport ESDs also increase under the RSL strategy, however they are not included in Figure 6.8.

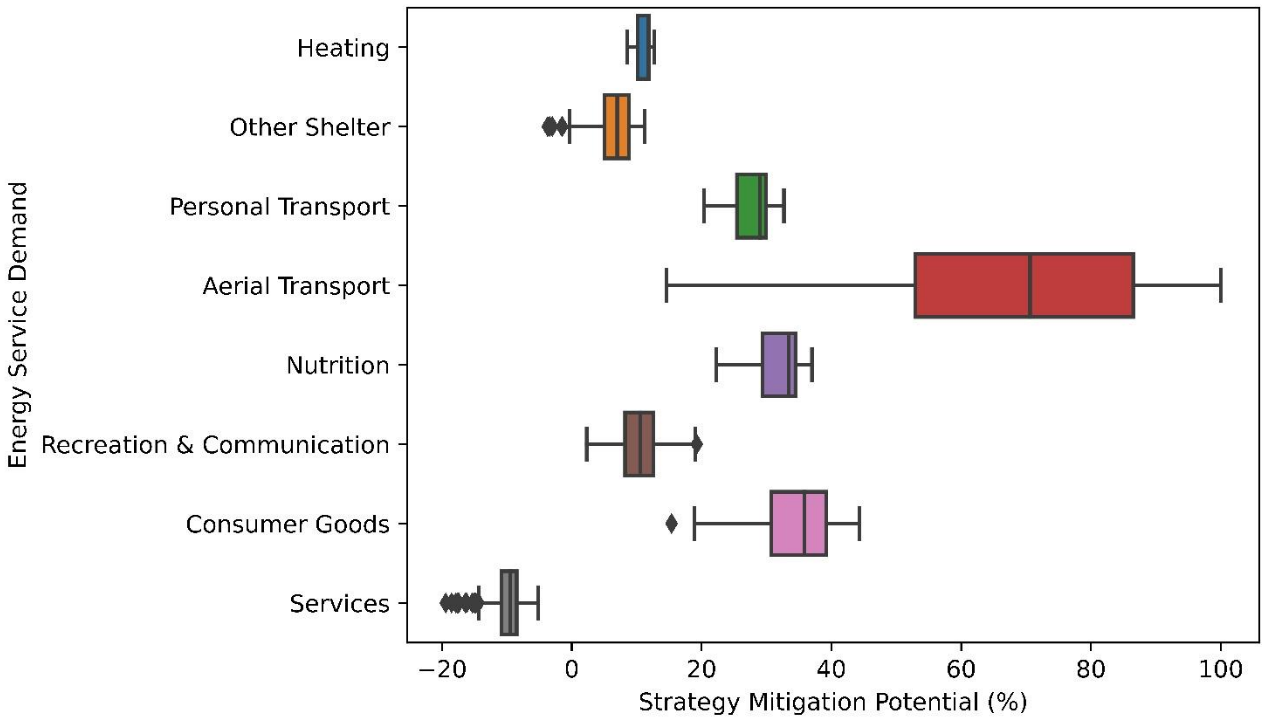

Figure 6.8 The EDR potential range for each LA under the RSL strategy. Public transport ESDs have been omitted from this graph due to the large rebound effect modelled for public transport ESDs under the RSL strategy. The effect of each EDR strategy upon public transport ESDs can be seen in Appendix 9.

Unlike the energy efficiency and MSL strategies, the modelled results for consumer goods ESDs and recreation & communication ESDs show that no LAs would experience an increase in energy consumption for these ESDs under a RSL strategy. The RSL strategy therefore appears more balanced than the energy efficiency and MSL strategies (Figure 6.5; Figure 6.7 and Figure 6.8) despite the RSL strategy being driven by reductions in aerial transport ESDs. The efficiency and MSL strategies relied upon EDR for heating and personal transport ESDs to negate the rebound effect in services, personal transport, consumer goods and recreation & communication ESD categories, whereas minimal rebound occurs under the RSL strategy (Figure 6.8).

As with the MSL strategy, a spatial autocorrelation analysis of the modelled reductions in the RSL strategy suggest that heating ESDs have a very low level of spatial autocorrelation (0.07) and the areas of higher and lower EDR for heating ESDs are randomly dispersed. However, the Moran's I value for aerial transport ESDs (0.60), and recreation & communication ESDs (0.59) indicate moderate-to-high levels of clustering for the level of reduction modelled across GB for each LA. This implies that the LAs of high and low reduction for aerial transport and recreation & communication ESDs are more geographically clustered than LA reductions of other ESD categories. This clustering, combined with the large range of reduction for aerial transport ESDs suggests a more targeted approach towards LAs where households can reduce flights by more than one per year should be considered.

The modelling results generated for the RSL strategy results suggest an EDR strategy which reduces service levels of households is more effective than an energy efficiency strategy across all ESD categories, with the exception of heating and personal transport ESDs. For aerial transport ESDs, whereby a large range of EDR levels is modelled across LAs in GB, a disaggregated approach to EDR may be necessary in the future. However, for personal transport and heating ESDs, the range is low suggesting that ‘avoid’ measures have a similar effect for these ESD categories across much of GB.

Total reduction of ESD levels under the RSL strategy will be discussed in more detail in Section 6.2.5. However, before total ESDs are considered, the results of the FC strategy will be set out in Section 6.2.4.

6.2.4 Full consideration strategy

Figure 6.9 demonstrates the variation in the modelled level of EDR potential for the FC strategy across all LAs in GB. The FC strategy is the most comprehensive strategy modelled in Chapter 6, and shows reductions across all LAs for heating, other shelter, personal transport, aerial transport, nutrition and recreation & communication ESDs (Figure 6.9). Despite the national average and median EDR for consumer goods leading to a reduction in energy consumption in this ESD category across much of GB, households within 4.5% of LAs increase consumption for consumer goods through the rebound effect (Figure 6.9).

Unlike the consumer goods ESD category, no LAs have been modelled to experience a reduction in public transport (Appendix 9) and services ESDs (Figure 6.9). The increase in public transport and services ESDs is expected due to a reduction in car transport, and a shift of some car users to public transport, and the increase in services ESDs is driven by a reduction in households purchasing goods for private use through the rise in the number of households adopting a service/sharing economy approach to product purchasing (Ivanova *et al.*, 2020). Additionally, more disposable income from a reduction in heating bills through energy efficiency and fewer purchases may have also contributed to the modelled increases.

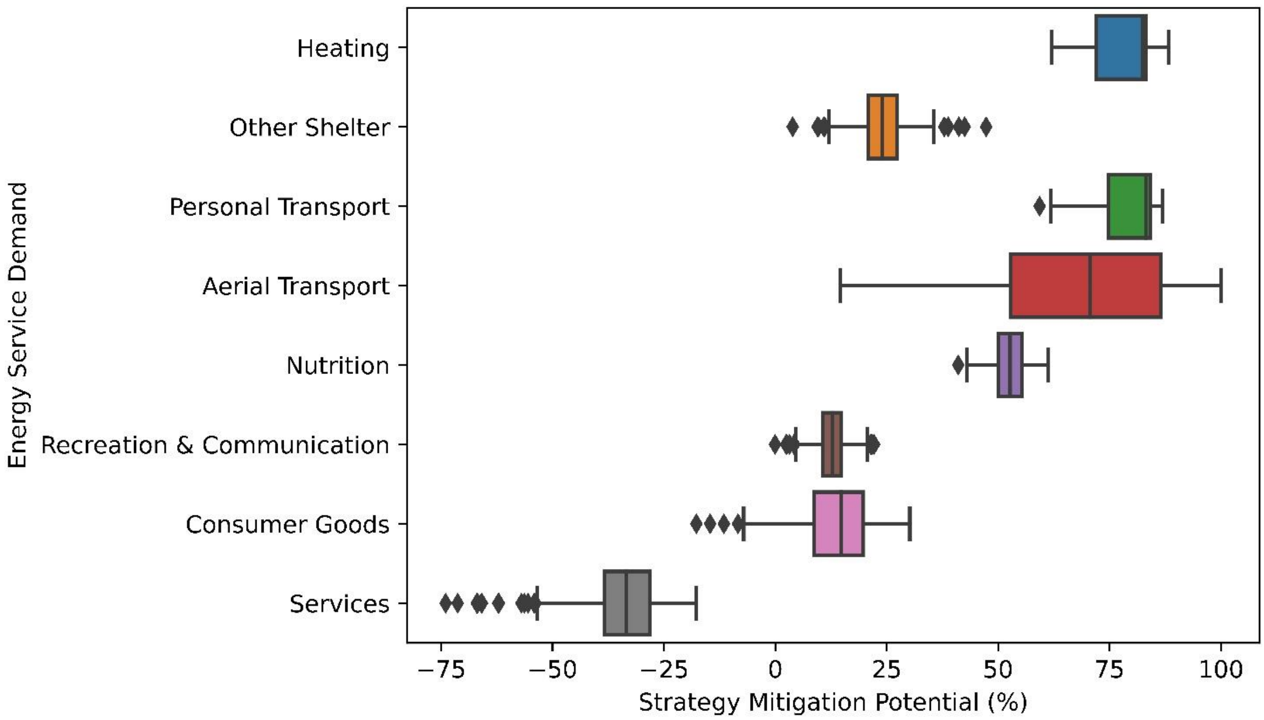

Figure 6.9 The EDR potential range for each LA under the FC strategy. Public transport ESDs have been omitted from this graph due to the large rebound effect modelled for public transport ESDs under the FC strategy. The effect of each EDR strategy upon public transport ESDs can be seen in Appendix 9.

At a national-level, personal transport ESDs and heating contributed the greatest level of reductions under the FC strategy, with aerial transport ESDs and nutrition ESDs decreasing by an average greater than 50% (Table 6.3). As Figure 6.9 shows, the ranges for each of these ESDs overlap, with some LAs in GB experiencing a greater reduction in aerial transport and nutrition ESDs than other LAs experience for heating and personal transport ESDs, despite these categories having the greatest reduction at a national-level in GB.

As with the previous EDR strategies, the Moran's I value generated using a spatial autocorrelation analysis suggests that the modelled EDR for heating ESDs (0.08) is almost randomly dispersed, meaning that there are no clusters of similar EDR for heating ESDs. Similarly, the Moran's I values for other shelter ESDs (0.25), personal transport ESDs (0.22), nutrition ESDs (0.30) and consumer goods ESDs (0.33) indicate that there would be low levels of clustering of EDR potentials for different LAs in different areas of GB.

However, the spatial autocorrelation analysis of the increase in modelled public transport ESDs for GB under the FC strategy suggests that there are high levels of clustering when considering the rebound in this ESD category (Appendix 9). The Moran's I value for public transport ESDs is 0.66. The high levels of clustering implies that the model suggests that there will be similar levels of public transport increase in different areas of GB. Similarity across different areas of GB implies that a coordinated, rather than a disaggregated, LA-specific approach fto increasing energy consumption of public transport ESDs may be beneficial.

6.2.5 All EDR strategies: Total ESDs

The national average reduction of each of the four strategies modelled in Chapter 6 is given in Table 6.3, however, in addition to identifying the national level EDR potential of each EDR strategy, the EDR potential of the consumption-based policy options from Ivanova *et al.*, (2020) was also modelled at a LA-level to identify the variation in EDR potential across space in GB. Figure 6.10 shows the variation of total reduction in energy demand for all ESDs across GB for each of the four strategies modelled in this chapter.

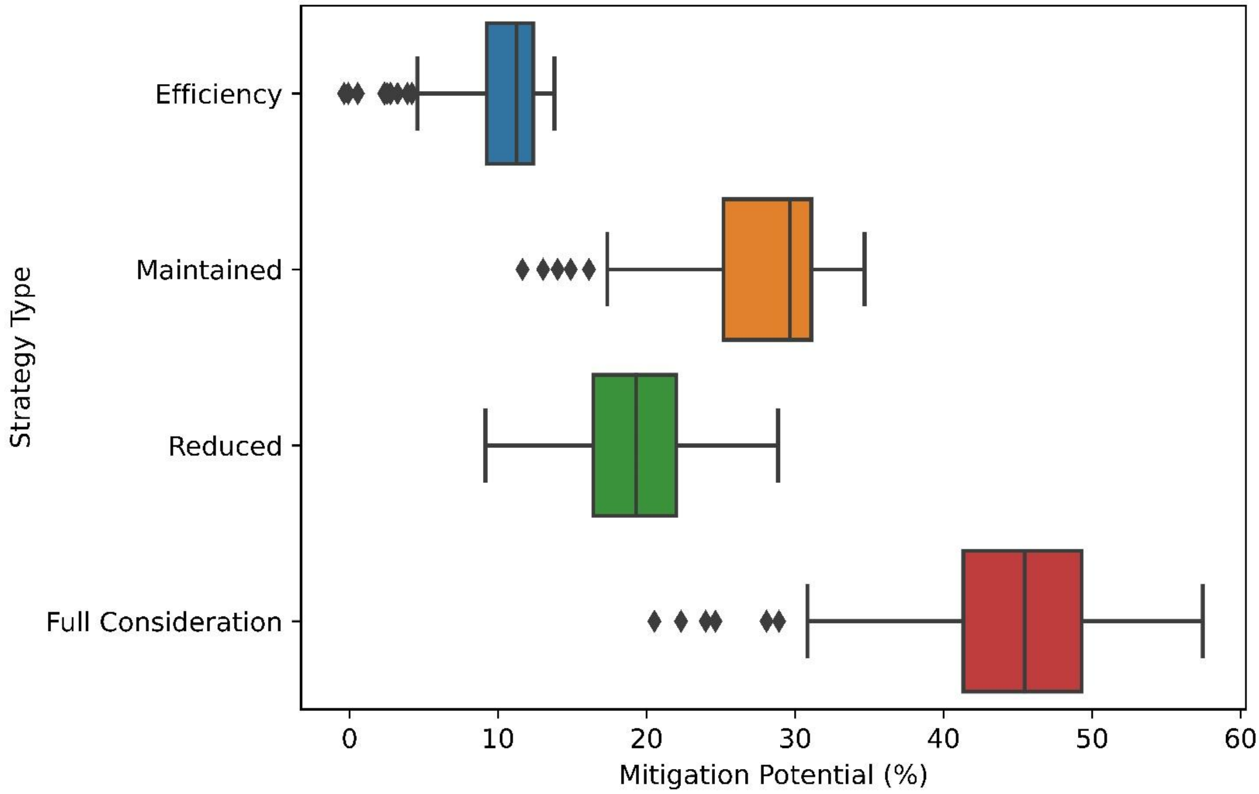

Figure 6.10 Variation in the total LA-level EDR potential for each EDR strategy in GB.

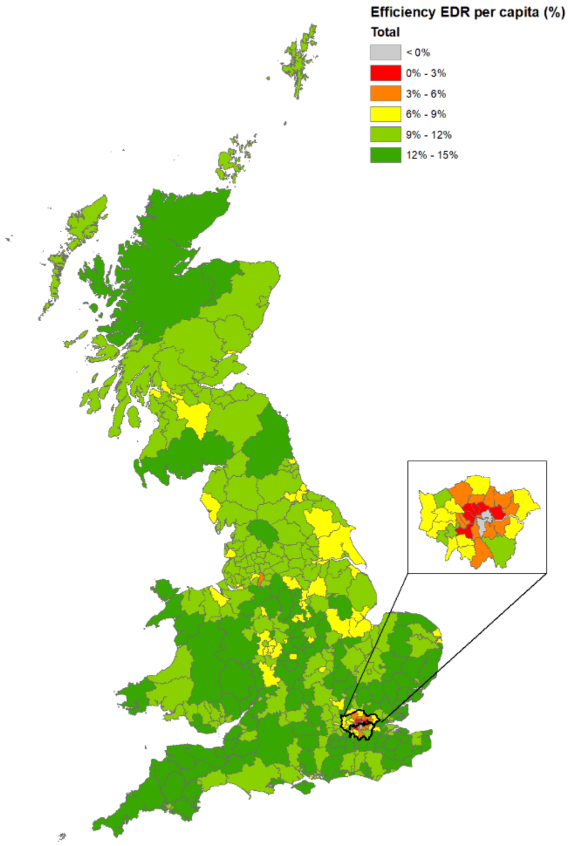

Figure 6.11 Variation in total EDR for all ESDs under the energy efficiency strategy.

Under the energy efficiency strategy, the lowest level of energy associated with total ESDs per capita in GB is 1.50 toe per capita in Tower Hamlets, while the highest is 2.95 toe per capita in Bromley in London, which previously had the highest level of total ESDs also (Section 5.2). The percentage reduction also varies with the lowest percentage reduction being an increase of 0.4% in Southwark, while in Swale, there is a reduction of 13.8% (Figure 6.11).

The LAs with the highest modelled reduction in total ESDs under the energy efficiency strategy overlap with the lowest reductions under both the MSL and RSL strategy (Figure 6.10). Total EDR under the MSL strategy varies between 11.6% for Southwark in London and 34.7% for Powys in Wales (Figure 6.12), while the variation under the RSL strategy is 9.1% for Newham and 28.9% for Wokingham (Figure 6.13). The FC strategy is the most comprehensive strategy modelled in Chapter 6 and varies between 20.5% in Southwark in London to 57.5% in South Oxfordshire (Figure 6.14).

The range of EDR from each strategy (Figure 6.10) shows that there is overlap between LAs experiencing the lowest level of reduction under the FC strategy and those modelled to have greater EDR under the MSL and RSL strategies. Under all four strategies London LAs have the lowest level of reduction (Figure 6.11; Figure 6.12; Figure 6.13; Figure 6.14).

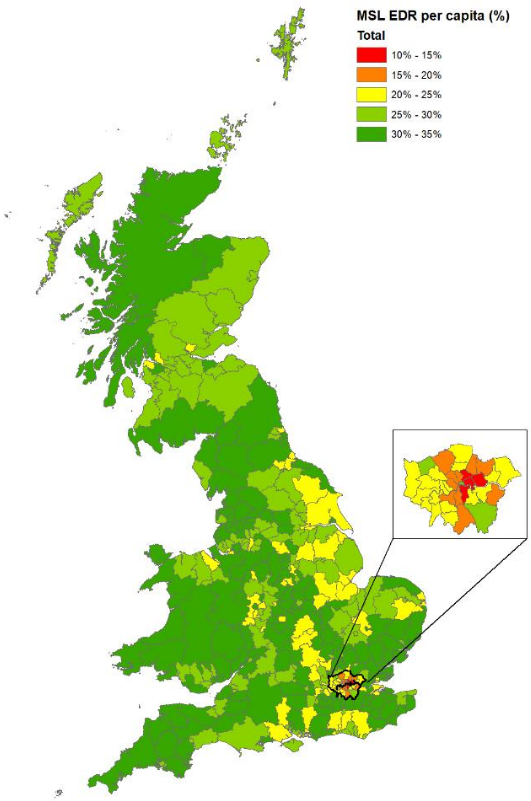

Figure 6.12 Variation in total EDR for all ESDs under the MSL strategy.

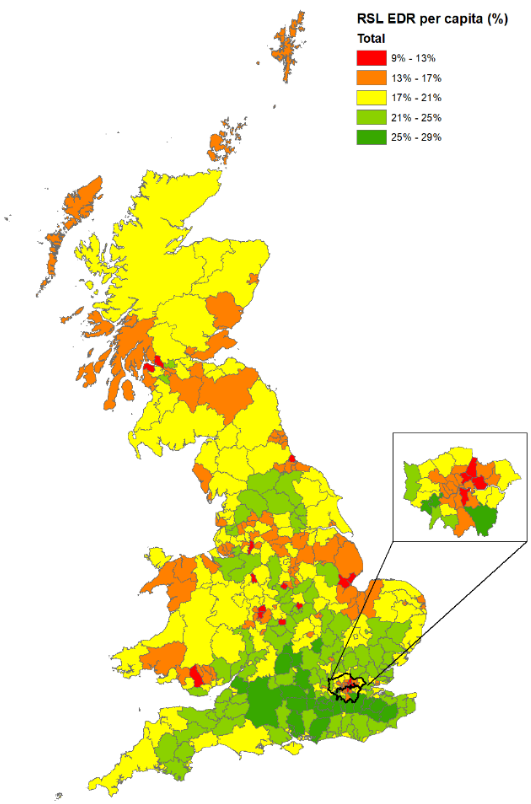

Figure 6.13 Variation in total EDR for all ESDs under the RSL strategy.

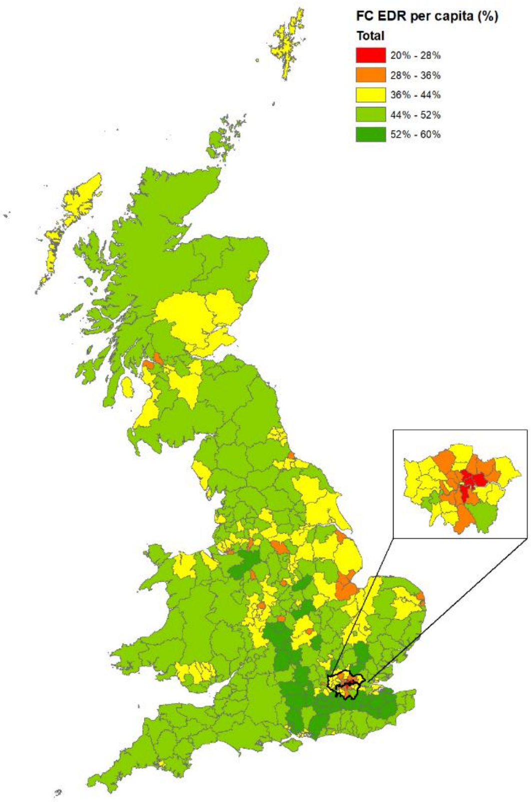

Figure 6.14 Variation in total EDR for all ESDs under the FC strategy.

The lower levels of EDR modelled for London are likely due to the nature of area in the model. LAs in central London were modelled in Chapter 5 to have lower ESDs than other areas of GB, meaning that less potential exists in these areas to reduce energy consumption for ESDs. Additionally, the density of the population, and infrastructure available to households, as well as the demographics of the population, in London mean that many households in London have already adopted measures such as 'shift to public transport', 'live car free' and 'shift to plant-based diets'. This means that the EDR measures across all strategies have a smaller effect than in other areas of GB.

Finally, a spatial autocorrelation analysis of each EDR strategy and the reduction in total energy consumption required to fulfil ESDs for all LAs in GB generates the Moran's I values in Table 6.4. The Moran's I value for the energy efficiency strategy suggest that the modelled EDR across all ESDs under the energy efficiency strategy has moderate-to-high levels of clustering (Figure 6.11) (Table 6.4). This is evident in Figure 6.11 whereby areas of higher reduction are shown across many areas of GB, with the exception of London.

Table 6.4 Moran's I values of for total reduction in energy consumption for ESDs in GB.

	Energy Efficiency	Maintained Service Levels	Reduced Service Levels	Full Consideration
Total ESDs	0.60	0.43	0.44	0.40

However, the spatial autocorrelation results for the MSL, RSL and FC strategies suggest more moderate levels of clustering of areas with similar levels of modelled EDR potential (Table 6.4). Clusters of higher levels of EDR for total energy consumption for all ESDs under the RSL and FC strategy can be seen in Figure 6.13 and Figure 6.14, while clusters of LAs with lower levels of EDR are more dispersed under the RSL strategy.

The spatial autocorrelation results for total EDR under the four EDR strategies modelled in this chapter, and the results in Section 6.2.1, Section 6.2.2, Section 6.2.3 and Section 6.2.4 suggests that areas of LAs with similar levels of EDR under the four EDR strategies modelled in this chapter are not clustered, with the exception of the results for the energy efficiency strategy. These results, modelled and generated across this section, demonstrate that under a universal approach to EDR, the level of reduction would vary across GB.

From a subsidiarity perspective, the results suggest that across all of the universal strategies, EDR would be reduced across GB to some extent, with the exception of two LAs under the energy efficiency strategy. However, this does not confirm that EDR strategies should be implemented solely at a national-level.

Examining the results in Section 6.2 shows that the ESDs which are expected to reduce energy consumption by the largest amount across all four strategies – heating and personal transport ESDs – have large ranges, but low levels of clustering. The low levels of clustering indicates that the measures in each of the four strategies would be effective across much of GB, however, the large range of results suggests that the combination of policies set out within these strategies are less effective in certain LAs.

Considering the individual strategies from a subsidiarity perspective, the low range of values generated under the energy efficiency strategy suggests that a national-level approach to EDR would be effective at improving efficiency when considering total ESDs. However, the larger range for the MSL, RSL and FC strategies suggests that a disaggregated approach to EDR, through subsidiarity, may raise the EDR potential of LAs where EDR results were modelled towards the lower end of the range.

However, before identifying whether the national-level EDR strategies modelled in this chapter should be supplanted by a disaggregated LA-level approach to EDR, the feasibility of implementing the four strategies modelled in this chapter needs to be considered. If LAs exhibiting higher levels of ESDs and EDR align, then a national-level approach would not harm the wellbeing of households in each LA throughout GB, thus ensuring an equitable approach. This needs to be considered before a disaggregated approach to EDR is considered a viable option for EDR.

6.3 ESD and EDR levels

Correlation coefficients were generated using a Spearman's Rank analysis of the ESD data in Chapter 5, and the EDR levels modelled in Chapter 6 (Table 6.5). The results for ESD categories exhibiting rebound under each strategy – e.g. public transport and services ESDs under all categories – have high correlation coefficients with ESD levels, therefore showing that LAs with higher ESDs presently are more likely to increase their consumption of ESDs not being reduced, by a greater extent.

However, the results for the ESDs undergoing EDR for energy consumption in each strategy are not as strongly correlated in areas of high consumption. Under the energy efficiency strategy, Table 6.5 and Figure 6.15 show that the correlation coefficients for heating and personal transport ESDs – the two ESD categories experiencing the greatest reductions under the energy efficiency strategy – are positively correlated with LA ESD levels, but only weakly. These results imply that an energy efficiency strategy, implemented universally, will not target areas of high energy consumption for these ESDs. This trend is also visible across the MSL (Figure 6.16), RSL (Figure 6.17) and FC strategies (Figure 6.18).

Table 6.5 Correlation coefficients between the different ESDs analysed in Chapter 5 and the four EDR strategies in Chapter 6. Red cells highlight very weak correlation coefficients between variables, orange cells highlight weak correlation coefficients between variables, yellow cells highlight moderate correlation coefficients between variables, light green cells represent strong correlation coefficients between variables and dark green cells represent very strong correlation coefficients between variables.

	Energy efficiency	MSL	RSL	FC
Heating	0.30*	0.22*	0.24*	0.22*
Other Shelter	0.77*	0.72*	0.68*	0.81*
Personal Transport	0.16*	0.15*	0.32*	0.20*
Public Transport	1.00*	1.00*	1.00*	1.00*
Aerial Transport	1.00*	1.00*	0.23*	0.23*
Nutrition	0.41*	0.54*	0.27*	0.48*
Recreation & Communication	0.97*	0.08*	0.66*	0.65*
Consumer Goods	0.99*	0.99*	0.39*	0.65*
Services	1.00*	1.00*	1.00	0.97*
Total	0.43*	0.16*	0.67*	0.53*

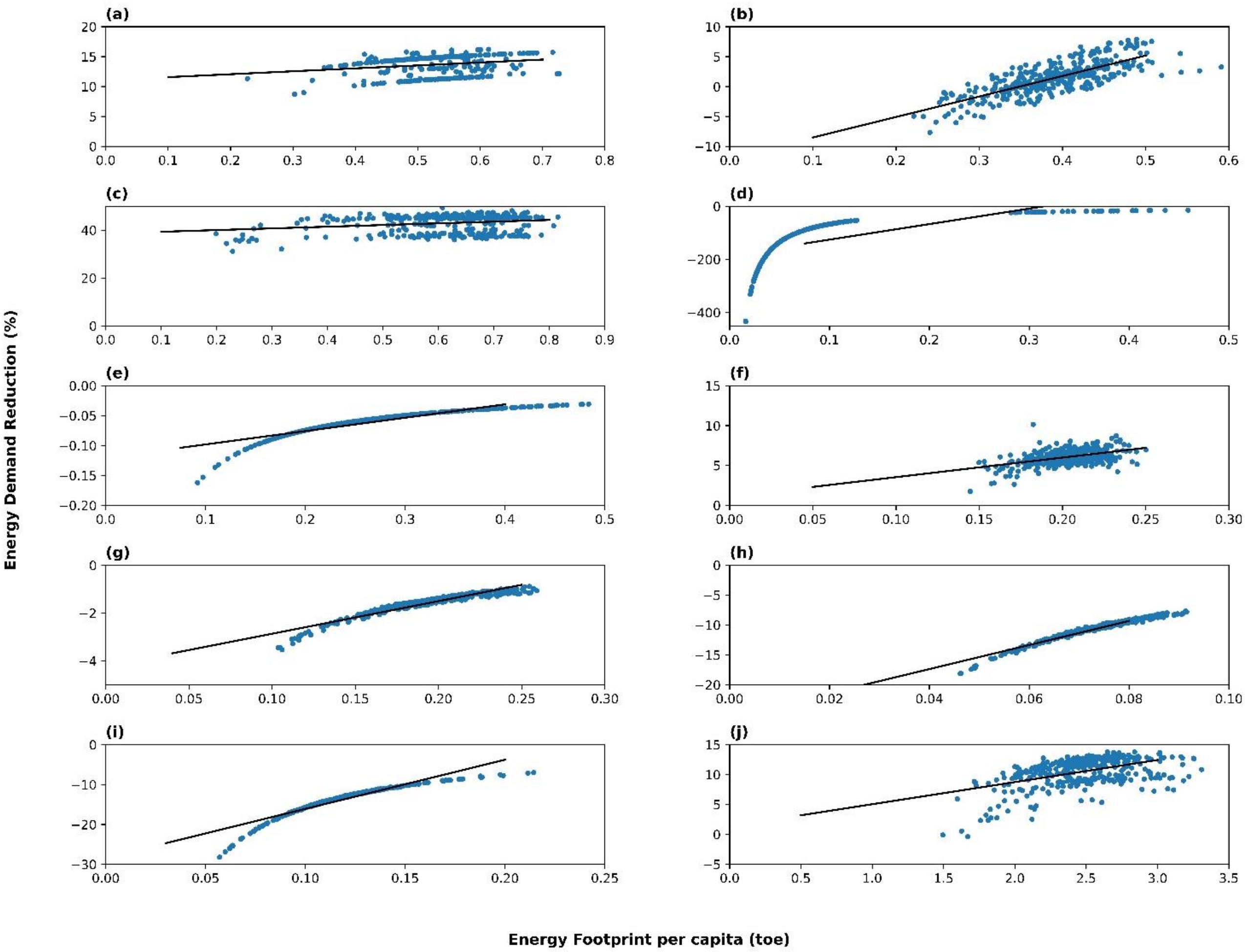

Figure 6.15 Scatterplots of a LA's ESDs and modelled EDR levels under the energy efficiency strategy. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Considering the MSL strategy, the level of reduction in LAs across all ESDs exhibits a very weak correlation coefficient with the size of a LA's footprint before EDR was undertaken. From an equitability perspective this implies that the MSL strategy does not address the energy consumption of households in LAs exhibiting higher levels of energy consumption to a greater extent than households in LAs exhibiting lower levels of energy consumption, thus reinforcing societal imbalances of energy consumption in GB.

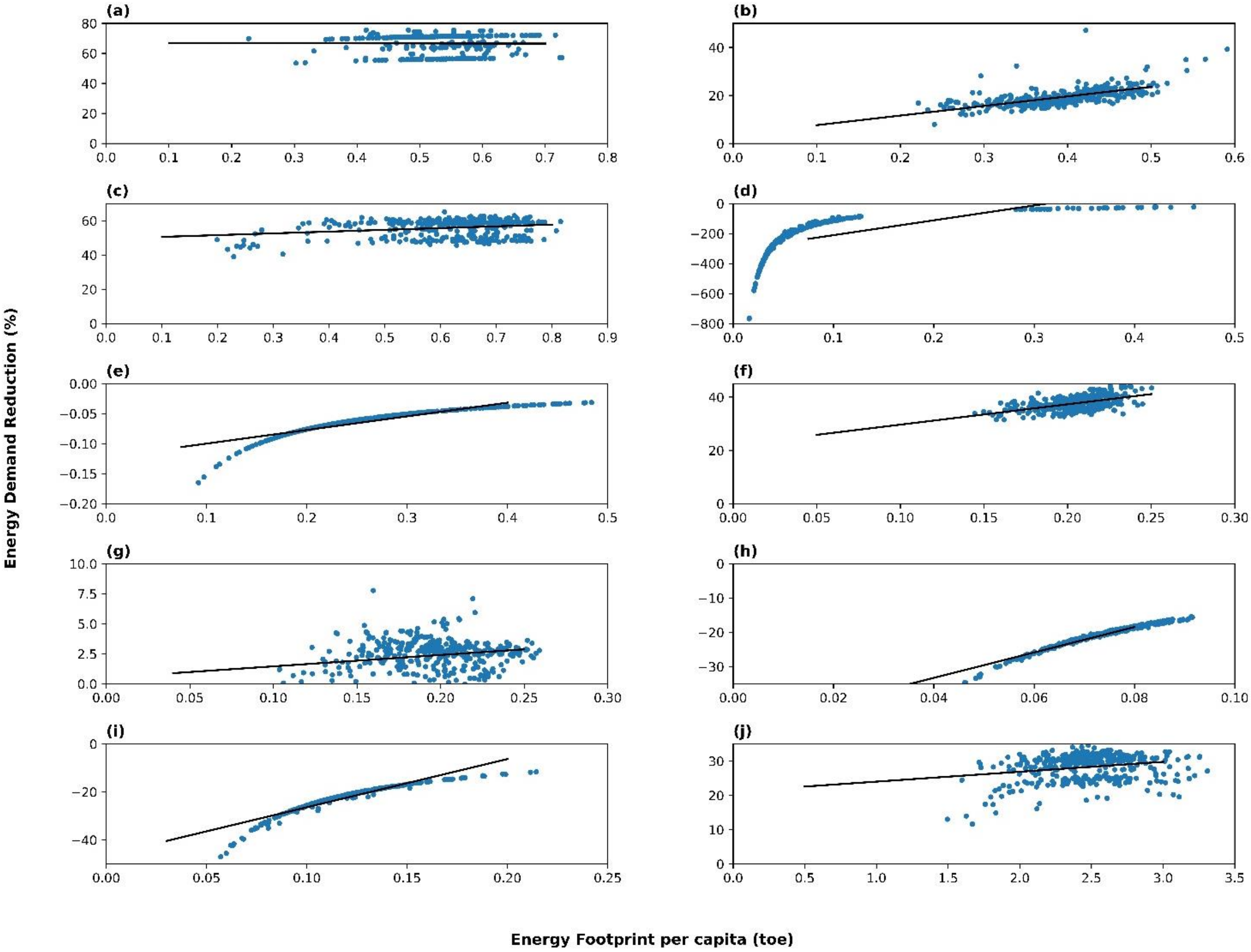

Figure 6.16 Scatterplots of a LA's ESDs and modelled EDR levels under the MSL strategy. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Conversely, the strategy which exhibits the greatest correlation with total ESD levels is the RSL strategy (Table 6.5; Figure 6.17). The strong positive correlation in the RSL strategy suggests that implementing this strategy universally across GB would broadly target high consumers of ESDs, and reduce their energy consumption by a greater extent than LAs where households consume less. From an equitability perspective, implementing measures from the RSL strategy is necessary to ensure that households with higher ESD levels reduce their overconsumption, thus ensuring a more equitable demand-side transition. A universal strategy encouraging households to reduce enegry consumption would generally be successful at this, however, the correlation coefficient of 0.67 (Table 6.5) implies that some households with lower levels of ESDs presently would be expected to reduce energy consumption across all ESD categories to a greater extent than households with larger ESD footprints.

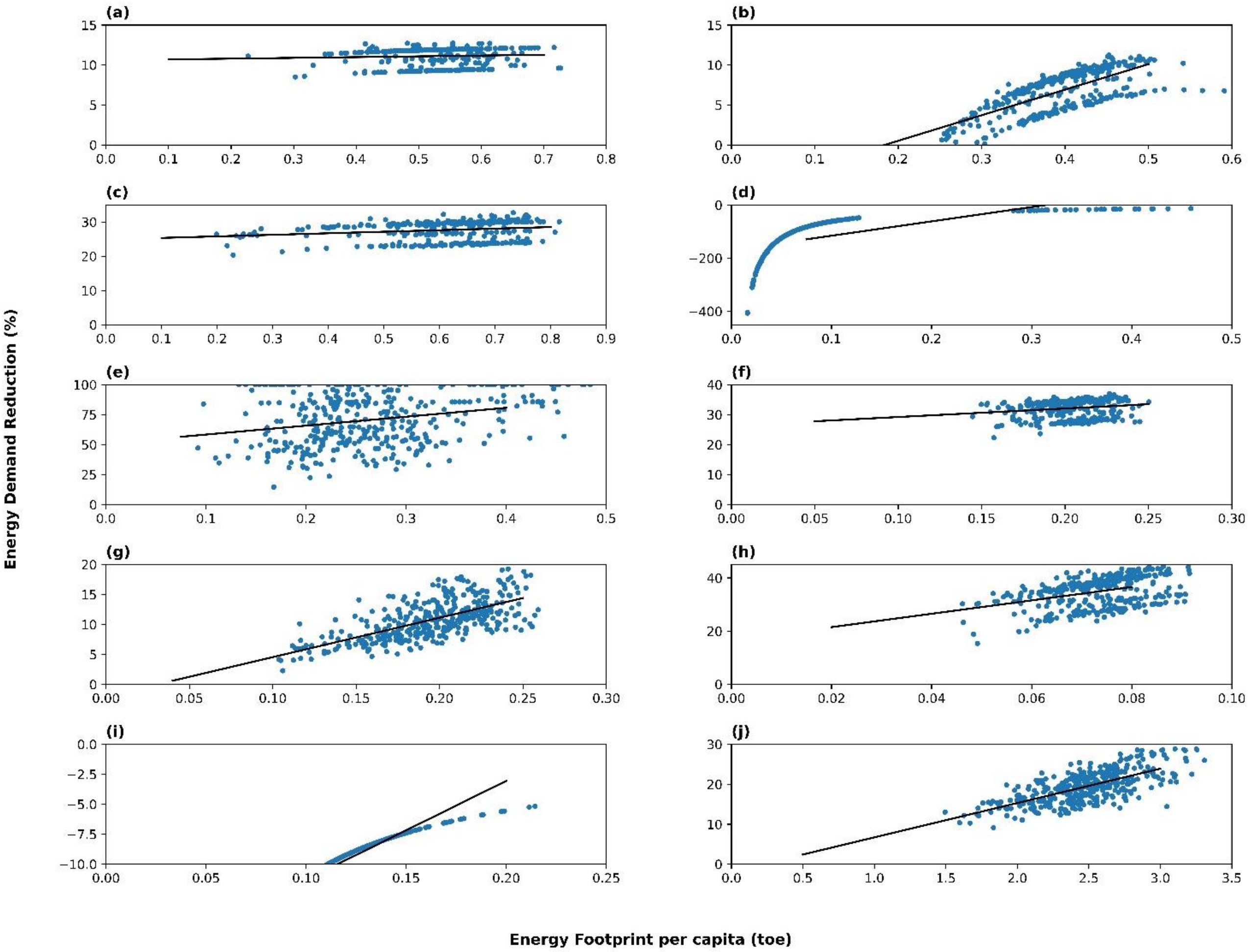

Figure 6.17 Scatterplots of a LA's ESDs and modelled EDR levels under the RSL strategy. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Finally, the FC strategy (Figure 6.18) exhibits the same effect for heating and personal transport ESDs as the previous three strategies (Table 6.5), with the two categories modelled to experience the greatest reduction in EDR under the FC strategy being weakly correlated with LAs exhibiting high household ESD levels per capita. The lack of correlation between level of reduction and previous ESD levels suggests that a universal approach to implementing a FC strategy would not be equitable in GB. Similarly, the correlation coefficients are only moderate (nutrition ESDs) and weak (aerial transport ESDs) for the ESD categories experiencing the next greatest national average reductions in energy consumption.

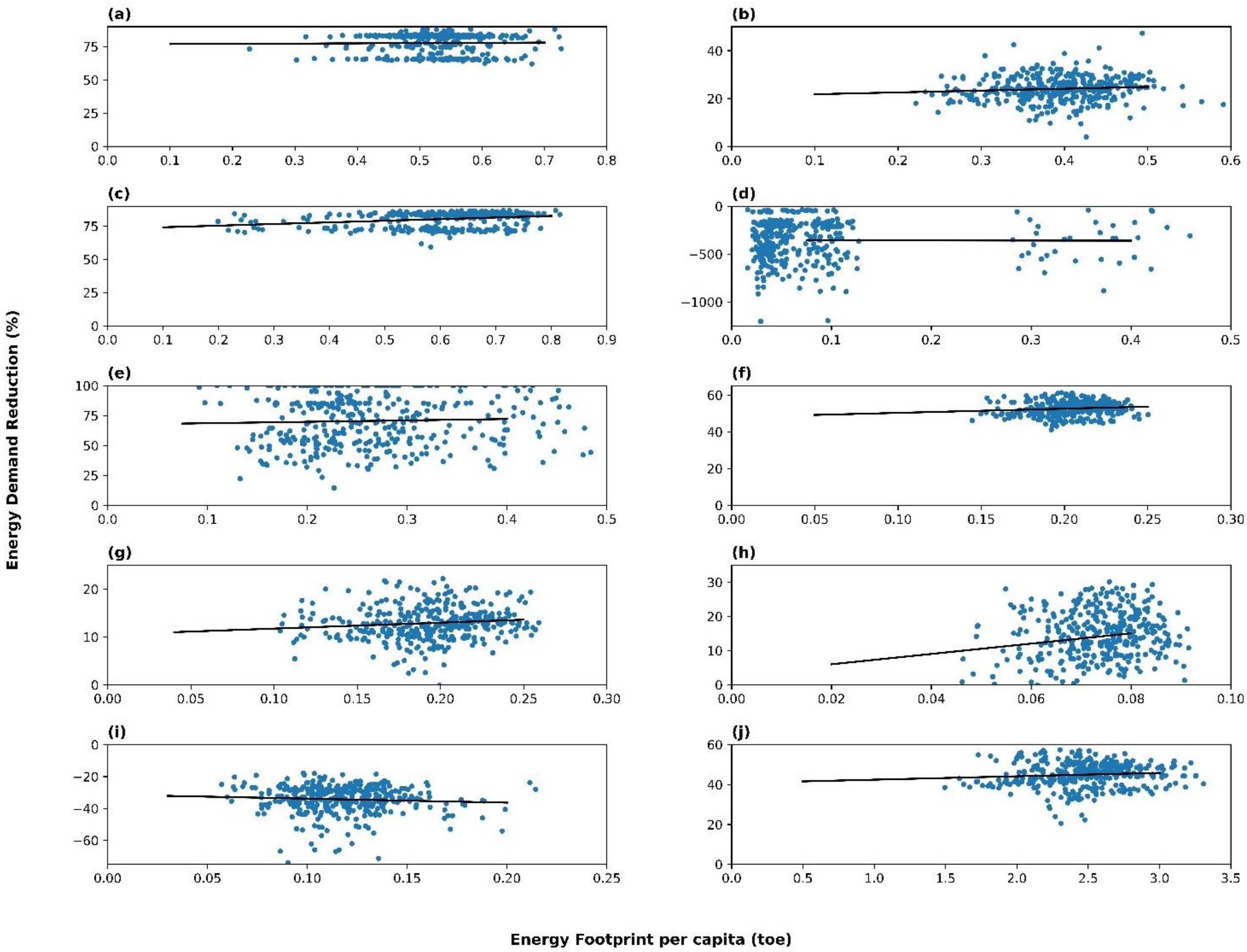

Figure 6.18 Scatterplots of a LA's ESDs and modelled EDR levels under the FC strategy. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

The results in Section 6.3 therefore suggest that universal approaches to EDR would not target LAs exhibiting high ESD levels. All four strategies highlight that implementing EDR measures aimed at reducing personal transport and heating ESDs – the two ESD categories with the largest ESD footprints in Chapter 5 – universally, would not have the greatest effect upon households in the LAs with the largest heating and personal transport ESD footprints. However, the RSL strategy shows strong positive correlation coefficients with total ESD footprints and EDR levels under this strategy. The results for the RSL strategy therefore suggest that measures which reduce the service levels of households are important to ensure the equitability of EDR strategies, and could also be implemented universally as they generally bring about greater reductions in LAs with greater ESD footprints, therefore ensuring this approach is equitable (Figure 6.17; Table 6.5).

6.4 Chapter summary

Chapter 6 modelled the potential of four EDR strategies designed to reduce energy demand for ESDs using an IO modelling technique (Wood *et al.*, 2018). Section 6.1 considered the national average reduction in energy demand across the energy efficiency, MSL and RSL strategies, while

Section 6.2 analysed the LA-level variation in the modelled reduction across GB for each EDR strategy.

Section 6.1 shows that the energy efficiency EDR strategy reduces energy consumption for total ESDs by the smallest amount compared to the MSL, RSL and FC strategies (Table 6.3). This demonstrates the need for EDR in GB to go beyond energy efficiency across GB. Maintaining service levels has a greater effect upon energy consumption than reducing service levels, however the RSL strategy reduces energy consumption for a wider number of ESD categories than the MSL strategy demonstrating that considering avoid measures, as well as shift and improve measures is important for EDR in GB (Figure 6.7; Figure 6.8; Table 6.3).

The FC strategy demonstrates the largest level of EDR across the four EDR strategies as the FC strategy is the most comprehensive strategy modelled in Chapter 6. The modelling results of the FC EDR strategy in Section 6.1 demonstrate that all measures in Ivanova *et al.*, (2020) must be considered if energy demand is to be reduced in line with the levels estimated for a 1.5°C future by Masson-Delmotte *et al.*, (2018). The overall, national-level EDR of 45.0% is less than has been modelled by previous studies, such as Grubler *et al.*, (2018) and Barrett *et al.*, (2022), however. The results in Section 6.1 will be discussed in the context of Grubler *et al.*, (2018) and Barrett *et al.*, (2022) in Chapter 8.

Section 6.2 demonstrates that the level of EDR modelled for a national-level in Section 6.1 is not universal across GB, with the results for different LAs modelling above national average EDR and some areas below national average EDR (Figure 6.5; Figure 6.7; Figure 6.8; Figure 6.9; Figure 6.10). The results for the energy efficiency EDR strategy demonstrate that while overall, in GB, an energy efficiency approach to EDR leads to a reduction in energy consumption across much of the country, there are some areas where focusing solely upon energy efficiency will lead to an increase in ESD levels (Figure 6.11).

Modelling results for more comprehensive strategies, such as the MSL strategy and RSL strategy, ensure that household energy consumption is reduced enough that the rebound effect does not negate the gains made from EDR across all of GB (Figure 6.12; Figure 6.13). However, a spatial analysis of the results suggests that clustering of LAs modelled to exhibit similar levels of EDR under the MSL and RSL strategies is only moderate. Moderate clustering and large ranges suggests that while a national-level approach to EDR would be effective, addressing certain ESD categories – such as personal transport and heating ESDs – at a LA-level may provide benefits for EDR.

Finally, the correlation coefficients between LA ESD footprint size per capita and the modelled EDR levels under each strategy were examined in Section 6.3. A universal approach to EDR would generally not reduce energy consumption levels at a greater rate in LAs with high ESD footprints under the energy efficiency, MSL and FC strategies. However, the correlation coefficient for total EDR across all ESDs and ESD footprint size under the RSL strategy is stronger than the other strategies, thus suggesting that a universal approach to EDR using measures in the RSL strategy would be equitable. With a focus upon heating and personal transport ESDs – the two largest ESD footprints modelled in Chapter 5 – correlation coefficients between rate of reduction under each strategy and ESD footprint size are positive, but weak, thus indicating that a universal approach to EDR under each of these strategies would not be an equitable approach to EDR.

The results in Section 6.3 demonstrate that universal approaches to EDR do not bring about greater levels of reduction in LAs with higher household ESDs per capita. Undertaking EDR in this manner would therefore not target areas of high consumption, and may therefore not be equitable. The inequitability of universal approaches to EDR suggests that subsidiarity, and more localised solutions to EDR, should be considered to potentially bring about greater reductions in energy demand in LAs with higher ESD footprints.

The broad, sweeping nature of the technological and behavioural shifts required to implement the level of EDR modelled in Chapter 6 may be more feasible in different areas of GB. Households with higher capacity to adopt EDR strategies may therefore experience greater reductions under the four universal EDR strategies modelled in Chapter 6. Chapter 7 will therefore focus upon the capacity of households in different LAs across GB to adopt the EDR strategies modelled in this chapter.

7 Household capacity to adopt energy demand reduction strategies at a Local Authority-level

In Chapter 5, local authority (LA)-level energy service footprints were analysed, while in Chapter 6, the potential of four different energy demand reduction (EDR) strategies was modelled. Understanding the present level of energy service demands (ESDs) in Great Britain (GB) is important for EDR, as is the EDR potential of different strategies for energy consumption. However, the analysis did not consider the capacity of households in LAs across GB adopting the four EDR strategies in Chapter 6.

Chapter 7 builds upon the EDR potentials modelled in Chapter 6 by analysing the capability of households in LAs to adopt the measures in the EDR strategies in Chapter 6. The analysis will identify areas of GB which are more vulnerable to EDR compromising household wellbeing if a universal, national-level EDR strategy is implemented across GB. Understanding the capacity associated with EDR strategies in GB, would improve the chances of implementing successful, equitable policy shifts swiftly to reduce the energy associated with ESDs across GB.

Chapter 7 is structured into two sections. In Section 7.1, the capacity index (CI) analysis is undertaken. In Section 7.1, five capital dimensions will be examined in different sections in order to understand which LAs in GB have greater household capacity to implement the EDR strategies modelled in Chapter 6. Following this, Section 7.2 subsequently considers the results of the CI analysis in the context of the ESD results in Chapter 5, and the EDR strategy potentials in Chapter 6.

7.1 Capacity Index Analysis of Households to Mitigate Energy Demand

The potential of different strategies (Chapter 6) is only one consideration when modelling EDR. EDR must not compromise wellbeing, therefore the capacity of households in LAs across GB to adopt EDR strategies must be considered (Nielsen *et al.*, 2020). Many studies have considered the feasibility of different options for EDR based upon their costs, technological availability and implementation capacity, while other studies have considered the capability of individual households to adapt to, and mitigate, climate change (Grubler *et al.*, 2018; Robinson and Mattioli, 2020; Barrett *et al.*, 2022).

Section 7.1 will conduct a CI analysis upon LAs throughout GB to assess five different dimensions of household readiness to adapt. The five dimensions focus upon different types of capital, which are financial capital, human capital, physical capital, natural capital and social capital (Masson-Delmotte *et al.*, 2018; Brutschin *et al.*, 2021). Assessing these five dimensions will allow LAs, where households may struggle to adopt the measures and strategies modelled in Chapter 6, to be identified.

In Section 7.2, the data generated by the CI analysis will then be examined alongside the ESD levels modelled in Chapter 5 and the EDR potentials modelled in Chapter 6. This analysis will outline whether the burden of EDR, under a universal strategy, is expected to fall upon LAs which have more capacity to adopt the EDR strategies or LAs with less capacity to act – due to preventative factors such as a dispersed population or less affluent households.

Each of the five dimensions: financial capital (Section 7.1.1), human capital (Section 7.1.2), physical capital (Section 7.1.3), natural capital (Section 7.1.4) and social capital (Section 7.1.5); and their respective results will be set out in different sub-sections. Section 7.1.6 will analyse the combined capacity index (CI) data from across all the capital dimensions, while Section 7.1.7 will summarise the work in Section 7.1 and draw conclusions from the research.

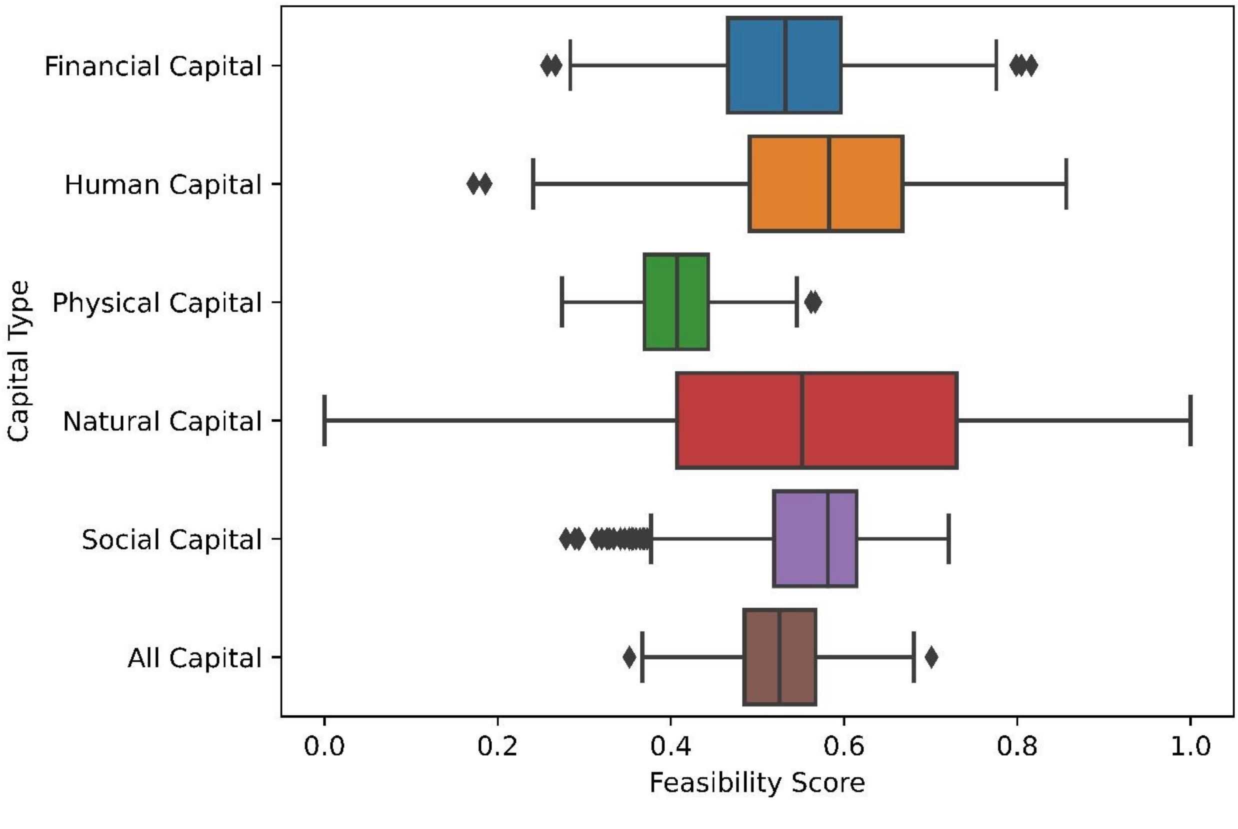

Figure 7.1 Range of CI scores across all five capital dimensions and all capital.

7.1.1 Financial capital

The criteria in the financial capital dimension of the CI analysis focus upon the financial capacity of households within a LA to adopt measures in the EDR strategies modelled in Chapter 6 (Siders, 2019). Considering the economic viability of households is important as some measures in the EDR strategies, such as the shift to battery-electric vehicles (BEVs) or the installation of heat pumps have a large, initial financial outlay which some households may not be able to afford. Financial capital is therefore important from an implementation perspective, and a justice perspective – i.e. enforcing expensive EDR measures upon households which cannot afford them would lead to inequitable EDR. The national average scores financial capital is 0.53, while Figure 7.2 shows the CI scores for all LAs across GB.

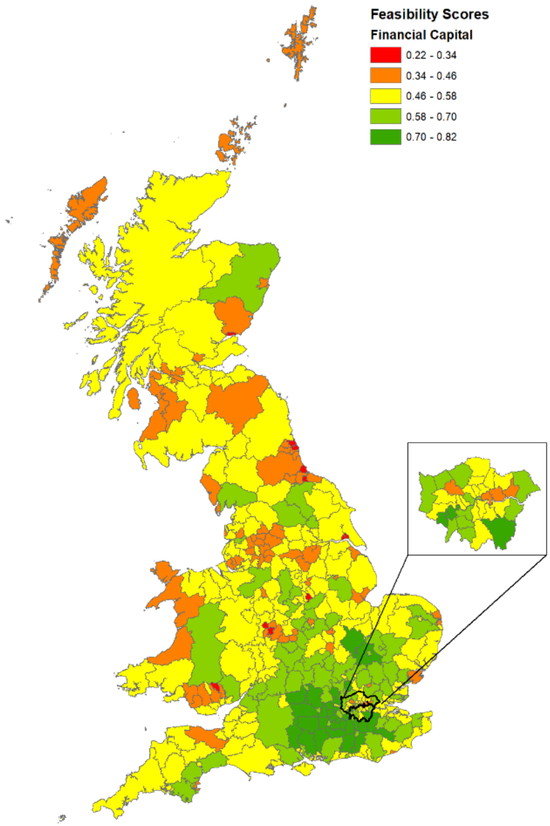

Figure 7.2 Financial Capital scores for each LA in GB. The higher the score, the greater the capacity of households within each LA to adopt EDR strategies.

Figure 7.2 shows that there is a cluster of LAs with high financial capacity to adopt EDR strategies in the south of England. However, no similar area of low financial capacity exists across GB, with the exception of a small cluster of LAs with low financial capacity to adopt EDR strategies in the north-east England region.

The range of CI scores for financial capital is 0.56 across all LAs in GB. The highest CI score is 0.82 in Hart, while the lowest is 0.26 in Wolverhampton. The range of values suggests that there is a large variation, in the financial capacity of households across LAs in GB to adopt the measures and strategies modelled in Chapter 6, this is evident in Figure 7.2. The imbalance in financial capacity must be considered in an analysis of EDR potential as some measures modelled in the EDR strategies in Chapter 6, such as 'shift to battery-electric vehicles' (BEVs) are more high cost than other measures such as 'shift to public transport'. Without considering the financial imbalance of households within LAs across GB, certain measures could compromise the wellbeing of households in different LAs.

A spatial autocorrelation analysis of the financial capital CI scores gives a Moran's I value 0.52 ($p<0.01$) indicating moderate clustering when considering the economic aspect of the CI study. The moderate clustering score of the spatial autocorrelation analysis aligns with the map of financial capital scores in Figure 7.2 which indicates a cluster of LAs with high CI scores of implementing EDR measures in the south of England, but more disparate scores throughout different regions of GB.

The Moran's I value for financial capital suggests that LAs of higher financial capacity to adopt EDR strategies exist in GB, as is evident in Figure 7.2. However, Figure 7.2 also shows that financial capacity to adopt EDR strategies remains moderate throughout many of the LAs in GB, thus indicating that the level of financial burden placed upon households within LAs throughout GB will be broadly similar. However, in areas where low financial capital is evident - e.g. Wolverhampton – some form of financial help to households may be necessary to ensure a just transition.

7.1.2 Human capital

The human capital dimension considers the capacity of households themselves to adopt the measures in the EDR strategies in Chapter 6. The CI analysis therefore focuses upon factors such as proportion of fuel-poor households within a LA, or the total number of food parcels distributed per 100,000 people in a LA. If households are already struggling to meet their fuel and food needs, it is likely that enforcing EDR measures upon households in these areas will compromise their wellbeing.

The capacity of households, rather than institutions is focused upon in the human capital dimension of the CI analysis as LAs themselves do not possess large amounts of funding to implement EDR strategies. Therefore, analysing the capacity of LAs at present will likely yield the same results across GB – that LAs do not currently possess high levels of capacity to reduce energy demand.

The national average score for the human capital component of the CI analysis is 0.57. Figure 7.3 shows the variation in human capital component CI scores for each LA across GB. 45.2% of LAs in Figure 7.3 have a high CI score for human capital. Much of the high CI scores in Figure 7.3 are located in England and Wales, with the pattern across Scotland and the east of England showing moderate CI scores for human capital. The range of values across GB is 0.68 (0.17 for Glasgow City and 0.86 for City of London). The high range suggests that human capital varies significantly across GB, which is evident in Figure 7.3.

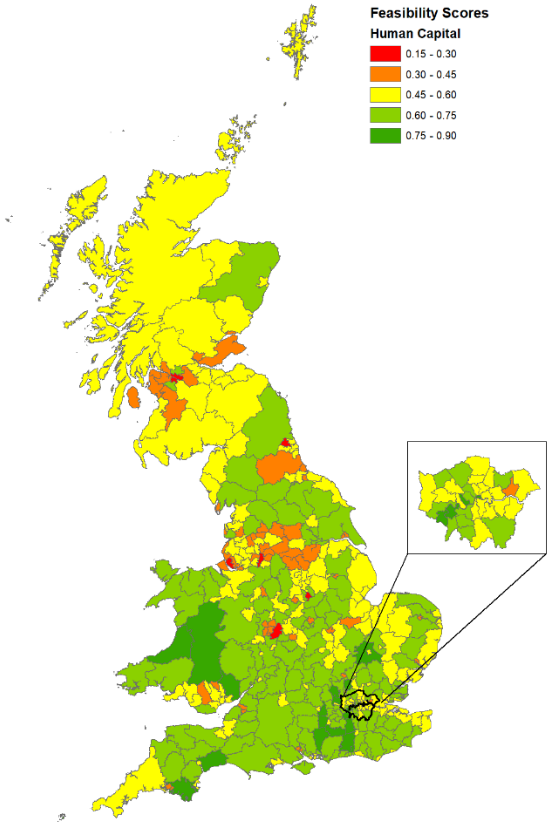

Figure 7.3 Human Capital scores for each LA in GB. The higher the score, the greater capacity of households within each LA to adopt EDR strategies.

Undertaking a spatial autocorrelation analysis of the human capital component suggests that there are low levels of clustering, with a Moran's I value of 0.31 ($p<0.01$). This is evident in Figure 7.3 whereby much of the LAs throughout GB score above 0.60 in the human capital component of the CI analysis, and areas of low human capital are dispersed across much of GB.

The results of the CI analysis upon the human capital dimension suggests that across much of England and Wales, LAs contain households which have high levels of human capital and therefore, the implementation of EDR strategies is more feasible in these areas. However, the low levels of clustering, and similar human capital CI scores suggests that households across much of GB possess similar levels of capacity to adopt EDR strategies from a human capital perspective.

A national-level approach may therefore be more appropriate for EDR from a human capital perspective as the level of human capital does not vary widely across GB. However, as with financial capital, targeted help would be required in areas of low human capital to ensure that EDR measures did not impact upon the wellbeing of households in these LAs.

7.1.3 Physical capital

The physical capital dimension of the CI analysis considers the availability of resources – i.e. infrastructure required to allow the transition to a low energy demand society – in each LA. The infrastructure density of each LA is important for transportation EDR options, as, for example, households switching private vehicle travel for public transport is not possible if the infrastructure which allows the shift is not locally available (Gifford, 2011). Additionally, elements of the physical capital dimension, such as the proportion of owner-occupied housing is important to consider from the perspective of heating and other shelter ESDs, as tenants, rather than property owners, are less likely to be able to implement EDR measures such as installing 'better thermal insulation' or shifting heating source to 'heat pumps' (Scrase, 2001). The physical capital dimension is therefore important for identifying areas of GB, in which a scale-up of households do or do not possess or have access the physical infrastructure required to implement EDR measures.

The national average score for the physical capital dimension of the CI analysis is 0.44, while Figure 7.4 shows the how the scores of physical capital vary for each LA across GB. The result that stands out in Figure 7.4 is the result for the Highland LA in Scotland. Highland is an extremely rural LA with a low population and the lowest population density per squared kilometre in GB. While population density is not considered in the physical capital CI scores, it would be expected that more urbanised LAs would score higher in this capacity dimension.

However, the high score of Highland for physical capital is due to the high number of rail stations across the LA, and the high proportion of owner-occupied housing. Therefore, despite the difficulty of utilising measures, such as the shift to public transport in this LA, buildings-related measures could be implemented more easily due to the higher number of homeowners.

Beyond examining a single LA, Figure 7.4 shows that many LAs throughout the GB region of London score moderately on the physical capital dimension, with LAs towards the outer edge of London scoring higher in this dimension of the CI analysis. As with Highland, this trend in London is due to the inclusion of an owner-occupied housing sub-component within the physical capital component of the analysis, alongside the transport infrastructural sub-components of physical capital.

From a transport perspective, London has the densest public transport system in GB (Rodrigues and Breach, 2021), however the results for London are skewed by the small proportion of owner-occupied housing in central London (Gleeson and Finnerty, 2021). This therefore implies that while, from a transport perspective, households within London have high capacity to make shifts such as 'shift to public transport' or 'shift to active transport'. However, considering measures within the EDR strategies in Chapter 6 which focus upon reducing energy consumption for heating ESDs or other shelter ESDs, households in this region have less capacity than other areas of GB.

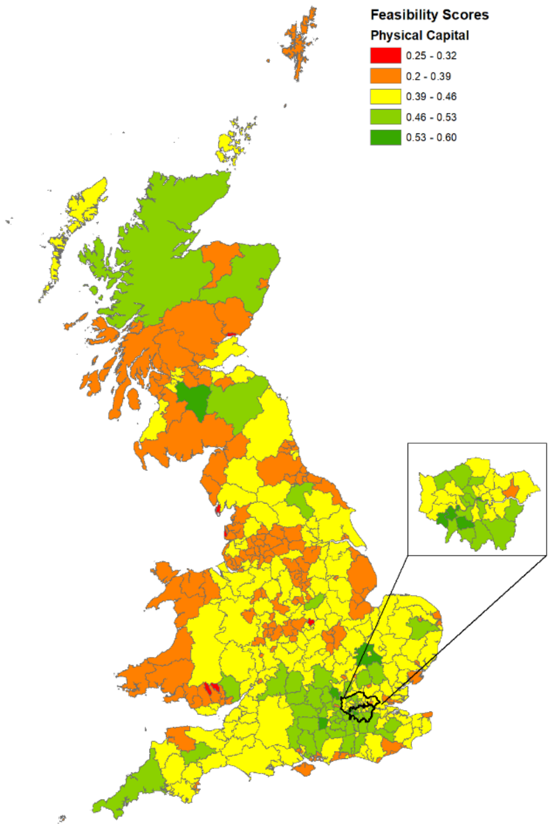

Figure 7.4 Physical capital scores for each LA in GB. The higher the score, the greater capacity of households within each LA to adopt EDR strategies.

Beyond London and Highland, the largest clusters of households within LAs, with lower capacity to adopt the EDR strategies in Chapter 6 are in Scotland, Wales and north England (Figure 7.4). Much of GB however can be considered to have moderate capacity to adopt EDR measures and strategies from a physical capital perspective (Figure 7.4).

The range for physical capital varies less than for financial capital (Section 7.1.1) and human capital (Section 7.1.2). The range for physical capital CI scores in GB is 0.29, varying from 0.27 in Blaenau Gwent to 0.57 in South Cambridgeshire. The smaller range suggests that there is less variation in the physical capacity of households at a LA-level than there is in financial capacity and human capacity.

A spatial autocorrelation analysis of physical capital scores for all the LAs in GB generates a Moran's I value of 0.44 suggesting moderate clustering of LAs with similar physical capital capacity to adopt EDR strategies. This aligns with the map of physical capital scores in Figure 7.4 which highlights some areas of clustered LAs with similar physical capital CI scores. Considering the moderate level of clustering for physical capital, and the map in Figure 7.4, the analysis suggests that again, much of GB has similar levels of physical capital at present. Therefore, a national-level approach to increasing the level of physical capital capacity across GB may be appropriate for EDR.

7.1.4 Natural capital

Considering the role of population density in EDR studies is important. Dense, urbanised environments allow for changes in behaviour, such as 'shift to public transport' or the use of the 'service/sharing economy' to be scaled more easily (Rodrigues and Breach, 2021). Sparse, rural environments encourage private ownership of goods and services and lead to infrastructure gaps in elements such as the gas grid which leads to the use of more energy intensive, polluting fuels to fulfil household ESDs and achieve wellbeing. Section 7.1.4 therefore considers this element of EDR.

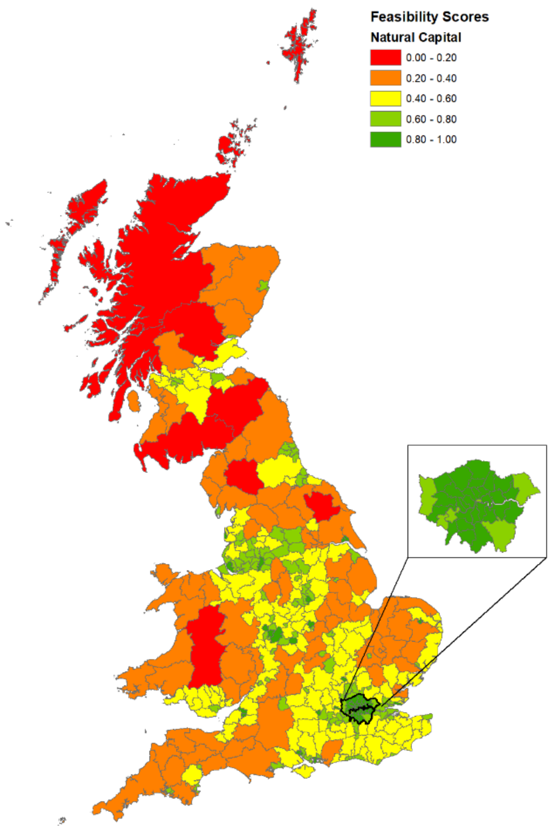

Figure 7.5 Natural Capital scores for each LA in GB. The higher the score, the greater capacity of households within each LA to adopt EDR strategies.

The national average score for the natural capital dimension of the CI analysis is 0.56. The range in variation is from 0.00 in Na h-Eileanan Siar in Scotland and 1.00 in Islington in London, with a range of 1.00. Figure 7.5 shows the variation in the scores of natural capital for each LA across GB.

Figure 7.5 shows that there are high levels of natural capital capacity to implement EDR strategies in London, as well as regions of north-west, Yorkshire and the Humber, the West Midlands and north-east England. However, the pattern across much of GB is mixed, with no large clusters of high or low scores (with the exception of London). This is evident in the spatial autocorrelation analysis which generates a Moran's I value of 0.45, thus indicating moderate clustering.

Large variations in the natural capital scores for neighbouring LAs are not evident in Figure 7.5 suggesting that the natural capital decreases gradually as LAs move away from large population centres. However, despite large areas of GB seeming to exhibit low natural capital scores in Figure 7.5, 76% of LAs in GB exhibit moderate scores or above. The dominance of low scores for natural capital capacity in Figure 7.5 is due to the largest LAs in GB exhibiting low population densities, and therefore low natural capital scores.

The results of the CI analysis in Figure 7.5, and the Moran's I value of 0.45, suggest that LAs have moderate capacity to adopt EDR strategies when considering natural capital. The large range of scores in Figure 7.5 is due to only one factor being considered in the natural capital dimension of the CI analysis. However, the range of scores, alongside the moderate clustering of scores, generated through a spatial autocorrelation analysis, suggests that while many of the LAs throughout GB would feasibly be able to adopt EDR strategies using a national approach, special consideration may need to be given to the LAs with low scores in this capacity dimension.

7.1.5 Social capital

Finally, the social capital dimension of the CI analysis considers the acceptance of EDR measures across GB. The acceptance of different EDR measures, and the EDR strategies, is important for EDR as without social acceptance or political will driving the implementation of EDR measures, it is unlikely that the potential of each EDR strategy will be realised. Section 7.1.5 therefore examines the proportion of the population already undertaking measures throughout GB. Higher uptake of measures presently will be used to indicate higher acceptance, and therefore greater likelihood that EDR measures will be welcomed by households. Additionally, the climate target date of each LA will be considered in the CI score as more ambitious climate targets are often devised after public consultation through climate commissions, meaning that the more ambitious targets likely mean that households within that LA are more willing to undertake EDR measures.

The national average scores for the social capital dimension of the CI analysis is 0.56, with the variation in score ranging from 0.28 in Dartford to 0.72 in South Oxfordshire (a range of 0.44). The variation in LA social capital CI scores can be seen in Figure 7.6.

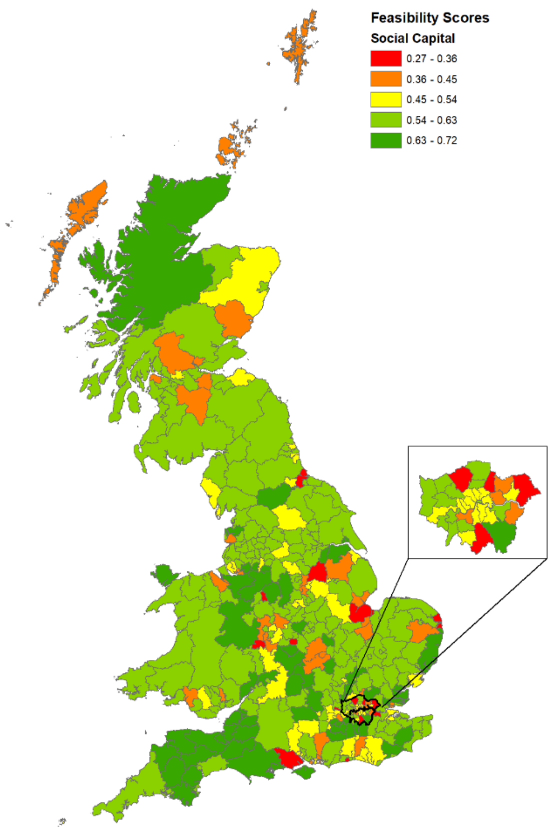

Figure 7.6 Social Capital scores for each LA in GB. The higher the score, the greater capacity of households within each LA to adopt EDR strategies.

The results of the analysis of social capital in Figure 7.6 show that LAs across much of GB exhibit similar scores for social capital, with 71.1% of LAs classed as having high levels of social capital for the demand-side transition. There is no specific cluster of high scoring areas in Figure 7.6, with much of GB scoring greater than 0.54 in the analysis. Figure 7.6 does also show that there are some LAs with very low levels of social capital for households, however, this accounts for only 4.5% of LAs.

Conducting a spatial autocorrelation analysis upon the results in Figure 7.6 generates a Moran's I value of 0.14, indicating very low levels of clustering, which is evident from Figure 7.6. This implies that LAs containing households with low levels of social capital are randomly dispersed throughout GB (a value of 0 would indicate this).

The results of the CI analysis for the social capital dimension of capacity suggests that many households across GB have similar attitudes towards EDR, and would be willing to undertake EDR measures to reduce energy consumption for ESDs. However as Figure 7.6 also shows, there are levels whereby low social capital scores also exist. Examining these areas in more detail to identify common attributes between areas of low social capital CI scores, however, Chapter 7 will not examine this.

The results in Figure 7.6 suggest that a national approach would be appropriate to implement EDR measures from a social capital perspective. Many LAs throughout GB exhibit high household acceptance of measures to reduce energy demand, while areas of low social capital are few and isolated. As with other forms of capital, a targeted approach in these areas to increase social capital, and the uptake of EDR strategies, rather than a fully disaggregated approach to EDR would be the most appropriate way forward in GB.

7.1.6 All capital

Finally, Section 7.1.6 will consider the combined score of all types of capital using a CI analysis to assess whether EDR strategies are less feasible in different LAs throughout GB. The all capital dimension will give consideration to the capacity of households to adopt EDR measures across all of the dimensions and components examined in Section 7.1. Considering all capital is important as, while individual capital dimensions in the CI analysis give an insight into the different levels of capacity for different factors across GB, all of the capital components will affect the capacity of household adopting EDR strategies across GB (Pandey and Jha, 2012; Siders, 2019).

The national average value for all capital across all LAs in GB is 0.53, indicating that households in GB generally have a moderate capacity to adopt the EDR measures and strategies modelled in Chapter 6. Figure 7.7 shows the variation in all capital values across GB.

Figure 7.7 shows that all capital scores are more clustered than the previous five capital dimensions scores (Section 7.1.1; Section 7.1.2; Section 7.1.3; Section 7.1.4; Section 7.1.5). A cluster of high scores for all capital is located in south-east England and London, with capital scores generally decreasing the further away from the south-east a LA is (Robinson and Mattioli, 2020). A spatial autocorrelation analysis of the LA-level values of the all capital CI scores generates a Moran's I value of 0.66, indicating high levels of clustering amongst LAs with similar CI scores in GB, which is evident in Figure 7.7.

Considering areas of low CI scores in Figure 7.7, these are predominantly located in the north of England, Scotland and west Wales. 25.3% exhibit low scores for the combined all capital dimension of capacity, however only 10.6% of the low scores are classed as very low (Figure 7.7).

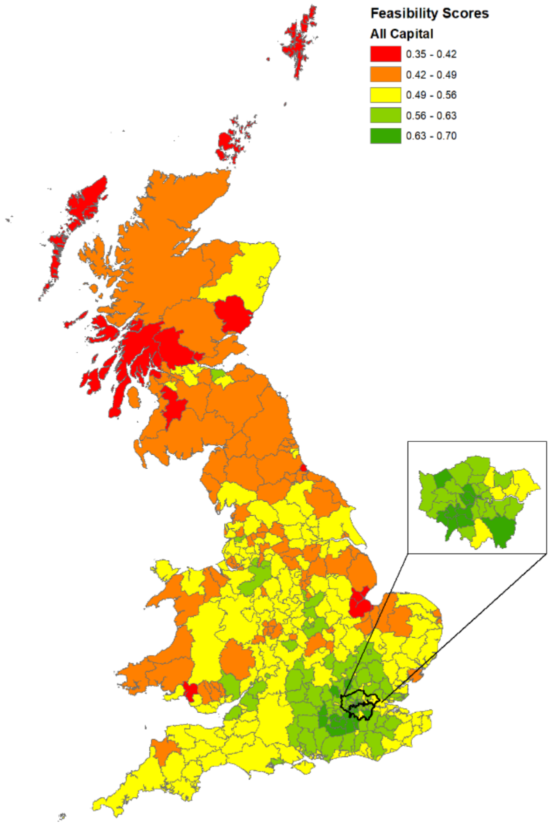

Figure 7.7 All Capital scores for each LA in GB. The higher the score, the greater capacity of households within each LA to adopt EDR strategies.

The variation in the CI scores of all capital and the high level of clustering of similar areas of CI scores suggests that a disaggregated approach to EDR may be appropriate for EDR, contrary to what the individual capital scores suggested. Households in different LAs throughout GB score similarly, therefore suggesting that they possess different characteristics and levels of ambition when considering EDR (Robinson and Mattioli, 2020). Therefore, households in different LAs have different requirements in different areas of GB, rather than households with similar requirements being randomly dispersed (Robinson and Mattioli, 2020).

A disaggregated approach to EDR would allow different options for EDR, which address the gaps in the needs of households in LAs throughout GB to be implemented, additionally, from a financial perspective, funding could be devolved to LAs and households to encourage the demand-side transition. However, the results in Figure 7.7 suggest that a regional approach to EDR, rather than a LA-specific approach would be a more appropriate approach to EDR due to the high levels of clustering of LAs with similar CI scores. Although due to the regions of GB being administrative – with the exception of London, Scotland and Wales – rather than having powers to enact policy of their own, a regional approach would still need to be set out at a national-level (ONS, 2021).

7.1.7 Summary

Analysing the CI scores of different types of capital required by households to transition to a low energy demand society in GB is important to ensure an effective, just transition takes place (Robinson and Mattioli, 2020). The method utilised in this section is often used to assess the vulnerability of regions in developed countries to climate change. However, the methodology has instead been used to index the capacity, or lack of capacity, of different LAs to adopt EDR strategies.

The national average CI scores remain similar across all dimensions (financial – 0.53; human – 0.57; natural – 0.56; social – 0.56), with the exception of physical capital (0.41). However, the variation across LAs is within each dimension of capacity is much larger than the national average values suggest.

With the exception of natural capital, which focuses upon only one sub-component, human capital has the largest range of CI scores across GB, with a range of 0.68, while physical capital has the lowest range of 0.29. This suggests that poverty factors, such as proportion of fuel-poor households, and other human factors, such as the median age of the population, vary greater across GB than the level of public transport infrastructure and the proportion of owner-occupied housing by LA. Similarly, the values in the financial capital dimension range have a range of 0.56 (0.26 to 0.82), thus also suggesting that the range in financial capital is larger than other capital dimensions when considering EDR in GB.

Considering the results of the individual capital dimensions, the results indicate that a national-level approach to EDR would be more appropriate than a LA-level approach due to the majority of LAs in GB possessing similar CI scores. However, the results for all capital in Section 7.1.6 show that there are clusters of LAs within GB with similar CI scores, which is confirmed by the Moran's I value generated in a spatial autocorrelation analysis (Section 7.1.6). These results suggest that households across LAs in different regions of GB have similar level of capacity when considering EDR. This implies that a regional approach to EDR may be appropriate when considering EDR in GB as while each dimension of capacity is important, all must be considered when enacting EDR to ensure a just transition. However, due to the regions of England lacking any powers to enact to enact policy, it is likely that a regional approach to EDR would need to be set out at a national-level.

Despite the clustering of LAs which have high levels of all capital, and therefore have the greatest capacity to adopt the EDR measures in strategies modelled in Chapter 6, the results of the CI analysis need to be analysed using correlation analyses alongside ESD data in Chapter 5 and EDR data in Chapter 6. Undertaking this analysis will allow this study to identify whether high levels of ESDs correlate with areas of high CI scores. Similarly, it can be examined whether areas which are projected to have greater levels of EDR by the model in Chapter 6 also have high CI scores. This analysis will be examined in Section 7.2.

7.2 Analysis of GB's LA capacity index

In Chapter 5, the ESDs of each LA in GB were modelled, while EDR for each LA under four different strategies was modelled in Chapter 6. Finally, Section 7.1 analysed the capacity of different areas of GB to assess the capacity of households in different LAs throughout to GB to adopt EDR strategies.

Section 7.2 will therefore draw the elements from Chapter 5, Chapter 6 and Chapter 7 together by analysing the CI scores alongside the ESD and EDR results from Chapter 5 and Chapter 6. The results are drawn together to identify whether ESD and EDR results correlate with areas of high capacity to adopt EDR strategies in order to assess whether the high ESD levels equate to high capacity and whether the universal strategies modelled in Chapter 6 reduce energy consumption by a greater amount in areas which have high CI scores, thus ensuring a just transition.

Section 7.2.1 will examine the ESD results alongside the CI scores to identify whether LAs which have high ESD levels indicate LAs where households have greater capacity to implement EDR measures. Following this, Section 7.2.2 will examine the EDR modelling results alongside the CI scores generated in Section 7.1 to identify whether areas of GB, which are modelled to have higher levels of EDR, can feasibly implement the broad, national-level strategies set out in Chapter 6.

7.2.1 ESD levels and household capacity

Previous studies have shown the link between high levels of ESDs and income (Owen and Barrett, 2020), therefore it would usually be assumed that LAs with high levels of ESDs would generally have a greater CI score for financial capital. However, Figure 7.8 and Table 7.1 show that areas of high ESDs only have a moderate level of correlation with financial capital. In the context of the socioeconomic factor results in Chapter 5, the moderate correlation can be expected as the ESD levels in Chapter 5 did not correlate as well with average household income as they have done in previous studies.

Figure 7.9 shows the results for LA human capital CI scores and LA ESD levels modelled in Chapter 5. Table 7.1 shows that the results for human capital correlate highly with six ESD categories modelled in Chapter 5, including total ESDs. This implies that higher ESD levels for many ESDs categories can be expected where the population is older, better educated and not experiencing food or fuel poverty. This trend has been identified in previous footprinting studies, such as Minx *et al.*, (2013).

Table 7.1 Correlation analysis of ESD levels in Chapter 5 and the CI scores in Section 7.1 of all LAs in GB. Red cells highlight very weak correlation coefficients between variables, orange cells highlight weak correlation coefficients between variables, yellow cells highlight moderate correlation coefficients between variables, light green cells represent strong correlation coefficients between variables and dark green cells represent very strong correlation coefficients between variables.

	Financial Capital	Human Capital	Physical Capital	Natural Capital	Social Capital	All Capital
Heating	0.15*	0.38*	0.08	-0.56*	0.19*	-0.11*
Other Shelter	0.50*	0.73*	0.43*	-0.71*	0.23*	0.16*
Personal Transport	0.55*	0.65*	0.43*	-0.59*	0.26*	0.25*
Public Transport	0.29*	0.05*	0.36*	0.46*	-0.19*	0.46*
Aerial Transport	0.44*	0.47*	0.39*	-0.34*	0.14*	0.24*
Nutrition	0.57*	0.65*	0.49*	-0.49*	0.19*	0.30*
R&C	0.51*	0.67*	0.39*	-0.62*	0.28*	0.21*
Consumer Goods	0.47*	0.50*	0.37*	-0.47*	0.07	0.17*
Services	0.56*	0.64*	0.49*	-0.26*	0.22*	0.43*
Total	0.60*	0.74*	0.52*	-0.57*	0.22*	0.30*

* Correlation coefficient is statistically significant to a 95% level ($p<0.05$).

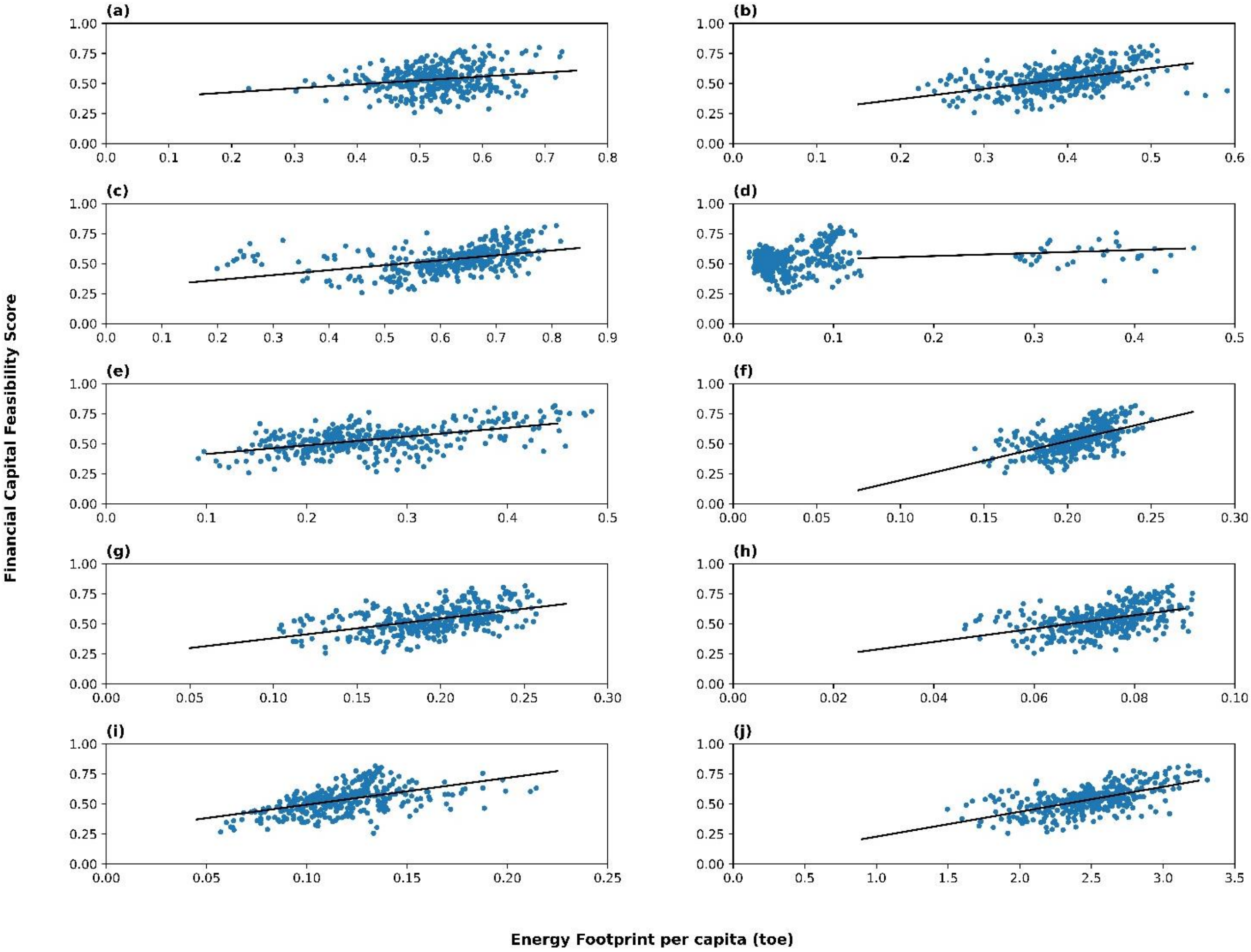

Figure 7.8 Scatterplots of the ESD levels of each LA in GB, modelled in Chapter 5 and the financial capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

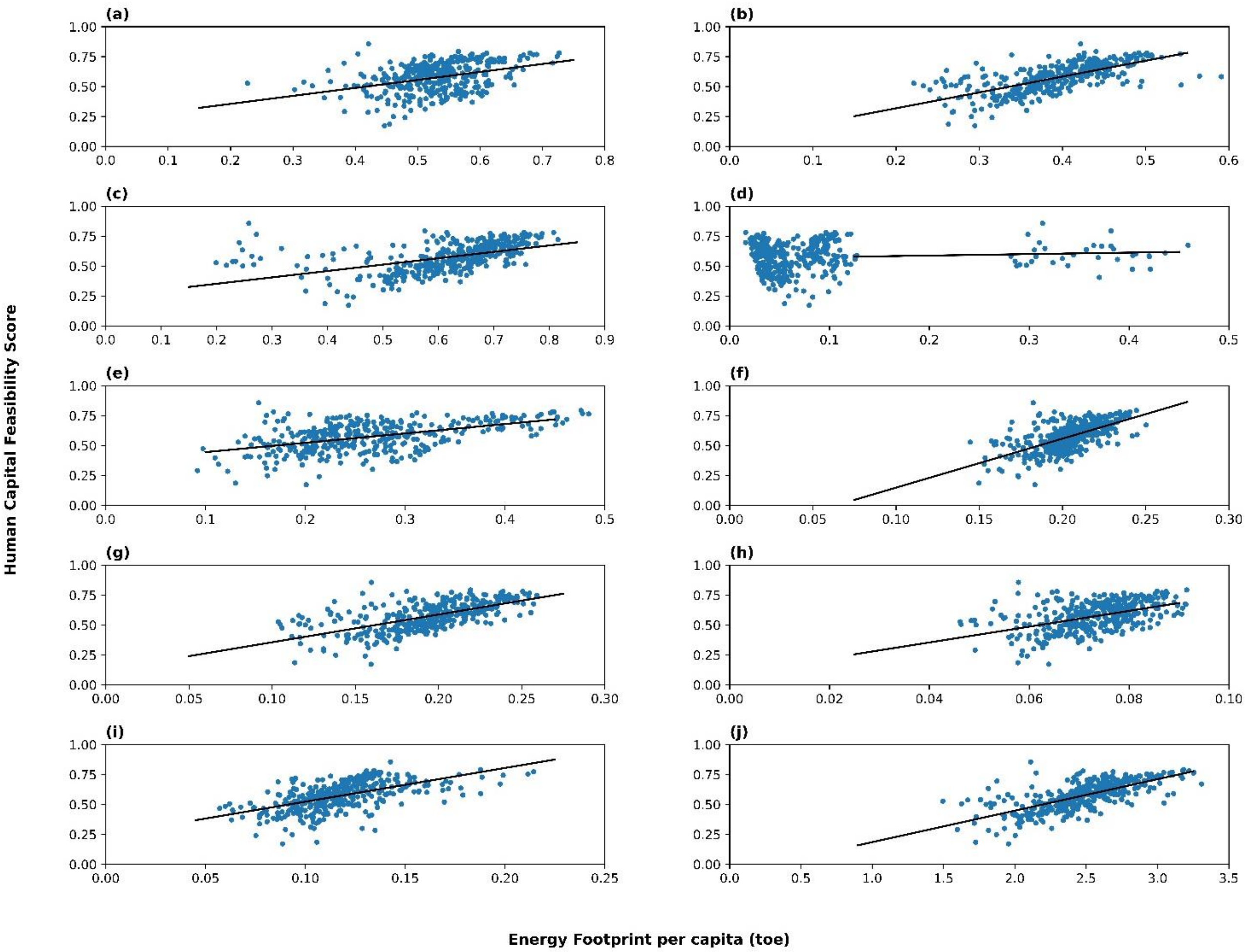

Figure 7.9 Scatterplots of the ESD levels of each LA in GB, modelled in Chapter 5 and the human capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Considering the correlation analysis between ESD levels and the physical capital CI scores of LAs across GB in Table 7.1 and Figure 7.10, the analysis shows that there is no high level of correlation between any ESD category and physical capital CI scores. Five categories display moderate, significant correlation with physical capital (Table 7.1). This therefore implies that high LA ESD levels do not mean that households within LAs have a high level of physical capital to adopt EDR measures, as physical capital is only a moderate indicator of high ESD levels.

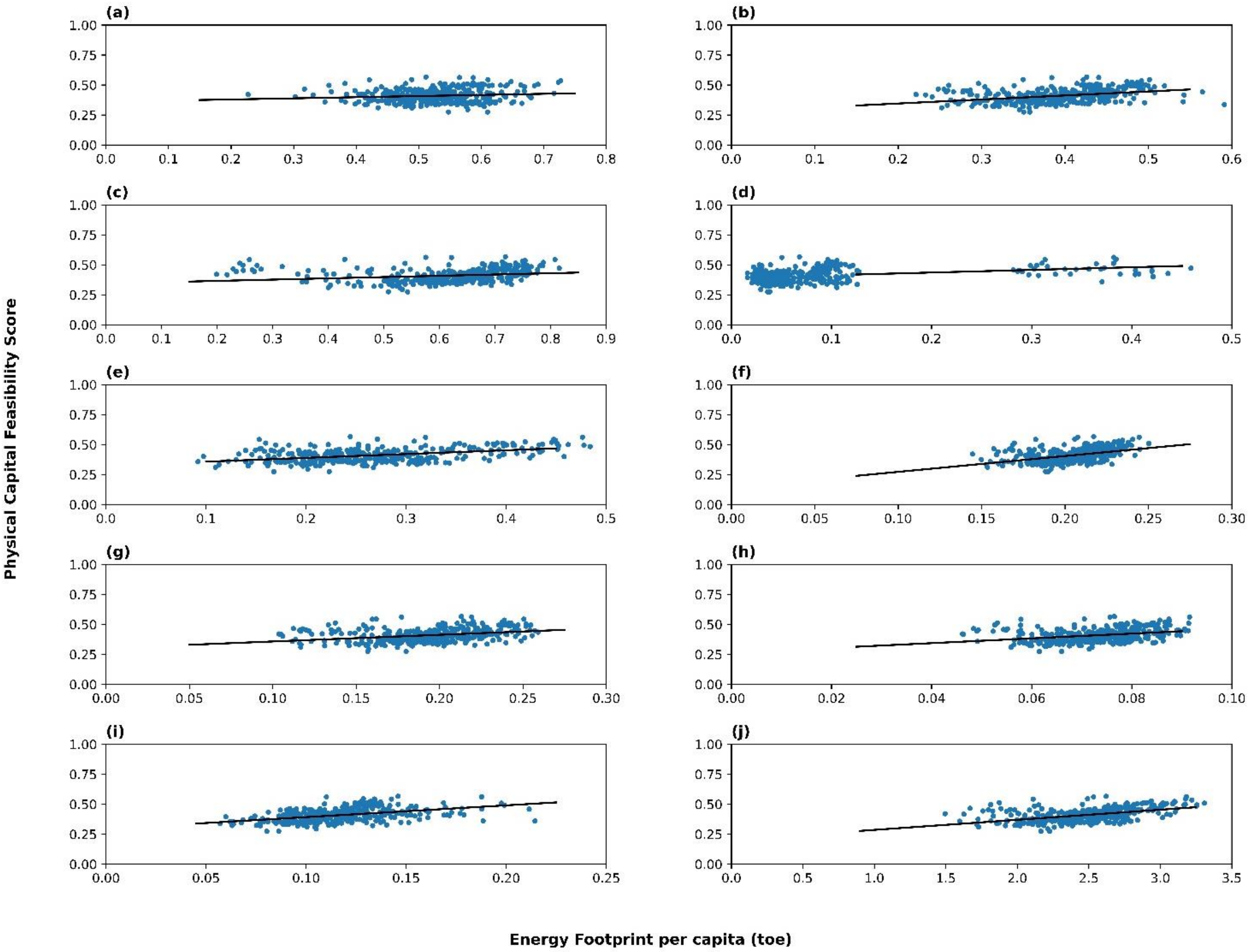

Figure 7.10 Scatterplots of the ESD levels of each LA in GB, modelled in Chapter 5 and the physical capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Compared to the previously analysed capital in Section 7.2, the scores for natural capital display a negative, rather than a positive correlation (Figure 7.11) (Table 7.1). This means that as ESD levels increase, the levels of natural capital possessed by a household decreases in each LA throughout GB.

Table 7.1 shows that other shelter ESDs and recreation & communication ESDs display high levels of negative correlation with natural capital, while other categories exhibit moderate to low correlation coefficients with the natural capital CI scores for all LAs in GB (Table 7.1). This therefore implies that as levels of household ESDs increase, households with higher ESD levels are less able to adopt EDR measures than households with lower ESD levels.

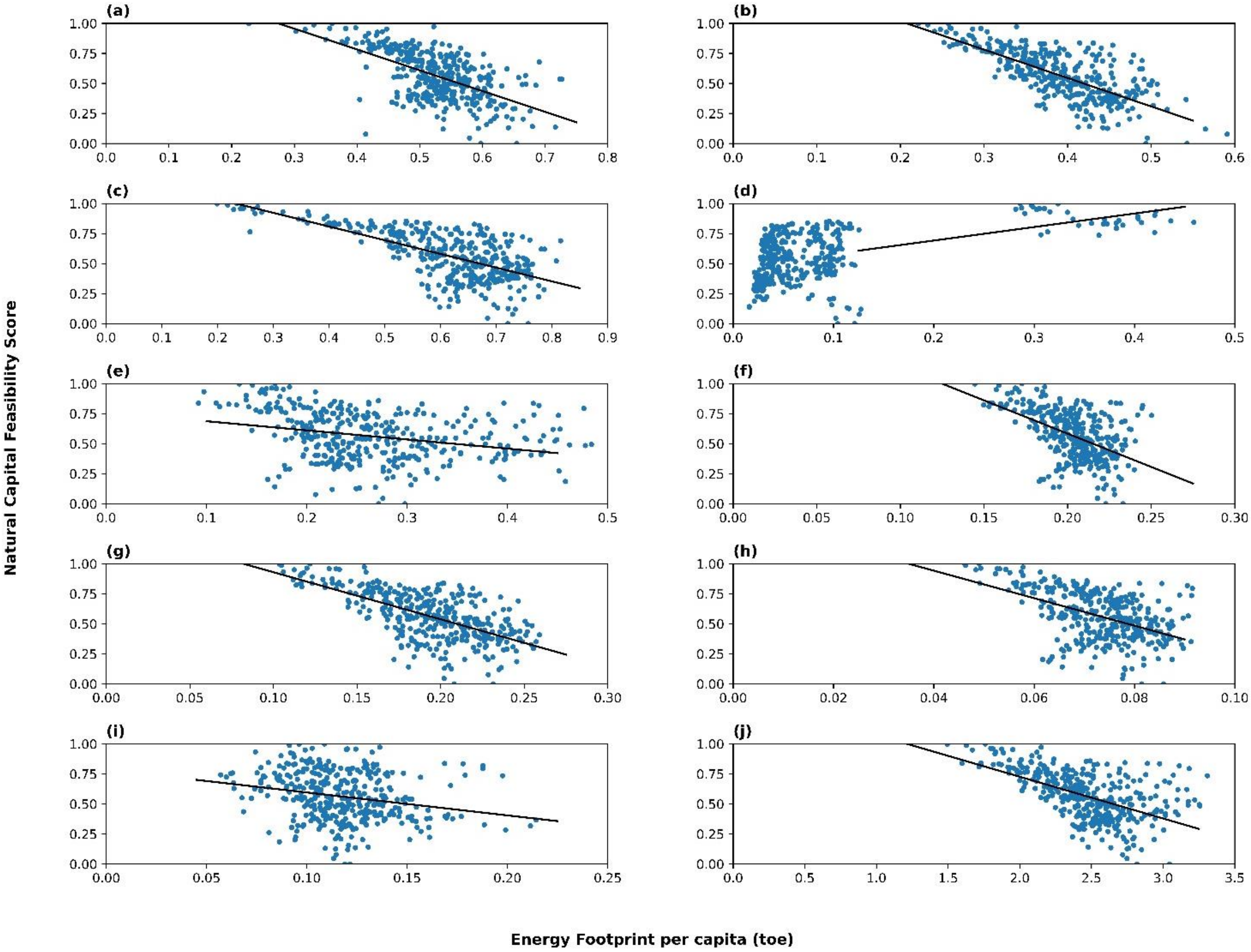

Figure 7.11 Scatterplots of the ESD levels of each LA in GB, modelled in Chapter 5 and the natural capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

The final individual capacity dimension examined in Section 7.2 is social capital. ESD levels and social capital display positive correlation across all categories, with the exception of public transport ESDs (Table 7.1) (Figure 7.12). However, the correlation between all ESD variables and social capital CI scores is weak. This implies that ESD levels and social capital are not coupled in GB, meaning that areas of high ESDs do not have higher social capital CI scores, and therefore have similar capacity to adopt EDR measures as in other areas of GB.

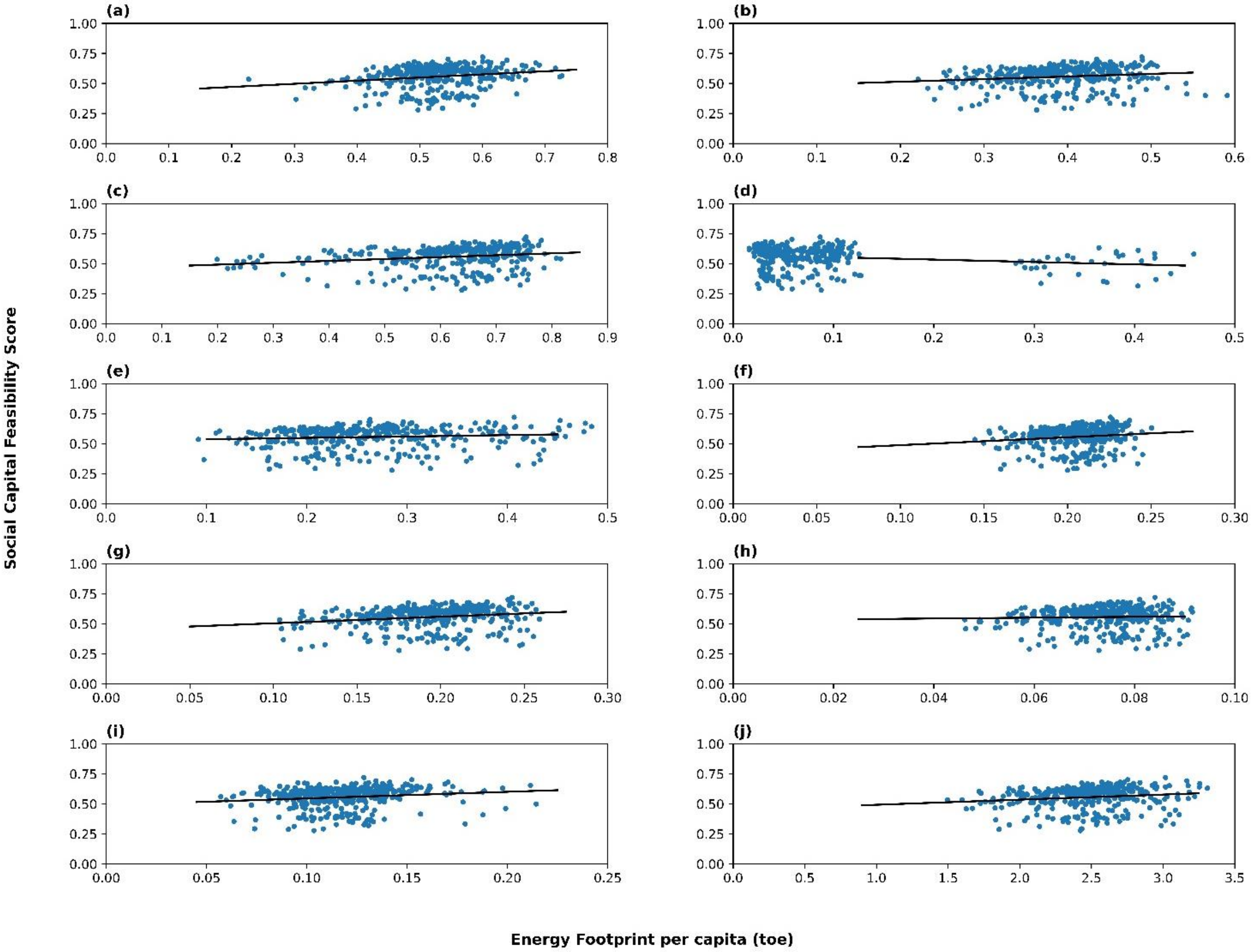

Figure 7.12 Scatterplots of the ESD levels of each LA in GB, modelled in Chapter 5 and the social capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

Finally, a correlation analysis of the ESD levels for all LAs in GB, modelled in Chapter 5, and the combined CI score for all capital shows a positive correlation with the scores, with the exception of heating ESDs (Table 7.1) (Figure 7.13). This implies that as ESD levels rise, so too does the capacity of households within LAs to adopt EDR measures. However, the correlation is weak for many ESD categories and all capital (Table 7.1).

Considering heating ESDs in Table 7.1 suggests that areas with high heating ESDs do not have capacity to adopt measures which could reduce ESD levels. As previously mentioned, heating ESDs are an essential energy service, and households across all LAs throughout GB have a relatively high level of heating ESDs, compared to other ESD categories, whether they are affluent or not (Chapter 5). The results in Table 7.1 and Figure 7.13 means that LAs with high consuming households of heating ESDs do not have greater capacity to adopt EDR measures than LAs with lower levels of heating ESDs.

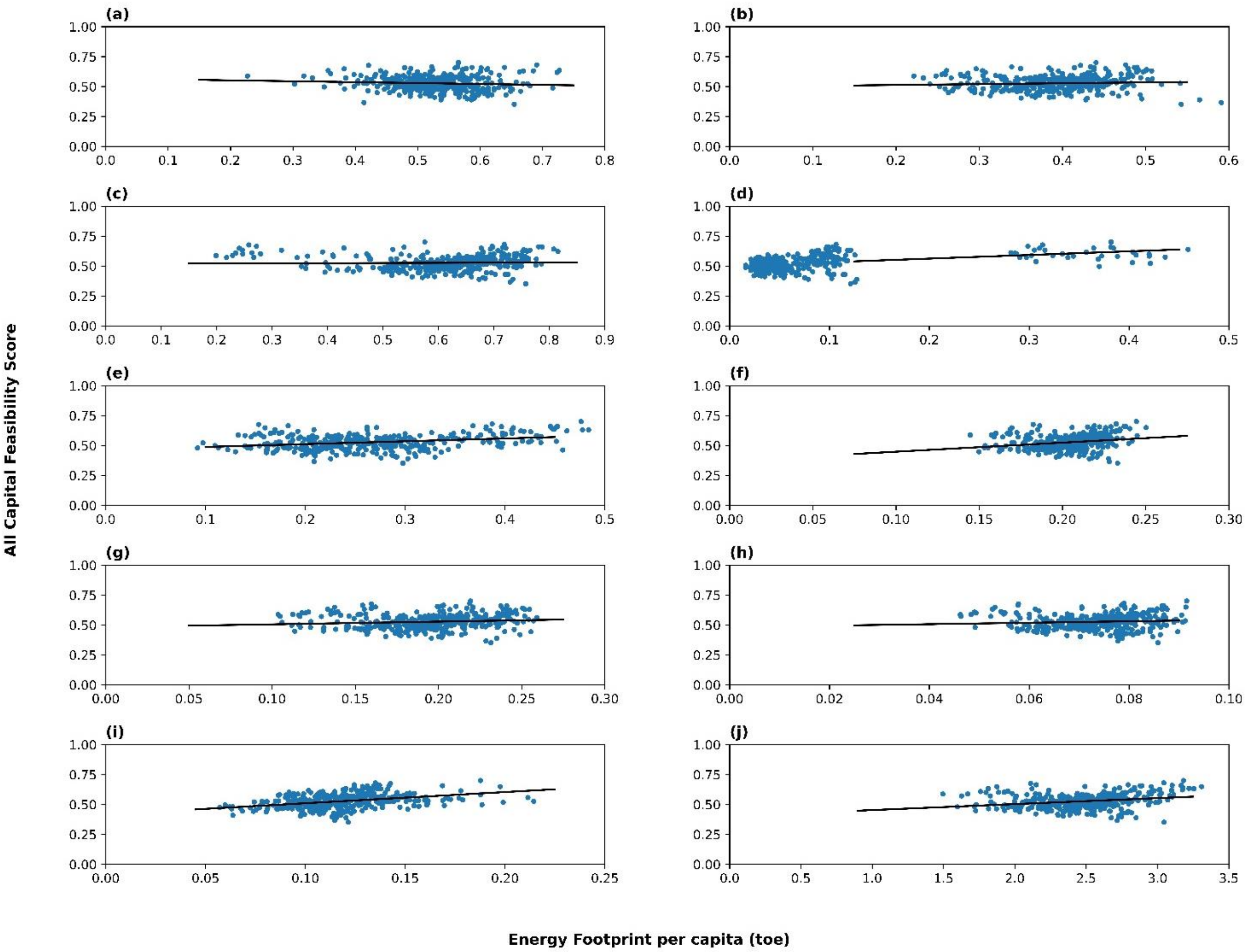

Figure 7.13 Scatterplots of the ESD levels of each LA in GB, modelled in Chapter 5 and the all capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

The results in Section 7.1, for 'all capital' suggested that a disaggregated approach to EDR would be an appropriate method of devising EDR strategies across GB when considering all capital CI scores. The results in Section 7.2.1 also show that all capital CI scores increase with energy consumption – with the exception of heating ESDs, an essential ESD – meaning that LAs containing households with greater capacity to adopt EDR measures generally have larger ESD footprints. The correlation between the heating ESD values and all capital CI scores reinforces previous work that has shown that consumption of essential services, such as heating, remains high amongst less affluent households (Kaygusuz, 2011; Owen and Barrett, 2020). Therefore, all households must reduce ESDs for heating, whereas for other ESDs, more affluent households must make a greater effort to reduce ESDs than less affluent households.

Chapter 5 modelled ESD levels across GB, while Chapter 6 modelled EDR for LAs throughout GB. Section 7.2.1 examined the ESD levels in Chapter 5 in the context of the CI scores generated in

Section 7.1. Section 7.2.2 will therefore consider the levels of EDR modelled in Chapter 6 with the CI scores generated in Section 7.1.

7.2.2 EDR and household capacity

As the full consideration (FC) strategy was the most comprehensive strategy modelled in Chapter 6, the analysis in Section 7.2.2 will consider this strategy alongside the CI scores for all the capital dimensions analysed in Section 7.1, as well as all capital. However, the correlation coefficients for EDR levels and CI scores will be considered collectively in this section.

Table 7.2 Correlation analysis of the FC strategy EDR potentials in Chapter 6 and the CI scores in Section 7.1 of all LAs in GB. Red cells highlight very weak correlation coefficients between variables, orange cells highlight weak correlation coefficients between variables, yellow cells highlight moderate correlation coefficients between variables, light green cells represent strong correlation coefficients between variables and dark green cells represent very strong correlation coefficients between variables.

	Financial Capital	Human Capital	Physical Capital	Natural Capital	Social Capital	All Capital
Heating	0.11*	0.05	0.04	-0.07	0.07*	0.09
Other Shelter	0.15*	0.08	0.08	-0.07	0.14*	0.10*
Personal Transport	0.21*	0.18*	0.10	-0.10	0.14*	0.17*
Public Transport	-0.06	-0.06	0.07	0.05	0.05	0.03
Aerial Transport	0.02	-0.06	0.06	0.01	0.03	0.01
Nutrition	0.16*	0.06	0.04	-0.06	0.12*	0.10
R&C	0.10	0.01	0.01	0.03	0.02	0.06
Consumer Goods	0.10*	0.03	0.00	0.02	0.11*	0.09
Services	0.01	0.05	-0.04	0.01	0.00	0.00
Total	0.21*	0.11*	0.07	-0.06	0.13*	0.15*

* Correlation coefficient is statistically significant to a 95% level ($p<0.05$).

The correlation analyses in Table 7.2 show predominantly very weak correlation between LAs modelled to have high levels of EDR in GB, and LAs with high CI scores, with the exception weak correlations for EDR levels under the FC strategy for personal transport ESDs and total ESDs and financial capital. The weak correlation can be viewed in Figure 7.14, Figure 7.15, Figure 7.16, Figure 7.17, Figure 7.18 and Figure 7.19.

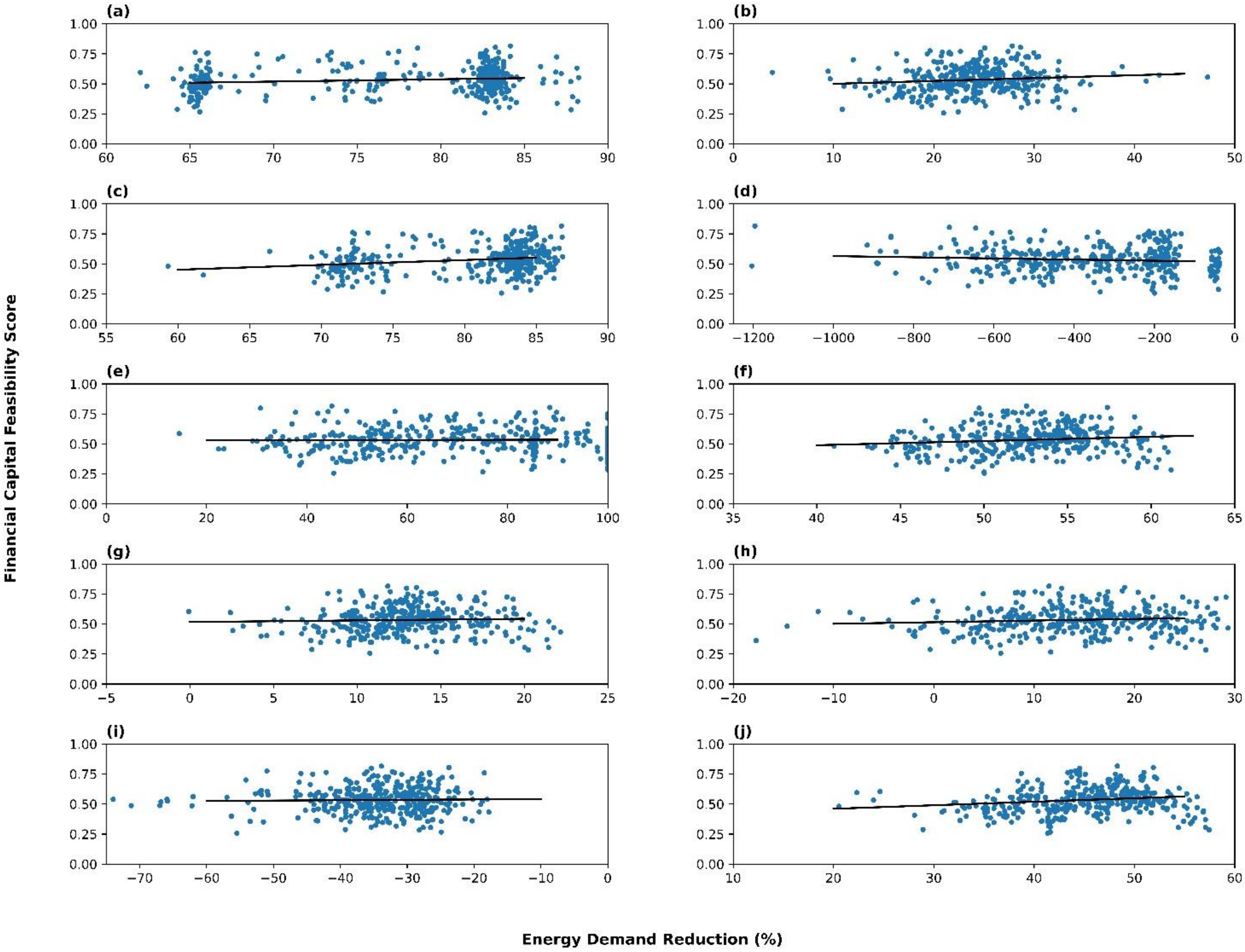

Figure 7.14 Scatterplots of the EDR levels of each LA in GB under the FC strategy, modelled in Chapter 6 and the financial capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

In addition to the weak correlation coefficients in Table 7.2, the Spearman's Rank analysis suggests that many of the coefficients generated by the correlation analysis are insignificant. It is therefore likely that the coefficients generated in Table 7.2 occurred by chance, and therefore cannot be used to assess whether LAs modelled to have high levels of EDR also possess high CI scores for different types of capital.

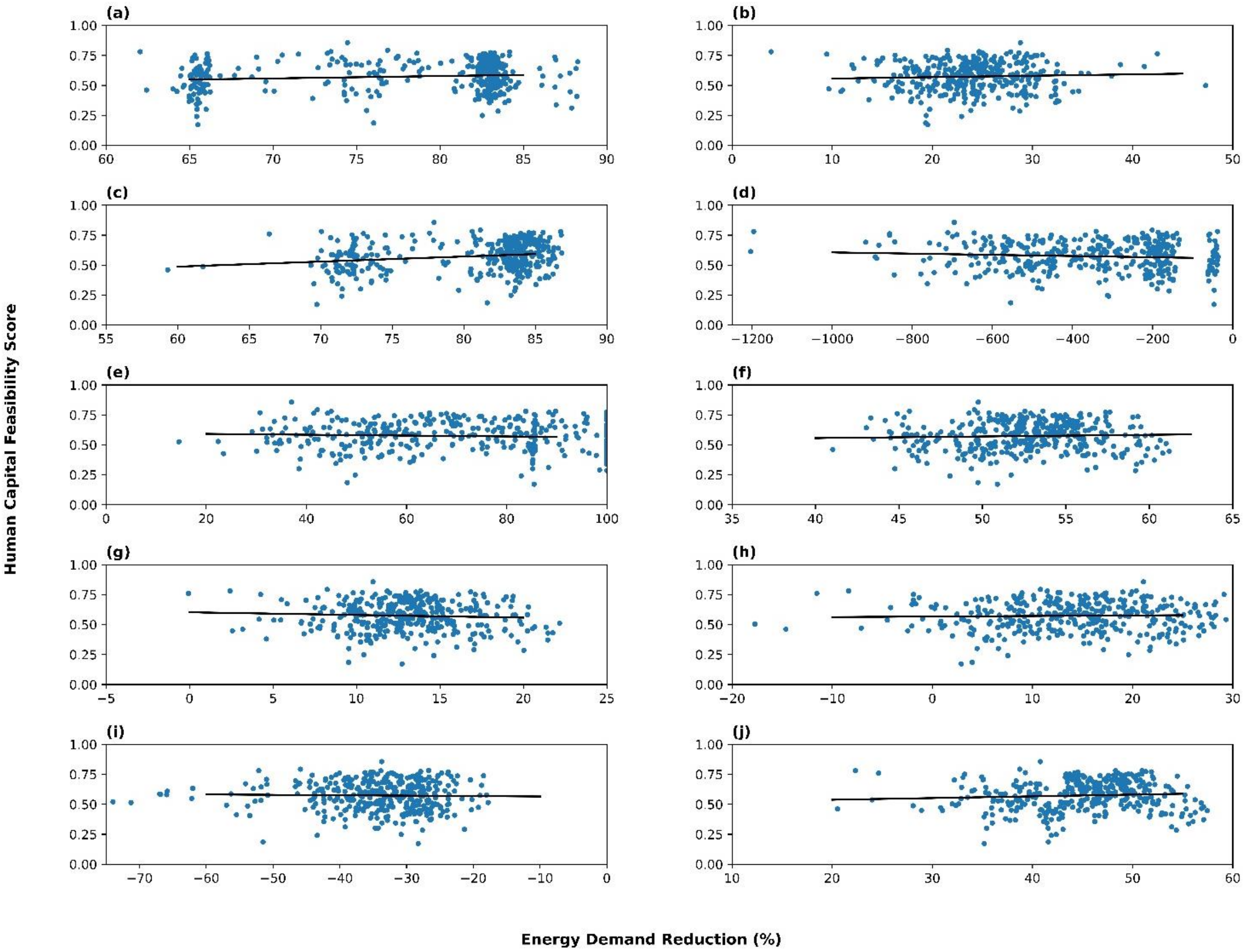

Figure 7.15 Scatterplots of the EDR levels of each LA in GB under the FC strategy, modelled in Chapter 6 and the human capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

The only two correlation coefficients in Table 7.2 which are not classed as 'very weak' are between financial capital and the level of EDR for personal transport and total ESDs under the FC strategy (Figure 7.14(c); Figure 7.14(j)). Instead these two ESD categories and the level of EDR for that category modelled under the FC strategy suggest a weak, but statistically significant, correlation coefficient between the ESD categories and their respective EDR in Chapter 6.

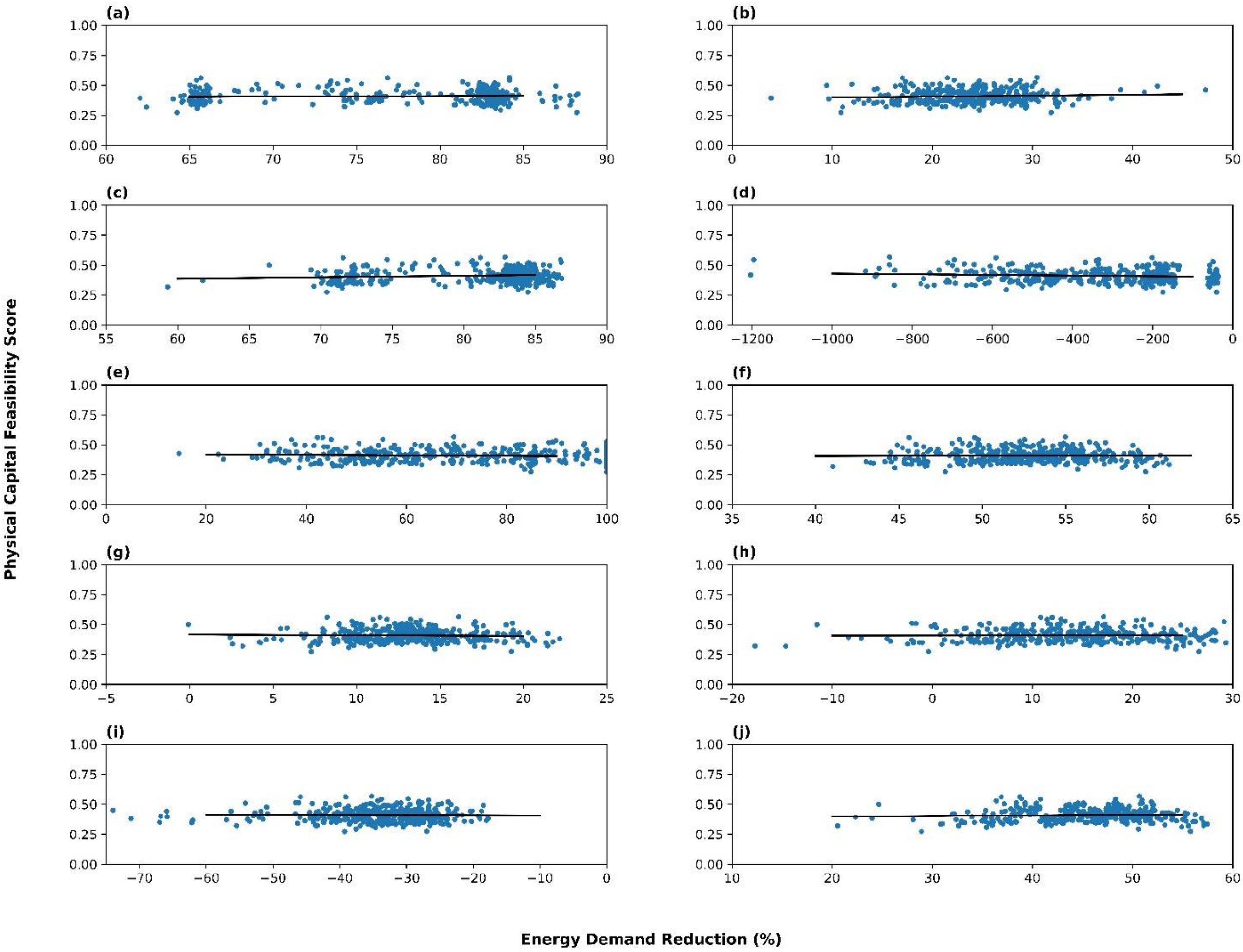

Figure 7.16 Scatterplots of the EDR levels of each LA in GB under the FC strategy, modelled in Chapter 6 and the physical capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

The weak, but statistically significant, correlation coefficient between personal transport ESDs, totals ESDs and their respective reduction modelled under the FC strategy in Chapter 6 suggests that utilising this EDR strategy has a greater effect upon households with higher CI scores, but not a large effect (Figure 7.14). These results, combined with the very weak correlation coefficients between the rest of the capital dimensions and ESD categories suggest that a nationally-led approach to EDR under the FC strategy does not have a greater effect upon areas which scored higher CI scores in Section 7.1 (Figure 7.15; Figure 7.16; Figure 7.17; Figure 7.18; Figure 7.19).

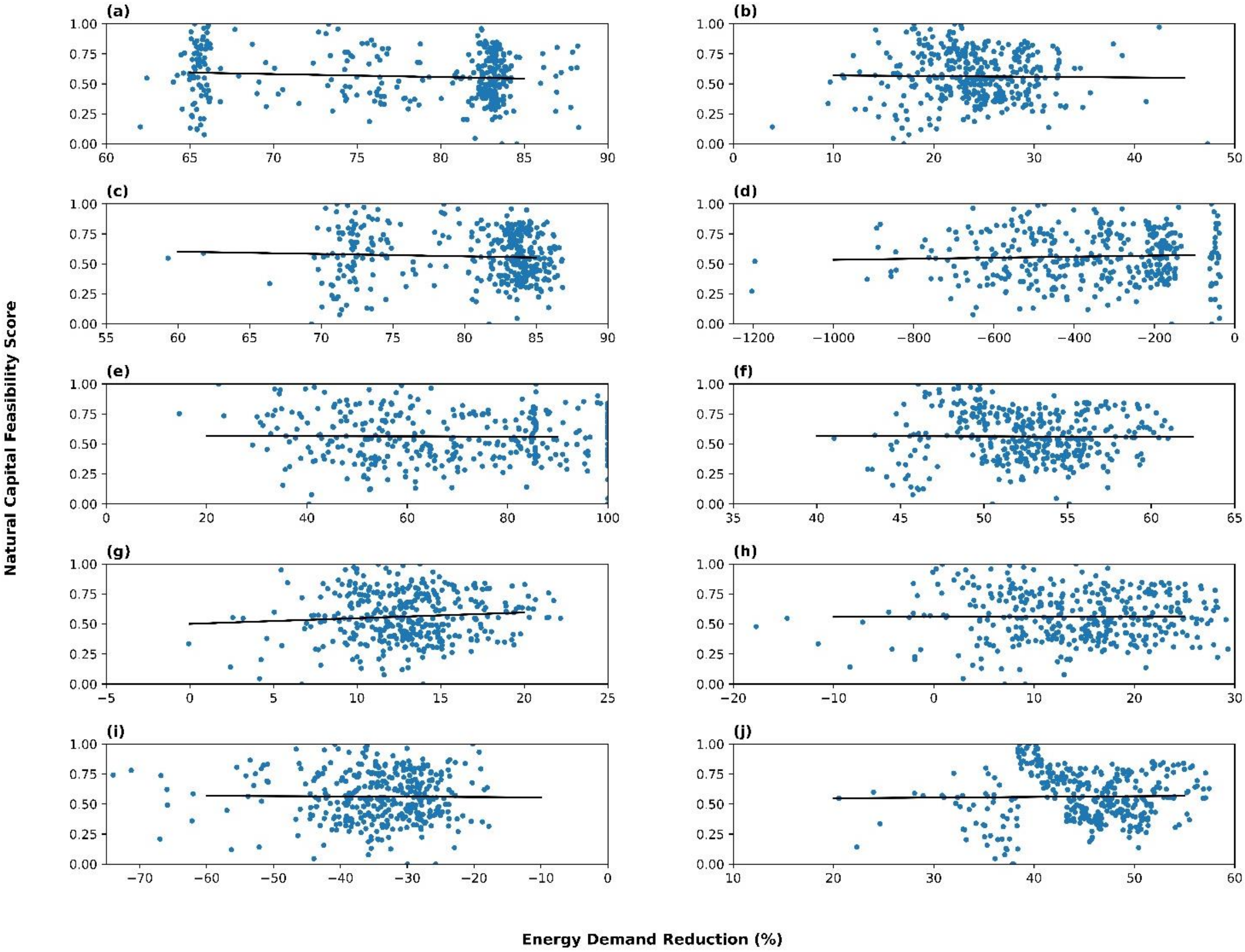

Figure 7.17 Scatterplots of the EDR levels of each LA in GB under the FC strategy, modelled in Chapter 6 and the natural capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

The very weak correlation coefficients across all the capital dimensions, including all capital show that implementing a universal approach to EDR at a national-level would not affect LAs of higher capacity to adopt EDR measures to a greater extent than LAs with lower CI scores. The FC strategy would therefore be an unjust, inequitable strategy to implement within GB without a more targeted approach to EDR, as under the current version of the FC strategy, LAs which have lower capacity to adopt EDR measures, would experience greater EDR than other LAs which have greater capacity to adopt EDR measures.

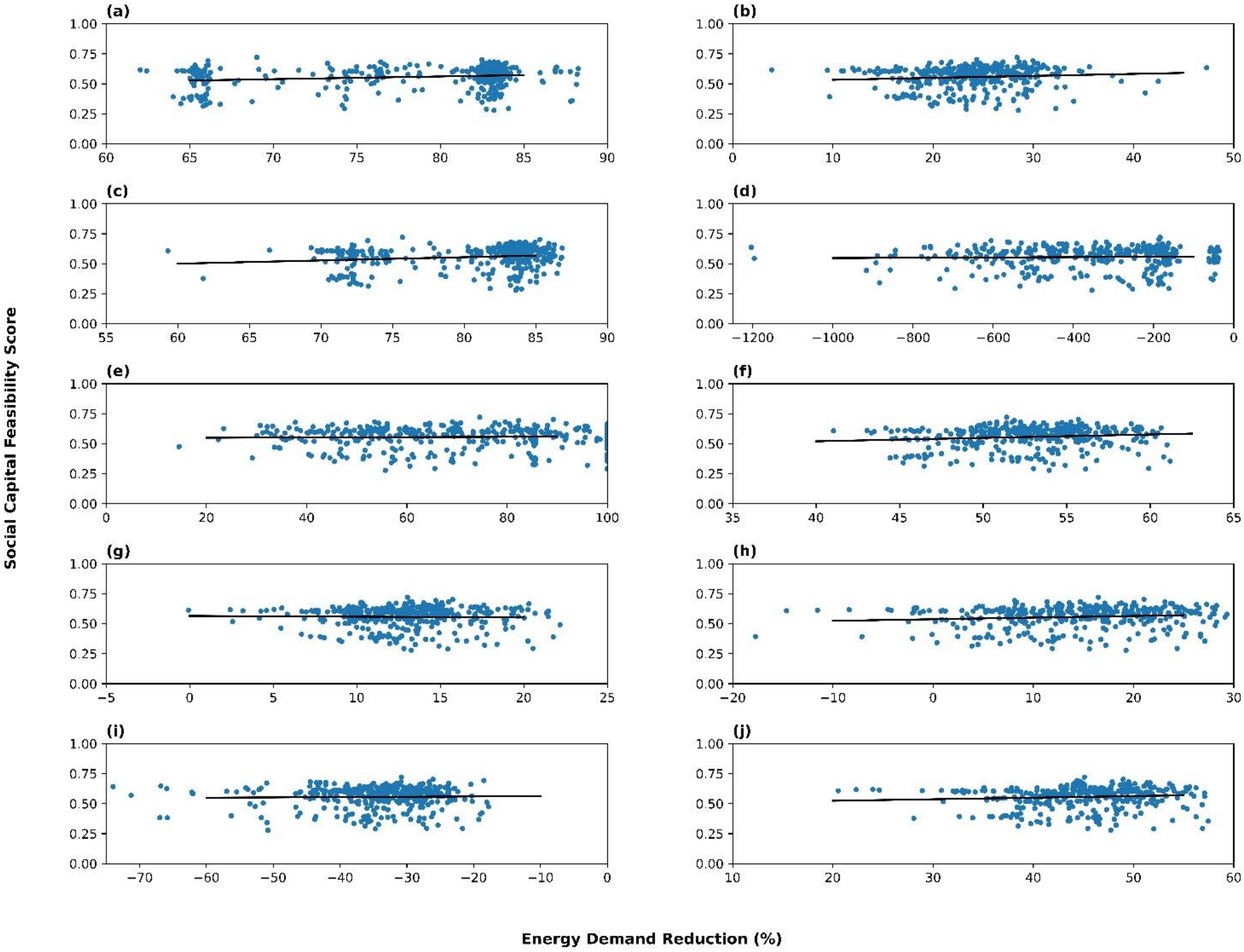

Figure 7.18 Scatterplots of the EDR levels of each LA in GB under the FC strategy, modelled in Chapter 6 and the social capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

The results in Section 7.2.2 therefore show that a national approach to EDR without any consideration of household capacity to act across GB would lead to an unjust demand-side transition which could compromise the wellbeing of households to meet their needs. Therefore, the results of the correlation analysis between EDR under the FC strategy and CI scores reinforce the results in Section 7.1 that consideration needs to be given to household capacity to adopt EDR measures in each LA, and that a disaggregated approach to EDR would benefit the demand-side transition.

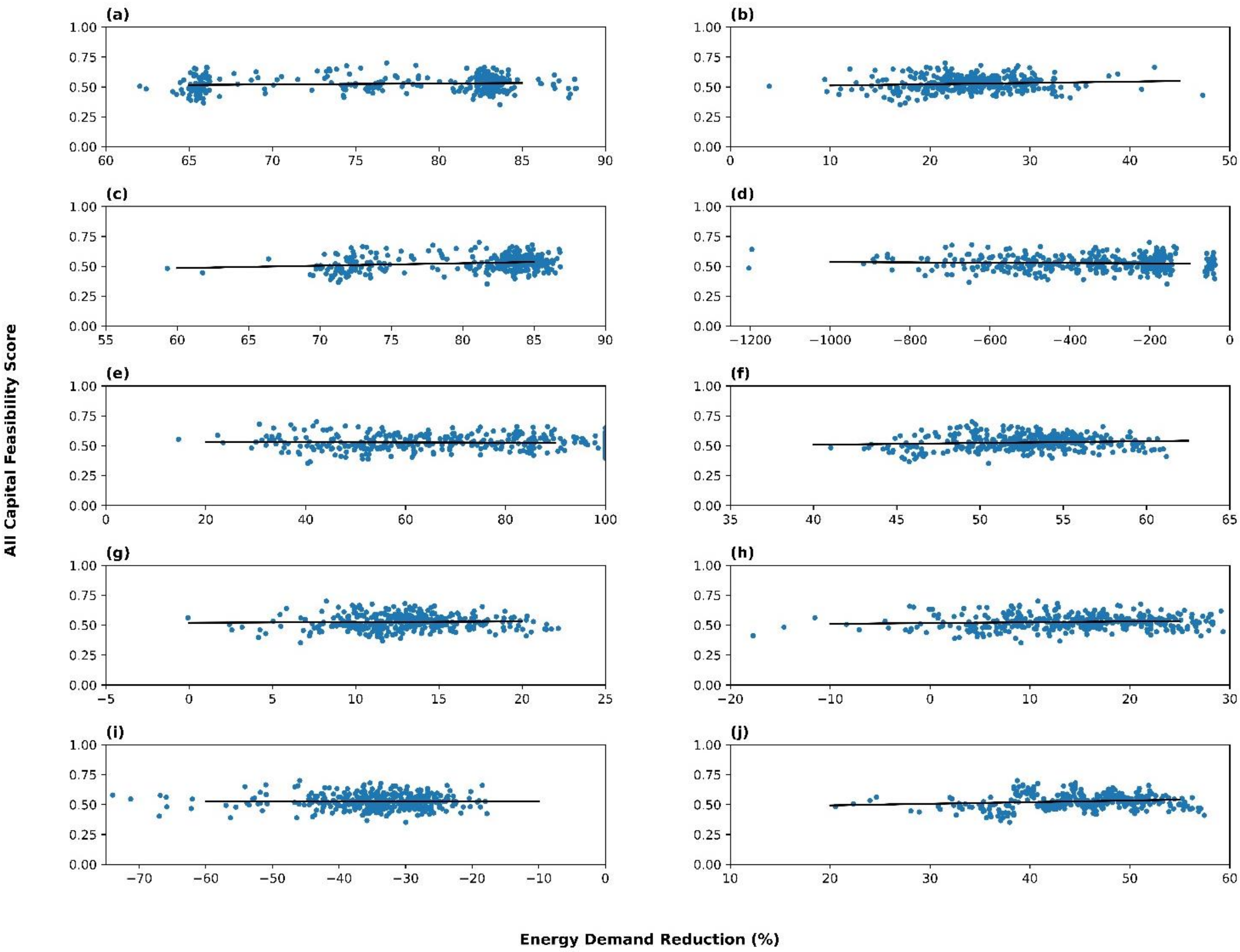

Figure 7.19 Scatterplots of the EDR levels of each LA in GB under the FC strategy, modelled in Chapter 6 and the all capital CI scores generated in Section 7.1. The graphs in the above are (a) heating, (b) other shelter, (c) personal transport, (d) public transport, (e) aerial transport, (f) nutrition, (g) recreation & communication, (h) consumer goods, (i) services and (j) the total ESD footprint.

However, the results in Section 7.2 do not suggest whether a LA-specific approach or a regional approach to EDR, set out at a national-level, would be more appropriate for EDR in GB. More research therefore needs to be undertaken in order to assess the costs, benefits and EDR potential of disaggregated approaches to EDR at the LA-level. However, assessing further EDR strategies is beyond the scope of this thesis.

To conclude, when considering all capital CI scores and the EDR potential of the FC strategy (Figure 7.19) (Table 7.2), the results demonstrate that a nationally-led approach, implementing all measures universally across GB would lead to an unjust transition. Therefore, consideration by policymakers must be given to either devolving more powers, as well as increased funding to LAs, to allow LAs to act upon climate targets and net-zero plans, or developing a regional approach to EDR which reduces energy consumption for ESDs across different areas of LAs throughout GB without compromising the wellbeing of households in these areas.

7.2.3 Summary
Section 7.2 analysed the ESD levels of each LA throughout GB modelled in Chapter 5, and the EDR levels by LA under the FC strategy, modelled in Chapter 6, with the CI scores generated in Section 7.1. Section 7.2.1 shows that moderate to strong correlation between the level of ESDs by category, modelled in Chapter 5, and the CI scores across the individual capacity dimensions, with the exception of social capital. The results therefore suggested that LAs with higher household ESDs also exhibited greater capacity to adopt national-level EDR measures and strategies.

Conversely, Section 7.2.2 showed that the level of EDR modelled by each LA, under the FC strategy, does not align with the CI scores generated in Section 7.1. The lack of correlation between the EDR and CI scores for each capital dimension suggests that a universal FC strategy would compromise the wellbeing of households in areas with less capacity to adopt EDR strategies and measures. This implies that a disaggregated approach to EDR may be more just than simply enacting a national-level strategy which affect all LAs across GB as this strategy does not target areas of high consumption. A LA-specific approach to EDR needs to be considered going forward in order to ensure an effective and just transition to EDR. This will be discussed in more detail in Chapter 8.

7.3 Chapter summary
Chapter 7 examines the capacity of households throughout GB to adopt a national-level FC strategy. Section 7.1 analysed five individual capital dimensions using a CI – financial capital (Section 7.1.1), human capital (Section 7.1.2), physical capital (Section 7.1.3), natural capital (Section 7.1.4) and social capital (Section 7.1.5) – as well as the CI scores for the combined category of all capital category (Section 7.1.6).

Section 7.1 demonstrates that the national average household capacity remains similar across all the capital dimensions, with the exception of physical capital. However, the variation across LAs is within each dimension of capacity is much larger than the national average values suggest. With the exception of natural capital, which focuses upon only one sub-component, human capital has the largest range of CI scores across GB, with a range of 0.68, while physical capital has the lowest range of 0.29. This suggests that poverty factors, such as proportion of fuel-poor households, and other human factors, such as the median age of the population, vary more across GB than the level of public transport infrastructure and the proportion of owner-occupied housing by LA. Similarly, the values in the financial capital dimension range have a range of 0.56 (0.26 to 0.82), also suggesting that the range in financial capital is larger than other capital dimensions when considering EDR in GB.

The results for all capital in Section 7.1.6 show that there are clusters of LAs within GB with similar CI scores, which is confirmed by the Moran's I value indicating high clustering of areas with similar

CI scores for all capital (Robinson and Mattioli, 2020). These results suggest that a disaggregated approach to EDR may be necessary to avoid households throughout GB compromising their wellbeing to enact EDR strategies, however, the results suggest that a regional approach, set out at a national-level due to the administrative nature of many of GB's region, rather a LA-specific approach to EDR may be effective.

Section 7.2 then analysed the LA-level CI scores against LA-level ESD levels from Chapter 5 and the LA-level EDR potentials from Chapter 6 using correlation analyses to assess whether areas of high ESDs and high EDR under the nationally-led FC EDR strategy, correlate with areas exhibiting high CI scores. Section 7.2.1 showed moderate and high levels of correlation between LAs with high ESDs, modelled in Chapter 5, and areas with high CI scores across many capital dimensions, and all capital, with the exception of social capital. However, the level of EDR modelled in Chapter 6 does not correlate with areas of high CI scores, meaning that EDR undertaken in a similar manner to the FC strategy, may compromise the wellbeing of households throughout GB if the approach to EDR is not disaggregated either regionally or locally. A regional or LA-specific approach to EDR may therefore be the most effective way to bring about an effective, just transition in GB, than a nationally-led strategy.

Section 7.2 attempted to draw the threads of the thesis results chapters together. The discussion chapter of the thesis in Chapter 8 will expand upon the results in all the results chapters (Chapter 4 – Chapter 7), and examine cross-cutting themes present throughout the results chapters.

8 Discussion

Chapters 4 to 7 have addressed the research gaps identified in Section 1.4, by answering the research questions in Section 1.2. Chapter 8 will therefore form the discussion section of the thesis.

Section 8.1 will consider the broader implications of Chapters 4 to 7 in the context of wider literature and policy, and will be structured based upon the chapter structure of the thesis. Section 8.1.1 will examine the service-driven energy demand chain (SEDC) framework to assess the benefits that can be gained from using this framing within a local context compared to other energy system frameworks. Section 8.1.2 will consider the Local Authority (LA) level energy service demands (ESDs) alongside footprinting studies, and the sub-national energy consumption data published by the Department of Business, Energy and Industrial Strategy (BEIS), to establish the similarities and differences between the results in Chapter 5 and previous work. Section 8.1.3 discusses the modelled results of the four EDR strategies in Chapter 6 – the energy efficiency, maintained service level (MSL), reduced service level (RSL) and full consideration (FC) strategies – in comparison to similar studies, and also considers the LA-level variation in EDR potential across GB. Finally, Section 8.1.4 examines the feasibility of implementing the four EDR strategies in Chapter 6 in GB, by considering scores, generated through a capacity index (CI) analysis, and the correlation analysis between LAs exhibiting high levels of ESDs, EDR and CI scores in Chapter 7.

Following Section 8.1, Section 8.2 will move beyond contextualising the research in Chapters 4 to 7, and identify the themes which cut across the research questions set out in Section 1.2. Section 8.2.1 will consider the analysis of ESDs at a LA-level in Great Britain (GB), and discuss the benefits of analysing a consumption-based account of ESDs, rather than energy demand, in detail at a small spatial scale. Section 8.2.2 will consider the role of energy efficiency as an EDR strategy in GB, its effect across space, and the implications of the results in Chapter 6 for EDR policy going forward. Finally, Section 8.2.3 will consider the governance of EDR in GB, the effect of national-level approaches to EDR upon different LAs throughout GB, and the role of subsidiarity in the transition to a low energy demand society.

8.1 Research findings in the context of wider literature and policy

8.1.1 The service-driven energy demand chain framework

The SEDC framework was developed in Chapter 4 and has been used to visualise a services framing of the whole energy system from a LA perspective, as well as the potential EDR intervention points used in Chapter 6. The SEDC framework set out a services-oriented perspective of the entire energy system from a LA perspective by reversing the traditional direction of energy system analysis, thereby placing ESDs as the starting point, rather than the end-goal, of the energy system (Nørgård, 2000). ESDs link the technical energy system to household wellbeing, meaning that wellbeing considerations of households within are taken into account at the start of a demand-side analysis (Brand-Correa *et al*., 2018). Additionally, the inclusion of indirect energy within the production system in the SEDC framework ensures that the full scope of energy associated with delivering ESDs to households within a LA is considered (Chapter 4) (Barrett *et al.*, 2013; Creutzig *et al.*, 2018; Ivanova *et al.*, 2020).

The SEDC framework was designed around considering ESDs and EDR in a local context, with the aim of highlighting the potential of a consumption-based approach to EDR, and the effect of household influence upon the entire energy system (Figure 8.1) (Moran *et al.*, 2018; Ivanova *et al.*, 2020). Framing ESDs and EDR from a services perspective aimed to link LA-level household consumption with the globalised energy supply chain and production system to remove the geographical separation between production and consumption (Tingey and Webb, 2020).

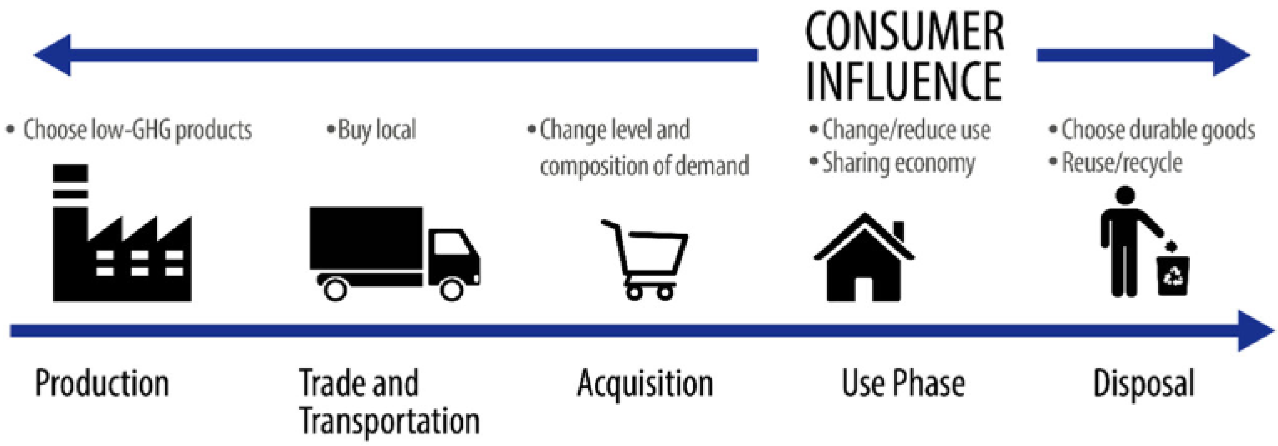

Figure 8.1 The potential effects of households upon the energy chain (Image source: Moran *et al.*, 2018).

As stated previously, LAs do not have specific powers to enact energy policy that would decarbonise the energy supplied to households within their localities (Figure 2.4 and Figure 2.5) (Smith, 2007; Ellis *et al.*, 2013; Cowell *et al.*, 2015, 2017), but are often more ambitious than the UK national-level government when considering emission reduction targets (Figure 1.7) (CCC, 2020). Utilising a policy framework which focuses purely on stages of the technical energy system (Figure 8.2), would not be effective in reducing energy demand at a LA-level (Tingey and Webb, 2020). The SEDC framework therefore provides an interdisciplinary perspective of the energy system which LAs can use to consider EDR options.

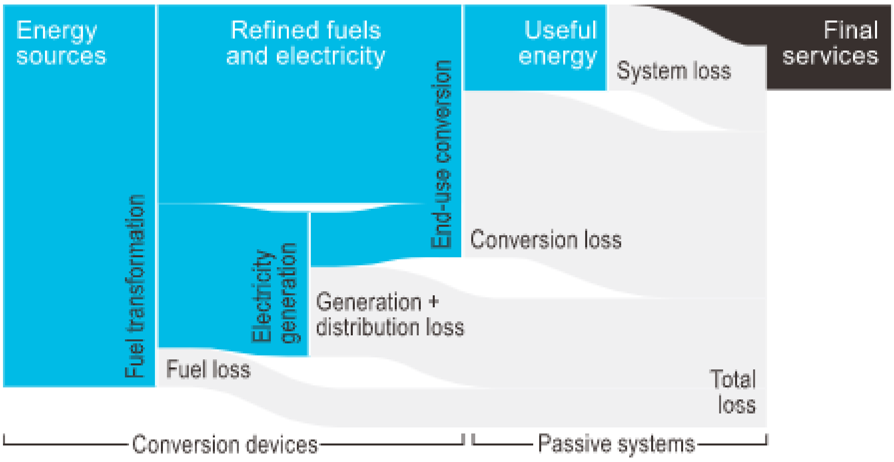

Figure 8.2 Framework of the technical energy system. (Image source: Cullen and Allwood, 2010).

Additionally, the link between the technical energy system and wellbeing in the SEDC framework is important, particularly in a local context. The SEDC framework facilitates questions around how energy consumption for different ESDs could be reduced within a LA without compromising the wellbeing of households (Creutzig *et al.*, 2018). In a local context, this is especially important as the decisions undertaken by LAs – e.g. removing bus routes or building roads – can have direct impacts upon wellbeing, as well as household ESDs (Royston *et al*., 2018). Few frameworks consider the full energy chain – from energy supply to wellbeing – within their boundaries meaning that wellbeing may be neglected from technical studies, and technical considerations may be neglected from wellbeing studies (Table 2.3) (Nørgård, 2000; Brand-Correa *et al*., 2018).

The SEDC framework therefore contributes to the literature on policy frameworks by considering the energy system in the context of subsidiarity, and a disaggregated approach to EDR. The SEDC framework has a number of advantages over energy system frameworks set out by previous studies. Firstly, the SEDC framework places household energy consumption into a local context by beginning analysis at this stage of the energy chain, as this is the stage which takes place in each individual LA throughout GB (Nørgård, 2000; Brand-Correa *et al*., 2018). Secondly, the SEDC framework places less focus upon the technical energy system than previous frameworks, e.g. Hafele, (1977); Nakićenović *et al*., (1996); Cullen and Allwood (2010b), in order to consider EDR options beyond technical energy efficiency options as LAs have limited control over the technical energy system (Ivanova *et al.*, 2020). Finally, LAs can identify which stage of the energy chain a consumption-based policy (Ivanova *et al.*, 2020), implemented at a LA-level, would affect, therefore allowing for targeted EDR action based upon whether LAs are aiming to reduce direct and indirect energy.

The SEDC framework was used in Chapter 6 to demonstrate which stage of the energy chain that each consumption-based policy option modelled in each of the four EDR strategies would affect.

However, before undertaking EDR modelling across GB, the LA-level ESD footprints needed to be modelled in Chapter 5 to assess household ESDs across space, and provide a baseline from which the EDR strategies could be modelled in Chapter 6.

8.1.2 Local Authority energy service demands in Great Britain

The ESDs of all LAs across GB were modelled in Chapter 5. Chapter 5 also examined the variation in household ESDs across all LAs, and analysed the ESD data against each LA's underlying socioeconomic factors to identify whether the ESD footprints for LAs aligned with analysis undertaken by previous footprinting studies upon household-level environmental footprints. Section 8.1.2.1 will discuss the LA-level consumption-based account of GB's ESDs (Section 5.1, Section 5.2 and Section 5.3) in the context of previous literature, while Section 8.1.2.2 will consider the analysis of the ESD footprints and underlying socioeconomic factors in Section 5.4.

8.1.2.1 Local Authority energy service demand footprints

In Chapter 5, total ESDs per capita were higher in the south of England, north of Scotland and outer London, while the LAs with the lowest total ESDs per capita were located in central London (Figure 5.2). Heating and personal transport dominated the ESD footprints of all LAs throughout GB, making up an average of 21.3% and 24.9% respectively of the total energy service footprint across GB (Figure 5.1).

In Chapter 5, heating and personal transport ESDs are modelled as a mix of direct and indirect energy. As stated previously, the UK government maintains records of household direct energy consumption by fuel type and sector at a LA-level, but that these results do not indirect energy (BEIS, 2021d). Figure 8.3 shows the difference between the level of direct energy and the level of total ESDs modelled in Chapter 5 from the Living Costs and Food survey (LCFS). Figure 8.3(a) and Figure 8.3(b) are displayed on the same scale for comparative purposes.

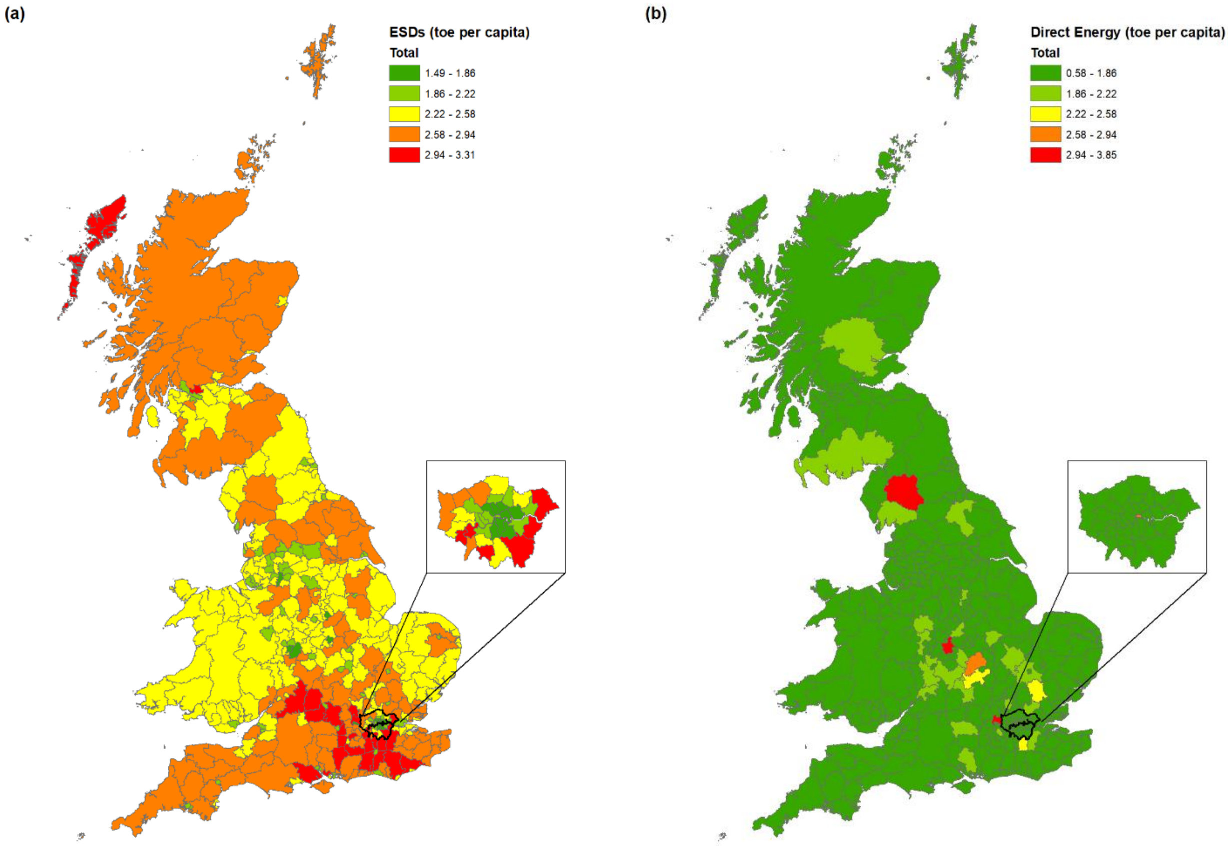

Figure 8.3 Comparison of Total ESDs per capita for each local authority across GB and the direct energy per capita across GB too. Direct energy in Figure 8.1(b) is placed on the same scale as in Figure 5.2 and Figure 8.1(a) for comparative purposes.[21]

Figure 8.3(b) shows that the government statistics, produced by BEIS underestimate the level of energy consumption required to deliver household ESDs across GB (BEIS, 2021d). The difference between the energy consumption accounts modelled in Chapter 5, and the figures produced by BEIS (2021) in Figure 8.3(b) is due to the underlying accounting methodology used to calculate the statistics in Figure 8.3(a) and Figure 8.3(b). Consumption-based accounting has a wider scope for including energy within the production system, as well as final energy consumed by households (Figure 8.3(a)) than the territorial method used to calculate the household energy accounts used in Figure 8.3(b) (Barrett *et al.*, 2013; BEIS, 2021d).

As stated previously, considering a consumption-based account of ESDs in GB widens the scope of ESDs which can be considered and attributed to households within LAs, and also ensures that the

[21] Direct energy data for different fuel types is used in the ESD footprints in Chapter 5 to avoid underestimating direct energy consumption in the footprints, with the exception of transport direct energy consumption data, which is generated from the LCFS. Differences in transport demand data between Figure 8.1(a) and Figure 8.1(b) is the cause of some local authorities in Figure 8.1(b) having higher energy footprints than in Figure 8.1(a), despite the wider scope of consumption-based accounting.

geographical separation of consumption and production, present in territorial accounts of energy, is removed (Barrett *et al.*, 2013; Ivanova *et al.*, 2020; Tingey and Webb, 2020). Additionally, the methodology used to model ESDs in Chapter 5 also allows for national-level totals of energy consumption to be calculated[22], as can be done with the data published by BEIS (2021), ensuring that the ability to move from national to a LA-level, as with territorial calculated data is not compromised in the consumption-based energy footprints accounts (Druckman and Jackson, 2009; Büchs and Schnepf, 2013; Owen and Barrett, 2020).

From a policymaking perspective – as the data in Chapter 5 was used as a baseline from which EDR strategies were modelled – the ESD data provides greater insight into how energy is utilised by households across GB, rather than the quantity of each fuel type delivered to households, as is provided by BEIS (2021) (Morley, 2018). Understanding the quantity of energy delivered to households is not enough when considering equitable EDR as reducing the level of fuel required to deliver energy to households, through efficiency, limits EDR measures and does not address the underlying behaviours driving energy consumption (Morley, 2018).

The ESD footprints modelled in Chapter 5 highlight the variation of energy consumption at a LA-level to fulfil ESDs in GB. The benefits of compact living can be visualised in the ESD dataset, as has been noted in previous studies (Minx *et al.*, 2013). Households in central London have the lowest per capita ESDs for all ESD categories, with the exception of public transport ESDs. Lower environmental footprints in London, have previously been noted by footprinting studies, such as Minx *et al.*, (2013) who examined the carbon footprints of settlements in the UK.

The ESD data in Chapter 5, also suggests that, beyond London, there are no large areas of GB which also exhibit low levels of energy consumption to meet ESDs, as has been modelled in previous studies (Chatterton *et al.*, 2016). The results in Chapter 5, as with previous studies, therefore demonstrate that EDR associated with ESDs can be implemented across all areas of GB, not just affluent LAs – as a link between higher income and higher energy footprints has been established previously (Oswald *et al*., 2020; Owen and Barrett, 2020) – meaning that EDR must not be limited to specific areas of GB. EDR must therefore be implemented in areas where justice issues exist, such as energy poverty, meaning that different EDR measures may not be equitable in different areas of GB[23]. Whether the differences in ESD footprints suggests that EDR should be disaggregated to LAs is discussed in Section 8.2.3.

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[22] Calculating national and regional totals of different ESDs was not undertaken in this thesis, however by adding the ESD totals for each LA modelled in Chapter 5 together, or the LA ESD totals within each geographic region of the UK, the national and regional ESD values can be calculated from the current dataset.

[23] The capacity of households to implement EDR policies will be discussed in more detail in Section 8.1.4.

8.1.2.2 Socioeconomic drivers of energy service demands

Analysing the LA-level ESD footprint data against the underlying socioeconomic factors of each LA in Section 5.4 showed that factors which had previously been identified as strong determinants of household ESD levels were less likely to indicate areas of high or low ESDs at a LA (Table 5.1 and Table 5.2). Although, the exception to this is the high correlation between number of vehicles per household within a LA, and the level of personal transport ESDs per capita for the respective LA (Table 5.1).

However, beyond the traditional determinants of high household ESDs – income, number of vehicles per household and household size – relationships were present between LA-level energy consumption and other underlying socioeconomic determinants of ESD footprints (Table 5.3 and Table 5.4) (Section 5.4). Unemployment rate and population density per squared kilometre were negatively correlated with ESD levels (Table 5.3). Median age of the population was positively correlated with the ESD levels modelled in Chapter 5 (Table 5.3), however, a regression analysis suggested weak relationships between the socioeconomic factors analysed in Section 5.4.1 and ESD levels for all ESDs (Table 5.4).

At a LA-level, unemployment rate has a stronger relationship with ESD levels than average household income. Previous studies have highlighted the link between higher levels of income and higher energy footprints (Zhang *et al*., 2015; Druckman and Jackman, 2016; Wiedenhofer *et al.*, 2018; Oswald *et al*., 2020; Owen and Barrett, 2020; Baltruszewicz *et al.*, 2021). However, the results in Table 5.2 highlight weak relationships between the average household income variable, and different ESDs, while the correlation coefficients in Table 5.2 suggest heating ESDs decrease with increased income (albeit, this is a very weak correlation). Unemployment rate may therefore be a stronger indicator of ESD levels than average household income at a LA-level.

Previous footprinting studies, such as Minx *et al.*, (2013) found that the link between spatial variables and household consumption footprints was less consequential than other socioeconomic variables, such as income and household size, but that increasing population density lead to a decreasing environmental footprint. Similarly, Ala-Mantila *et al.*, (2016); Gill and Moeller, (2018) and Salo *et al.*, (2021) identified that the environmental footprints of households varies across space, with higher footprints in rural areas. The results of this analysis therefore suggest that when considering LA-level ESD footprints for households, geography of a LA is a greater determinant of the ESDs across the LA rather than average household income or average household size.

Household ESD footprints within LAs are also shown to increase with the median age of the population in Section 5.4. The relationship between age and environmental footprint size has been inconclusive in the past (Wiedenhofer *et al.*, 2018). Salo *et al.*, (2021) found that consumption increased with age for certain services, such as nutrition, while for other services – e.g. consumer goods – consumption fell with age. Whereas, studies such as Büchs and Schnepf (2013) highlight a complex relationship between age and consumption whereby the type of household – a high or low consuming household – the type of consumption – direct or indirect – and the type of service demand – in-home energy or transport – affect the consumption of different age groups in different ways. The trend seen in Section 5.4.2 between age and energy consumption is likely due to underlying socioeconomic variables related to household requirements in different stages of life – e.g. older households may require greater levels of in-home consumption, such as heating ESDs (Salo *et al.*, 2021).

Additionally, considering the analysis of ESD footprints and the proportion of households not on the gas grid, the median household EPC rating of a LA, and the proportion of a LA's population with degree-level qualifications in Section 5.4.2, only weak relationships were found between ESD levels and these socioeconomic variables. However, other studies have noted the relationship between education level attained and the size of a household's environmental footprint in the past (Minx *et al.*, 2013; Salo *et al.*, 2021)

The weak relationship between income, and household size – traditional determinants of environmental footprint size – at a LA-level is likely due to choice of average household income and average household size as variables for analysis. Using average income and household size indicators is appropriate for analysis at a LA-level as LAs are areas of aggregated consumption. For example, the LA of Derby is populated by 49 Output Area Classification (OAC) subgroups (out of 76), with the population spread across all 10 income deciles. Comparing the income or size of all households within a LA, and their respective ESD footprint in Chapter 5 would be difficult, due to the availability of data, and time consuming. Therefore in the context of this study, analysing average household income and household size variables was appropriate.

LAs are the lowest-level of government in GB with powers to enact policies which could reduce energy demand (Paun *et al*., 2019; ONS, 2021). The analysis in Section 5.4 suggests that unemployment rate, population density per squared kilometre and median age of the LA's population are better determinants of household ESD footprints at a LA-level than traditional determinants such as household income and household size. However, LAs are aggregated areas of consumption, meaning that while these variables may be better determinants of ESD footprint size, it is likely that within a LA, households with greater income and a greater number of residents will be larger than less affluent and smaller households. Therefore, while average household income and average household size should not be considered determinants of the LA-level ESD footprint of households across GB, within a LA, these variables should not be discounted.

8.1.2.3 Summary

The ESD results in Chapter 5 follow the trend of previously published studies, with no large areas low consumption beyond central London as has been identified in previous studies (Minx *et al.*, 2013; Chatterton *et al.*, 2016). However, Section 5.4 and Section 8.1.2 shows that consumption calculated through environmental footprints is more nuanced than analysing individual household-level footprints (Salo *et al.*, 2021). LAs are aggregated areas of consumption, therefore the relationship between socioeconomic variables and environmental footprints often visualised in other studies are less pronounced in the dataset modelled in Chapter 5. However, the similarity between the ESD results in Chapter 5 and previous studies ensure that the ESD provides a reliable baseline from which EDR strategies can be modelled in Chapter 5.

8.1.3 What is the mitigation potential of four energy service-oriented approaches to EDR?

Four EDR strategies were modelled in Chapter 6, and the LA-level variation of EDR potential across GB was considered. The four EDR strategies were an energy efficiency strategy, the MSL strategy, the RSL strategy and the FC strategy.

In Chapter 6, the FC EDR strategy reduces energy demand of household by an average of 45.0% across GB, with larger percentage reductions occurring for heating, personal transport and aerial transport ESDs (Table 6.3). The FC strategy (average reduction of 45.0%) varies between 20.5% (Southwark) and 57.5% (South Oxfordshire). The energy efficiency strategy, modelled in Chapter 6, has the smallest effect upon total ESDs (a 10.5% reduction varying between a rebound of 0.4% in the Southwark LA in London, and 13.8% in Swale), however personal transport ESDs are reduced by 42.9% under this strategy. The modelled EDR potential of the MSL and RSL strategies is greater than the energy efficiency strategy, and less than the FC strategy, with a 28.3% (varying between 11.6% (Southwark) and 34.7% (Powys)) and 19.4% (varying between 9.1% (Newham) and 28.9% (Wokingham)) EDR potential respectively. The MSL strategy potential is driven by a reduction in energy consumption for heating, personal transport and nutrition ESDs, while the RSL strategy potential is driven by a 63% reduction in energy consumption for aerial transport ESDs (Table 6.3).

To the author's knowledge, no study has yet modelled the variation of EDR strategy potential at a LA-level in GB, therefore there are no directly comparable results to the EDR potentials in Section 6.2. However, previous studies by Grubler *et al.*, (2018) and Barrett *et al.*, (2022) have modelled the effect of radical and transformative changes in energy demand across different sectors, institutions, technologies and social practices.

Grubler *et al.*, (2018) modelled a 53% reduction in energy demand in the global north between 2020 and 2050 under their low energy demand scenario, while Barrett *et al.*, (2022), under their most radical scenario – Transform – modelled a 52% reduction in energy demand between 2020 and 2050. The EDR potential modelled by Grubler *et al.*, (2018) and Barrett *et al.*, (2022) is therefore greater than the EDR modelled under the FC EDR strategy.

Considering individual services also demonstrates how the studies are different, with the national average reduction for personal transport ESDs in Chapter 6 reaching 80.4% - above the levels in Grubler *et al.*, (2018) (60%) and Barrett *et al.*, (2022) (68%). Alternatively, agriculture EDR in Barrett *et al.*, (2022) is estimated to reach 62% by 2050 under the most radical scenario, while in Chapter 6, EDR for nutrition ESDs is only 52.6%. Similarly, when considering consumer goods ESDs, the EDR results under the FC strategy in Chapter 6 model a 14.1% reduction, while in Grubler *et al.*, (2018), a 25% reduction in energy demand for consumer goods in the global north was modelled.

However, the results are similar when considering national average reduction in heating ESDs under the FC strategy (77.7%) and the low energy demand scenario in Grubler *et al.*, (2018) (74%). Additionally, the national average results for building-related ESDs in Chapter 6 (a national average reduction of 50.9% across heating and other shelter ESD categories) and the reduction for residential buildings in Barrett *et al.*, (2022) (52%) are similar.

The difference in EDR potential between the EDR strategies in Chapter 6 and the scenario set out by Grubler *et al.*, (2018) is possible due to the energy demand of GB already being lower than the average for the global north, meaning that EDR potential will be less for GB (Barrett *et al.*, 2022). Additionally, differences in study boundaries (global north vs. UK vs. GB), methodological differences (mixed bottom-up scenario development with system modelling of energy supply and land use vs. an integrated modelling framework vs. input-output (IO) modelling) and ESDs considered may have contributed to the differences between the studies.

IO modelling of EDR strategies is less commonly used than dynamic models (e.g. macroeconometric models) which can also be used in energy consumption calculations and EDR modelling (Section 2.4) (Hardt *et al.*, 2019). However, the use of IO modelling removed the geographical separation between production and consumption by linking LA-level EDR with the globalised energy supply chain and production system, and incorporating household response to changes in energy service levels through income and substitution effects. The modelling methodology developed by Wood *et al.*, (2018) was therefore useful for modelling the EDR of household ESDs at a LA-level as environmentally extended multi regional input-output (EE-MRIO) modelling is designed to calculate the effects of household consumption upon different environmental indicators.

The ability to examine the effect of EDR strategies upon different areas of GB is important if the power to set EDR remains with the national-level government. EDR will be an important aspect of the transition towards a net-zero society in GB, and therefore implementing EDR options which would be ineffective in specific areas of GB, would slow the demand-side transition.

8.1.4 Energy demand reduction strategy feasibility

In Chapter 7, CI scores of each LA were calculated based upon five capital dimensions – financial capital, human capital, physical capital, natural capital and social capital – and were also drawn together under 'all capital'. Following the generation of the CI scores in Section 7.1, the scores for each dimension were analysed against the ESD values, modelled in Chapter 5, and the modelled EDR values for each LA under the FC strategy, in Chapter 6, to identify whether areas of high CI scores, high ESD levels and high EDR levels were correlated. Section 8.1.4 will discuss the results of Chapter 7 in the context of other studies to identify whether a nationally-led strategy to EDR is the most just method of delivering low carbon ESDs in GB.

8.1.4.1 CI scores summary

The results in Section 7.1 showed that across the 'all capital' dimension, areas of high CI scores, due to high levels of different types of capital were located in the south of England, with LAs of lower capacity to adopt EDR measures located in areas such as Scotland, Wales and the north of England (Section 7.1.6). However, considering the individual capital dimensions showed that this pattern was not universal for each type of capital – in particular the social capital dimension which exhibited very low levels of clustering (Moran's I value of 0.14) and high levels of capital across much of GB (Section 7.1.5; Figure 7.6). Although, the national average scores across all dimensions were similar, with the exception of physical capital (Section 7.1.7).

Following the generation of CI scores in Section 7.1, the correlation coefficients generated in Section 7.2 show that essential ESDs, such as heating, do not correlate with the CI scores generated in Section 7.1. However, more correlation can be seen between less essential services, such as recreation & communication. Additionally, the FC strategy EDR correlation coefficient results in Section 7.2.2 showed that there is limited correlation between the percentage reduction by ESD under the FC strategy and a LA's CI score.

8.1.4.2 CI scores context

The results in Chapter 7 considered household capacity to adopt EDR strategies set out at a national-level. Section 7.1 therefore framed the CI through the lens of different capital dimensions available to households, rather than focusing purely on energy poverty indicators – which were included in the human capital dimension (Table 3.5) – as has been done by previous studies (Robinson *et al*., 2019; Robinson and Mattioli, 2020).

Previous studies have shown that households in the south of England have a greater capacity to adapt to EDR measures than households in other areas of GB (Robinson and Mattioli, 2020). The results in Section 7.1 demonstrate this also, for the 'all capital' dimension scores, thus ensuring the robustness of the CI scores.

The implications of the results in Section 7.1 therefore also align with conclusions drawn by previous studies that households in LAs beyond the south of England are 'systemically disadvantaged' by their position in GB (Golubchikov and O'Sullivan, 2020). In GB, economic and political power is located in London, therefore the greater the distance from London, the more likely that households beyond this region are considered to be on the 'energy periphery' whereby the spatial distribution of capital necessary for EDR is asymmetrically concentrated elsewhere in the territory (Golubchikov and O'Sullivan, 2020).

Beyond the results in Section 7.1, the results in Section 7.2.1 showed that there is correlation across the CI scores for each capital dimension and a LA's corresponding ESD levels. However, the correlation is not evident across all ESD categories and capacity dimensions (Section 7.2.1). Analysing ESD levels and human capital generates the strongest correlation coefficients in Section 7.2.1, thus demonstrating that areas with higher levels of human capital – i.e. lower levels of energy and food poverty – generally consume more ESDs than areas with high levels of poverty (Table 7.1).

However, heating ESDs and human capital – as well as the other types of capital that CI scores were generated for – do not generate a strong positive correlation coefficient in Section 7.2.1 (Table 7.1). Heating is an essential ESD (Kaygusuz, 2011). Essential ESDs are required by every household, whether affluent, or not, therefore meaning that ESD level for essential ESDs are high across much of GB (Section 5.3), despite underlying differences in the socioeconomic factors of households (Kaygusuz, 2011). Previous studies have also highlighted this, focusing upon the fact that as income rises, ESD levels for essential services do not rise greatly, but begin to make-up a smaller proportion of the whole energy footprint (Owen and Barrett, 2020). Similarly, the proportion of energy consumption for non-essential services, such as recreation & communication also rises where poverty rates are smaller (e.g. the human capital column of Table 7.1).

Finally, Section 7.2.2 showed that analysing EDR levels by LA under the FC strategy, and the CI scores of LAs generated very weak correlation coefficients (Table 7.2). The results therefore demonstrate that implementing the FC strategy at a national-level, with no consideration given to local context, would not lead to households within LAs with higher CI scores reducing their energy consumption associated with ESD levels by a greater extent, and could therefore compromise the wellbeing of households in these LAs.

The results in Section 7.2.2 and Table 7.2 therefore draw in the concept of subsidiarity, and the use of local solutions for local problems (Table 2.2) (Wanzenböck and Frenken, 2018). A national-level EDR strategy which reduces energy demand in line with the levels required for a 1.5°C future (Masson-Delmotte *et al.*, 2018) – i.e. the FC strategy in this study – would bring about effective EDR, but not equitable EDR across GB.

The results in Section 7.2.2 highlight the importance of subsidiarity for an equitable demand-side transition which does not compromise the wellbeing of households. National-level strategies miss the nuance of energy demand, and capacity to adopt measures, across space. Without accounting for LAs exhibiting high and low ESDs, and high and low CI scores, nationally implemented EDR measures will attempt to address energy consumption universally, leading to varying levels of effectiveness, and higher levels of EDR expected for households within LAs where capacity to adopt EDR measures is low, thus compromising wellbeing. The concept of subsidiarity and the results generated in Chapter 5, Chapter 6, Chapter 7, will be discussed in Section 8.2.3.

8.1.4.3 Summary

The CI scores for 'all capital' in Section 7.1 broadly align with results generated by previous studies examining household capacity in GB (Robinson and Mattioli, 2020). The CI scores have high correlation coefficients with households which have high levels of human capital – i.e. where a LA's population is older, and both energy and food poverty are low (Section 7.2.1). Whereas, the EDR results, under the FC strategy, and the CI scores generate very low correlation coefficients (Section 7.2.2).

The results in Chapter 7 therefore build upon previous studies which have indicated that beyond London, households have lower capacity to adopt EDR strategies in GB (Robinson and Mattioli, 2020), as well as studies which show that essential ESD consumption does not correlate with wealth. Additionally, the ESD results have strong, positive correlation coefficients with human capital meaning that the results further confirm the robustness of the ESD footprints in Chapter 5 as higher human capital means lower poverty rates in a LA, therefore implying that more affluent households have greater ESD footprints.

Finally, the analysis of modelled EDR levels and the CI scores by LA shows that the correlation coefficients between these two variables are weak. In the context of previous studies, the need to ensure that EDR does not compromise the wellbeing of households was considered. A national-level approach assuming universal implementation of policies is effective (Chapter 6), however, without considering local context, measures may not be as effective as modelled in Chapter 6 or equitable when areas of low CI scores are expected to reduce energy consumption of ESDs at a similar rate as areas with high CI scores (Tingey and Webb, 2020). The concept of subsidiarity and the results generated in Chapter 5, Chapter 6, Chapter 7, will be discussed in Section 8.2.3. Subsidiarity has been a cross-cutting theme throughout this thesis, and is therefore considered in its own section.

8.2 Cross-cutting thesis themes

Section 8.1 assessed the research of the thesis in the context of previous work, and how each thesis chapter makes a contribution to the wider literature. Each of the four research chapters in this thesis answered a research question set out in Section 1.2. Each research chapter has answered its respective research question, however, beyond the research questions in Chapter 1, there have been cross-cutting themes which have been prevalent throughout each chapter of the thesis.

The research conducted in this thesis has sought to emphasise a focus upon the end goals of energy demand – energy services – rather than energy demand itself. ESDs were used as a framing device for the thesis, due to the potential of the services discourse to link the social and technical aspects of the energy system. Wellbeing and energy demand are intrinsically linked, but not directly coupled in GB, where overconsumption of services occurs throughout different segments of the population. The differences between GB's energy demand and ESDs will therefore be considered in order to identify the benefits of the services framing of energy demand.

Secondly, the thesis has emphasised the need to go beyond energy efficiency when considering EDR. Framing the EDR strategies in Chapter 6 from a LA perspective using the SEDC framework in this study allowed the effect of EDR options from the 'avoid' and 'shift' columns of the avoid-shift-improve (ASI) framework upon the whole energy system to be modelled. Energy efficiency has not been completely neglected in the thesis however, with the energy efficiency strategy in Chapter 6 modelling the potential of an energy efficiency only approach to EDR in GB, while the MSL EDR strategy also modelled the effect of efficiency options alongside 'shift' options from the ASI framework. Based upon this work, the dominance of energy efficiency approaches to EDR in national policy throughout the world, and the pre-existing concerns surrounding the ability of energy efficiency to deliver EDR mean that new strategies for EDR need to be considered.

Finally, the governance of the demand-side transition has been a driving factor of all the research undertaken in Chapter 4, Chapter 5, Chapter 6 and Chapter 7. The research in this thesis has considered the ESDs of LAs throughout GB, the potential of EDR strategies at a LA- level across GB, the ability of LAs to adopt EDR strategies and whether areas of high ESDs, high EDR potentials and high CI scores all correlate. Using this research, the current, national-level approach to EDR needs to be examined, with consideration being given to the devolution of funding to enact EDR strategies to LAs.

Section 8.2 will therefore be set out into three sections. Section 8.2.1 will consider the differences between the energy demand statistics maintained by the UK government and the ESD footprints set out in Chapter 5, as well as the benefits of widening the scope of energy included within the ESD footprints. Secondly, Section 8.2.2 will consider energy efficiency as an EDR strategy to establish the benefits of implementing an EDR strategy which goes beyond energy efficiency. Finally, Section 8.2.3 will consider the governance of the demand-side transition in relation to the concept of subsidiarity. The role of LAs in the demand-side transition has been a driving factor of the research undertaken in each chapter of the thesis, and will be considered in this section.

8.2.1 Theme 1: Energy service demands vs. energy demand

As stated previously, the UK government provides annual statistics of domestic energy consumption in each local authority throughout GB by fuel type (BEIS, 2021d). However, while the domestic energy consumption statistics set out how much direct energy is consumed within each LA on an annual, there is no indication as to how the energy is used by households across GB (BEIS, 2021d). This thesis, in particular, Chapter 5, therefore sought to give deeper insight into energy demanded from the energy system by households, by extending the statistics in BEIS (2021c) to ESDs, while also building upon the statistics using consumption-based accounting.

Considering ESDs using a consumption-based approach, rather than direct energy demand, in this thesis broadened out demand-side analysis beyond fuels, such as electricity, gas and coal, thus allowing the underlying services which drive energy demand to be identified. It is beyond the scope of this thesis, but the energy service footprints could have also been broken down into direct and indirect energy – as seen in Eriksson *et al*., (2021) – therefore adding another layer of understanding as to how ESDs vary across GB.

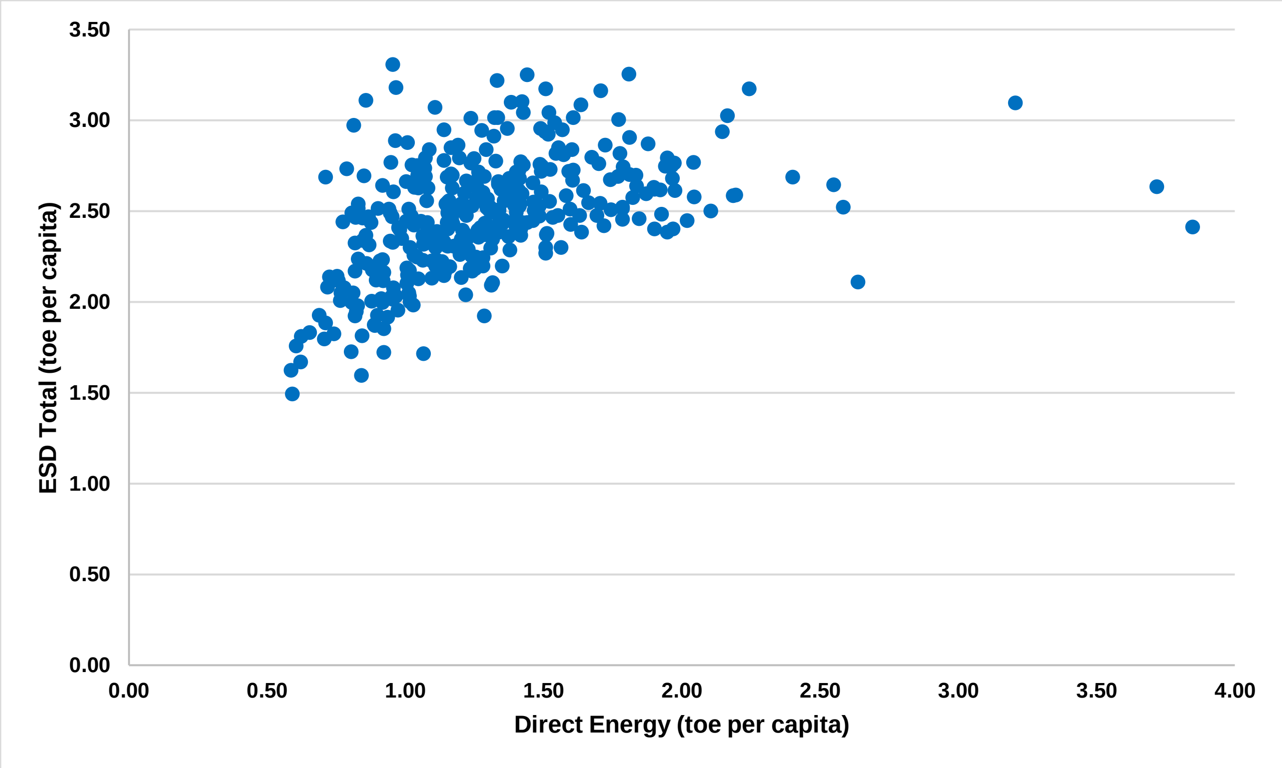


Figure 8.4 Scatter plot showing the difference between the level of energy consumption in the BEIS (2021c) statistics and the ESD totals generated using consumption-based accounting from the Living Costs and Food Survey.

Figure 8.4 shows the difference between direct energy per capita for each LA in GB and the ESD totals which include indirect energy. Undertaking a correlation analysis of the data in Figure 8.4 generates a correlation coefficient between the direct energy statistics and total ESD footprints generated from the LCFS data of 0.53. The magnitude of the ESD totals per capita is greater than the values for direct energy consumption for the majority of LAs, with the exception of a few outliers (Figure 8.4). ESD totals therefore reflect the true impact of energy consumption in LAs GB, which is not fully realised by only considering direct energy.

The breakdown of energy demand by ESD category in this thesis also directly links the energy consumption data for each LA to a variety of potential EDR options (Ivanova *et al.*, 2020). For example, heating ESDs can be linked to measures such as heat pumps or lower room temperature. Whereas considering only energy demand does not link the type of fuel used by households to a specific measure. Only considering the fuel type of the energy demanded by households therefore encourages demand-side studies to focus on delivering less energy to households as it is unknown which type of ESD fuel is being used upon by households (Morley, 2018). Without an understanding of how the energy is used, and therefore which energy service to reduce the levels of, EDR will favour focusing upon energy efficiency which reduces the potential of the demand-side mitigation through EDR (Morley, 2018).

8.2.2 Theme 2: Energy efficiency as a mitigation strategy

The national average results of the energy efficiency EDR strategy are set out in Section 6.1. The measures utilised in this strategy focused primarily upon improving rollout of more efficient technologies, such as battery-electric vehicles (BEVs), the thermodynamic energy efficiency of conversion devices to deliver household ESDs or the improved material efficiency of goods bought by households (Creutzig *et al.*, 2018).

The energy efficiency EDR strategy results modelled an average reduction of energy consumption for ESDs of 10.5% across GB (Table 6.3 and Table 8.1). Nationally, adopting an energy efficiency EDR strategy led to reduction in energy demand for heating, other shelter, personal transport and nutrition ESDs, with all the other ESD categories experiencing rebound which negates the gains made from improving the efficiency of technologies and practices (Table 6.3). However, the national level of reduction was not universal across GB, with some LAs experiencing an increase in total ESDs under the energy efficiency EDR strategy (Figure 6.11).

The energy efficiency strategy had the smallest EDR potential of the four modelled strategies in Chapter 6 (Table 8.1). The results of the modelled energy efficiency EDR strategy suggest that a strategy which relies heavily upon energy efficiency to reduce energy demand, will reduce energy demand across much of GB, but will not reduce it to the level needed for a 1.5°C future. The reduction modelled in the energy efficiency EDR strategy therefore implies that greenhouse gas (GHG) removals would be required to meet the level of EDR required for a 1.5°C future in Masson-Delmotte *et al.*, (2018) (Figure 1.4) (Table 8.1).

Table 8.1 Comparison of the Final Energy Demand required to deliver 1.5°C in scenarios P1 and P2 from Masson-Delmotte *et al.*, (2018) and the national average reduction from the four EDR strategies in Chapter 6. Negative numbers show an increase in energy demand.

Energy Strategy/Energy Scenario	Level of EDR Required/Delivered
Masson-Delmotte *et al.*, (2018) P1	32%
Masson-Delmotte *et al.*, (2018) P2	-2%
Energy Efficiency	10.5%
Maintained Service Levels	28.3%
Reduced Service Levels	19.4%
Full Consideration	45.0%

In the context of wider literature, the results of the energy efficiency EDR strategy in Chapter 6 demonstrate that the EDR gained using an energy efficiency-only EDR strategy would not be fully negated by the rebound effect. This reduces concerns that energy efficiency will lead to a large rise in the consumption of energy across and within the ESD categories each energy efficiency option affects and suggests that energy efficiency is a viable strategy for reducing the level of energy consumption associated with household ESDs, without reducing household service levels, across much of GB.

However, Table 6.3 shows that under an energy efficiency strategy, the majority of EDR is driven by one ESD category (personal transport ESDs). Personal transport ESDs are modelled to reduce by an average of 42.9% across GB (Table 6.3), with heating ESDs (13.7%), other shelter ESDs (1.5%) and nutrition ESDs (6.1%) experiencing smaller reductions. The reduction in personal transport ESDs is driven by an increase in the use of alternative fuel vehicles, such as BEVs (Appendix 5) (Creutzig *et al.*, 2018).

The results in Table 6.3 therefore confirm concerns that energy efficiency limits the scope of EDR. Under the EDR strategy, public transport ESDs (134.6%), aerial transport ESDs (0.1%), recreation & communication ESDs (1.6%), consumer goods ESDs (10.7%) and services ESDs (13.9%) all experience an increase in household demand for these energy services.

As personal transport ESDs represent the largest proportion of household ESD footprints at a LA-level across much of GB, the decarbonisation and reduction in the use of personal transport is expected to form a core component of the transition to a net-zero society in GB. However the measures in Ivanova *et al.*, (2020) and the modelling results for the MSL, RSL and FC strategies in Chapter 6 demonstrate that EDR can address energy consumption across all areas of household consumption. Additionally, diversifying the measures utilised in an EDR strategy leads to a reduction of energy demand across a wider number of ESD categories, therefore providing a greater balance of reduction, and reducing the impact of the rebound effect (Section 6.2).

Utilising energy efficiency as a mitigation strategy on its own would therefore significantly hamper efforts to reduce energy demand in line with the levels necessary for a 1.5°C future. The results in Chapter 6 imply that energy efficiency should remain a core aspect of GB's EDR strategy, but that it should form a smaller part of the strategy than other aspects of EDR.

Chapter 6 shows that combining energy efficiency measures with mode switching and changes in behavioural practices have a much greater effect upon the level of energy demand required to deliver the present level of energy services (a 28.3% reduction) than the energy efficiency strategy alone (a 10.5% reduction). Additionally, reducing service levels, and therefore energy demand for energy services, also offers a larger reduction than the energy efficiency strategy (a 19.4% reduction). The results in Chapter 6 therefore imply that the government should be focusing on driving through changes to household behaviours and practices than investing heavily in technical efficiency improvements, as presently the level of potential EDR associated with these measures is being neglected, and opportunities to enact quick, effective EDR are being overlooked (Grubler *et al.*, 2018; Shove, 2018; CCC, 2021; Barrett *et al.*, 2022).

Based upon the results in the scenarios developed by Masson-Delmotte *et al.*, (2018), it can be assumed that GHG removals would be required in order to achieve the level of EDR necessary in GB to achieve the Paris Agreement's 1.5°C temperature goal (Masson-Delmotte *et al.*, 2018). As stated in Section 1.1.1, GHG removal technology, such as bio-energy carbon capture and storage (BECCS) is unlikely to be available on a large enough scale by 2050 to make-up the shortfall in emission reductions, which could be achieved through EDR (Anderson and Peters, 2016; Cox *et al.*, 2018). Therefore it is unlikely that an energy efficiency EDR strategy would allow GB to transition to a net-zero society, and achieve its long-term climate goals.

8.2.3 Theme 3: Demand-side Governance and Subsidiarity

Section 2.2.2 highlighted the role that subsidiarity is expected to play in the demand-side transition across the world, and the benefits that devolving EDR policy to this level would provide – e.g. local solutions to EDR and increased democratisation of the policy process (Table 2.2) (Wanzenböck and Frenken, 2018). However, Section 2.2.2 also highlighted that the UK government has, thus far, been unwilling to engage with, and devolve power to, LAs to bring about increased EDR action (LGA, 2019).

Based upon the unwillingness of the UK government to work with LAs on EDR (Section 2.2), the limited successes of national-level EDR policies such as the Green Deal and the Green Homes Grant (Section 2.2.1), and the ambition of LAs to enact EDR policies (Section 2.3), this thesis sought to examine the differences in the ESDs of households at a LA-level across GB, and the potential of a nationally-led approach to EDR to establish whether a disaggregated approach to EDR could benefit demand-side action for different ESDs in GB (Section 1.2). The theme of demand-side governance and subsidiarity has therefore been present across all chapters of this thesis.

Chapter 4 set out the SEDC framework, from which LAs could identify the stage of the energy system that a consumption-based EDR option implemented within that LA would affect, and demonstrated that LAs have the power to affect all stages of the energy system considered by the SEDC framework. The results in Chapter 5 then demonstrated that different LAs across GB exhibit different levels of household ESDs, with the range of values modelled for heating ESDs, and the range and clustering of values modelled for personal transport and public transport ESDs suggesting a universal approach to EDR may improve the effectiveness of demand-side policy.

Chapter 6 showed that the EDR strategies modelled in this chapter would be effective at reducing energy demand for household ESDs across GB – with the exception of two LAs under the energy efficiency strategy. However, the effectiveness of each strategy across all LAs varied, meaning that a national-level approach to EDR, would lead to a greater burden being placed upon different LAs to reduce energy consumption for ESDs.

Finally, Chapter 7 established the capacity of households within all LAs across GB to adopt EDR strategies. Combining the CI analysis in Chapter 7 with the ESD and EDR values of each LA – modelled in Chapter 5 and Chapter 6 – demonstrated that LAs exhibiting high ESDs in GB do not align with LAs which have high household capacity to adopt EDR strategies. Similarly, the correlation analysis also showed that LAs modelled to experience the greatest levels of EDR under a universal, nationally-led EDR strategy do not align with LAs which have high household capacity to adopt EDR strategies.

The results from Chapters 4 to 7 of the thesis demonstrate that nationally-led approaches for ESDs such as consumer goods and nutrition ESDs are appropriate due to the low range of variation in ESD levels (Chapter 5), and similar levels of reduction across GB under each EDR strategy (Chapter 6). However, the results also suggest that while nationally-led approaches to EDR would reduce the energy consumption of household ESDs – in line with the levels required for a 1.5°C future under the FC strategy (Masson-Delmotte *et al.*, 2018) – the four EDR strategies do not reduce energy demand to the same extent across GB for the most energy intensive ESDs, and do not bring about the greatest EDR in areas with high capacity to act. Comparing ESD and EDR levels under each of the four strategies also shows that when considering the two most energy intensive ESD categories – heating and personal transport ESDs – there is poor correlation between the level of EDR within a LA and the size of the LA's initial household ESD footprint.

The lack of correlation between LAs exhibiting high ESDs and high levels of EDR for heating and personal transport ESDs suggests that national-level approaches to EDR would not address overconsumption of energy in these ESD categories. In addition to reducing the effectiveness of EDR strategies, the lack of correlation between LAs exhibiting high ESDs and high levels of EDR for heating and personal transport ESDs under a national-level approach also suggests that the approach is not just as LAs with lower ESDs for heating and personal transport are modelled to reduce their energy consumption by a similar level as households in LAs with higher ESDs.

More funding should therefore be devolved to LAs to encourage the uptake of heating measures – such as the shift to heat pumps and lower household room temperatures – and transport measures – such as the shift to BEVs, public transport or living car free. Additionally, LAs can ensure that the implemented measures are tailored to each area, so heating and transport ESDs can be reduced without compromising the wellbeing of households. For example, if households within a LA had high financial capital, but low natural capital (due to a low population density), LAs could encourage the switch to BEVs by building more electric car charging infrastructure. Whereas, if households within a LA had low financial capital, and therefore couldn't afford to purchase a BEV, but high natural capital (due to a high population density), LAs could increase the level of cheap public transport infrastructure to encourage the switch to public transport instead.

Defining the level of funding which should be devolved to LAs under subsidiarity is beyond the scope of this thesis, however, these are the two methods through which subsidiarity could be utilised more effectively in EDR strategies in the UK. LAs already have significant control over many policy areas (Section 2.2), which has allowed LAs to set out ambitious net-zero plans (Section 2.2.3) (Paun *et al*., 2019; Leeds Climate Commission, 2021a; Climate Emergency UK, 2022; mySociety, 2022). This means that a focus upon devolving extra powers to LAs is unlikely to improve demand-side ambition or strategy effectiveness.

However, lack of funding often cited as a barrier to LA plans being acted upon (Tingey and Webb, 2020). Overcoming the financial barrier to EDR at a LA-level could therefore accelerate the demand-side transition whether it would be through public transport infrastructure improvements, increases or ticket subsidisation, cycling infrastructure improvements or increases, or improving the energy efficiency of council-owned housing (Tingey and Webb, 2020).

Adopting subsidiarity to enact ambitious, LA-level, net-zero plans could be advantageous for EDR and accelerating strategy implementation, particularly for heating and personal transport ESDs (Wanzenböck and Frenken, 2018). It is unlikely that subsidiarity for EDR policy, through increased funding, will be enacted soon in the UK, due to the government's unwillingness to work with LAs to bring about increased demand-side action (LGA, 2019). However, the concept offers a potential route for accelerating the demand-side transition in the future, when a new government may be more willing to devolve more funding, and more powers, to LAs (Labour, 2022). The pledge by the Labour party, in 'A New Britain', to allow LAs to raise additional revenue, is a positive move for UK-based subsidiarity and may offer the opportunity to accelerate the demand-side transition in the future (Labour, 2022).

8.3 Summary

Chapter 8 has sought to draw the threads of the PhD together, in order to draw out the themes, results and implications of the work presented in this thesis. The framework in Chapter 4, and the results presented in Chapter 5, Chapter 6 and Chapter 7 each contribute to the literature in the EDR and ESDs space in their own respect, and also broadly align with results generated by previous studies (Minx *et al.*, 2013; Grubler *et al.*, 2018; Robinson and Mattioli, 2020; Salo *et al.*, 2021; Barrett *et al.*, 2022).

The cross-cutting themes identified across the thesis demonstrate that the consideration of ESDs rather than energy demand broadens the scope of EDR options and subverts the current demand-side discourse of energy efficiency by focusing upon ESDs provided by indirect energy as well as direct energy. Considering ESDs, rather than energy demand removes the geographical separation between production and consumption, and demonstrates that using a services-oriented framing of the energy system would allow LAs to affect the whole energy system by implementing consumption-based EDR strategies (Chapter 4).

Additionally, the thesis demonstrates that energy efficiency will not reduce energy consumption for ESDs in GB by the level necessary for a 1.5°C future. Energy efficiency is the EDR strategy which modelled the smallest potential in Chapter 6, partly due to the rebound effect, and partly due to the limited number of measures available to consider in this strategy. The MSL, RSL and FC strategies have a much greater potential, according to the modelled results in Chapter 6, therefore meaning that EDR must go beyond energy efficiency in order for the demand-side transition to be effective.

Finally, the governance of the demand-side transition and subsidiarity was considered across all chapters of the thesis. Chapter 5, Chapter 6 and Chapter 7 all demonstrate the difference in ESDs, EDR potential and capacity to adopt EDR strategies across the thesis, while the SEDC framework in Chapter 4 sets out a method of considering EDR from a local perspective. The results in Chapter 5, Chapter 6 and Chapter 7 suggest that a universal approach to EDR, using a FC strategy, does not reduce energy consumption associated with ESD levels in LAs with larger ESD footprints to a greater extent than LAs with smaller ESD footprints, which would not be an equitable demand-side transition, and may compromise the wellbeing of households. Additionally, there was no correlation exhibited between LAs with high or low CI scores, meaning that household wellbeing could be compromised under a universal strategy, therefore consideration of a more disaggregated approach must be undertaken in the future when aiming to reduce energy consumption for ESDs in GB.

Further work may therefore be required to understand how EDR strategies could reduce energy consumption for ESDs across space in GB. The conclusion in Chapter 9 will summarise the work conducted in this thesis and set out areas of future work.

9 Conclusion

Building on Chapter 8, which discussed the research findings of this thesis in the context of previous research, and sought to draw out themes present across each of the results chapters (Chapter 4 to Chapter 7), Chapter 9 will conclude the thesis. Chapter 9 will therefore summarise the research findings of the thesis, and how the findings contribute towards the overall aim of the thesis (Section 9.1) before examining each chapter's contribution to the knowledge base in the research areas of energy service demands, energy demand reduction and demand-side governance (Section 9.2). Section 9.3 will address the limitations of the work, before Section 9.4 highlights potential areas of future research.

9.1 Overall summary

The overarching aim of the thesis was **to assess the variation in energy service demands of households at a local authority-level across Great Britain, and the potential of a nationally-led approach to energy demand reduction to establish whether a disaggregated approach to energy demand reduction could benefit demand-side action for different energy service demands in Great Britain**. The aim was established based upon the research undertaken during a literature review in Chapter 2.

In Chapter 2, it was established that despite reductions in emissions since 1990, energy demand reduction through energy efficiency had not reduced UK energy consumption significantly over the same time period, meaning that energy demand reduction must go beyond energy efficiency if the UK is to meet its net-zero emission target in 2050 (Section 2.1.3). Section 2.2 then identified that local authorities are generally more ambitious than the UK national-level government when considering mitigation through energy demand reduction, and are well-placed to make some of the infrastructural changes necessary to bring about energy demand reduction. However, due to a lack of funding local authorities do not presently possess the capacity to implement effective energy demand reduction in the UK as energy policy remains under the control of the national-level government in Westminster.

This thesis therefore sought to assess whether a disaggregated policy approach to energy demand reduction may bring about more effective energy demand reduction in the UK in a just manner. Although the focus was shifted to Great Britain after it was established that local authorities in Northern Ireland are ceremonial and possess no powers to implement policy at present. The concept of energy service demands was then established as a lens through which energy demand and energy demand reduction could be examined at a local-level (Section 2.3). The services framing also broadened out the scope of energy demand reduction beyond the technical energy system, and links the technical aspects of the energy system with the underlying social drivers of energy service demands and the energy system.

Finally, a review of modelling approaches to energy service demands suggested that using an environmentally extended multi-regional input-output modelling technique would allow energy service demands to be examined at a local authority level (Section 2.4). Input-output modelling links micro-level household consumption data with the overarching, globalised energy system, therefore adopting this approach would allow the energy service demands of each local authority throughout Great Britain to be modelled, while also allowing the effect of energy demand reduction strategies implemented at a local authority level to be modelled, and their effect upon the global energy system assessed (Section 2.4).

To achieve the overarching aim of the thesis, four results chapters (Chapter 4 to Chapter 7) were set out. Chapter 4 established a framework entitled the service-driven energy demand chain framework which set out the framing of energy demand and the energy system from a local authority perspective using a services framing. The service-driven energy demand chain framework tied the social and technical aspects of the energy chain together, and removed the geographical separation between consumption and production at a local authority level.

Chapter 5 modelled the energy service demand footprints of each local authority in Great Britain[24] to understand the variation in ten energy service categories – including total energy service demands – at a local authority level, and to establish a baseline from which energy demand reduction strategies could be modelled. Chapter 6 modelled four energy demand reduction strategies to assess the potential variation in energy demand reduction potential across different local authorities throughout Great Britain and understand the difference in energy demand reduction between an energy efficiency-only strategy and other strategies – a maintained service level strategy, a reduced service level strategy and a full consideration strategy – which include measures which shift and avoid energy demand.

The final results chapter, Chapter 7, sought to understand the capacity of households in each local authority to adopt the energy demand reduction measures and strategies modelled in Chapter 6, using a capacity index. The capacity index scores were subsequently analysed alongside the energy service demand levels modelled in Chapter 5, and the energy demand reduction levels for the full consideration strategy, modelled in Chapter 6, to draw together the thesis by assessing whether the

[24] The results chapters focused upon England, Scotland and Wales, “Great Britain”, rather than the UK as local authorities in Northern Ireland are purely administrative and have no powers to set policy, and would therefore be unable to implement energy demand policy at this level.

burden of energy demand reduction under a universal strategy falls upon households with higher energy service demands and high capacity to adopt energy demand reduction strategies.

Finally, Chapter 8 discussed the results from each chapter in the context of other studies, while also identifying the cross-cutting themes present across all the results chapters in the thesis. The cross-cutting themes focused upon the use on energy service demands rather than energy demand in the thesis, the limitations of an energy demand reduction strategy focused solely upon energy efficiency, and demand-side governance in the UK, with a focus upon the context of subsidiarity.

9.2 Contribution to the knowledge base

9.2.1 Chapter 4: The service-driven energy demand chain framework

The service-driven energy demand chain framework in Chapter 4 set out a framing of the energy system from a local authority level using a services-oriented perspective. The service-driven energy demand chain framework reversed the traditional framing of the energy system, and direction of analysis to place energy services at the beginning of energy demand reduction considerations. As local authorities are located at the point of household energy consumption, placing this stage of the framework at the beginning of an energy system analysis places consumption and its effect upon the globalised energy system at the forefront of analyses using the service-driven energy demand chain framework. The service-driven energy demand chain framework in Chapter 4 significantly alters current perspectives of energy demand, removing the geographical separation between consumption and production, and can be used as a planning tool by policymakers at a local authority level to identify energy demand reduction strategies which affect different points of the energy chain.

9.2.2 Chapter 5: Great Britain's energy service demands

The energy service demand footprints in Chapter 5 showed how Great Britain's household energy service demands vary across space and energy service demand category at a local authority level. Analysis in Chapter 5 also identified the socioeconomic variables which correlate strongest with energy service demand levels across Great Britain. Prior to the generation of the energy service demand footprints, the breakdown of energy service demands by local authority in Great Britain was unknown. The UK government does not maintain local authority level statistics of energy use by service type, instead the statistics generated by the UK government focus upon energy consumption by fuel type.

The energy service demand footprints in Chapter 5 therefore expand upon current knowledge by attributing direct energy use to different energy service demands, while the energy service demand footprints also model the indirect energy associated with energy service demands at a local authority level. The database of energy service demand footprints in Chapter 5 gives a comprehensive overview of energy service demands in Great Britain, and how they vary across space, thereby allowing areas of both high and low consumption of different energy service demands to be identified, and the determinants of both high and low energy consumption for different energy service demands to be established.

The results in Chapter 5 suggested that subsidiarity, and therefore a disaggregated approach to energy demand reduction could be applied to heating, and personal transport energy service demands. The large range of values modelled across Great Britain for these categories means that energy consumption for each energy service demand needs to be examined more in-depth. Similarly, the high levels of clustering for personal transport and public transport energy service demands suggested that households in different areas of Great Britain consume these energy service demands in significantly different ways, meaning that different energy demand reduction measures may need to be implemented in different local authorities throughout Great Britain.

9.2.3 Chapter 6: Energy demand reduction strategy potential

Chapter 6 modelled the effect of four energy demand reduction strategies upon the present-day energy service demand baseline, modelled in Chapter 5, and considered the differences in energy demand reduction potential under each strategy at a national-level and across space at a local authority level. An energy demand reduction strategy solely focused upon energy efficiency will not reduce energy demand in Great Britain by the level estimated by Masson-Delmotte *et al*., (2018) for a 1.5°C future without the need for greenhouse gas removal. Energy efficiency will remain an important aspect of energy demand reduction in Great Britain, however energy demand reduction strategies which go beyond energy efficiency – e.g. the maintained service levels, reduced service levels and full consideration strategies – have a greater effect upon household energy service demands at a local authority level.

The modelling results in Chapter 6 demonstrate that a full consideration strategy – the most comprehensive strategy modelled in this thesis – can reduce energy consumption for energy service demands in line with the levels set out by Masson-Delmotte *et al*., (2018) for a 1.5°C future. The results also demonstrated that below a national-level, energy demand reduction varies across space, with the four strategies affecting different local authorities to varying degrees of reduction. The results also demonstrated that input-output modelling can be used to model energy demand reduction effectively at a local authority level, with the levels of reduction in the full consideration strategy in Chapter 6 being broadly in line with modelling studies which have examined the potential of an ambitious demand-side transition in the global north (Grubler *et al.*, 2018) and the UK (Barrett *et al.*, 2022).

The level of energy demand reduction for heating and personal transport energy service demands under each of the strategies in Chapter 6, by local authority, does not align with the local authorities exhibiting the largest energy service demand footprints for these energy service categories. The results in Chapter 6 therefore imply that a disaggregated approaches to energy demand reduction in Great Britain is appropriate for heating and personal transport energy service demands, to avoid compromising household wellbeing. From a subsidiarity perspective, local authorities already control policy areas such as housing and transport planning, therefore no new powers need devolved in order for local authorities to address these energy service demands in a disaggregated manner. However, increased funding would allow local authorities to act upon their ambitious, locally-specific climate plans for reducing energy demand associated with transport and heating.

9.2.4 Chapter 7: Energy demand reduction strategy feasibility

Finally, Chapter 7 undertook a capacity index analysis to generate capacity index scores for each local authority to identify whether households within a local authority had a high capacity for adopting energy demand reduction strategies. The analysis in Chapter 7 focused upon five types of capital – financial, human, physical, natural and social – before considering the capacity index scores in the context of the energy service demand results in Chapter 5, and the energy demand reduction results in Chapter 6 to assess whether high levels of energy service demand, and high levels of energy demand reduction under the full consideration strategy, correlated with high capacity index scores.

The results of the analysis suggested that high levels of energy service demands broadly correlate with local authorities which have a high level of capacity to adopt energy demand reduction strategies. However, local authorities with high levels of energy demand reduction, modelled in Chapter 6, do not correlate with local authorities which contain household that had high capacity index scores. The results of the correlation analysis between levels of energy demand reduction under the full consideration strategy and the capacity index scores therefore shows that a universal strategy to energy demand reduction would not bring about greater levels of energy demand reduction in local authorities with greater capacity to adopt energy demand reduction strategies. There is therefore a concern that universal energy demand reduction strategies may compromise the ability of households within local authorities to achieve wellbeing, and that greater subsidiarity, and therefore a disaggregated approaches to energy demand reduction in Great Britain, are necessary for an equitable demand-side transition, particularly for heating and personal transport energy service demands.

9.3 Limitations

9.3.1 The service-driven energy demand chain framework and the services approach to energy demand reduction shortcomings

Adopting a service-based approach, from a local authority perspective, to the demand-side of the energy system has been beneficial to this study for understanding the level of energy service demands demanded from the energy system by households at a local authority level (Chapter 5), and the level of energy demand reduction for different energy service demands under four different energy demand reduction strategies (Chapter 6). However, there are shortcomings to the approach used in this thesis, and the service-driven energy demand chain framework itself.

Firstly, while the approach set out in Chapter 4 is insightful – i.e. placing the energy service demands of a local authority at the beginning of an analysis which focuses upon energy demand reduction – when considering the flow of energy, the perspective is counter-intuitive. The current framing of the energy system used in policymaking, academia, frameworks and models generally adopts a top-down perspective of the energy system as energy flows from primary to final energy before it is converted to energy service demands which are demanded by households. Therefore there may be a risk of confusion from stakeholders attempting to utilise this framing and the service-driven energy demand chain framework.

Additionally, the framing of the energy system using the service-driven energy demand chain framework requires the use of input-output methodologies to model household energy service demands at a local authority level and the effect of energy demand reduction strategies upon Great Britain. Input-output modelling is increasingly used in academic studies, but is not widely utilised by governments for energy accounting. Therefore, government officials are unaccustomed to using consumption-based accounting and making policy decisions based upon such datasets.

The shortcomings of the service-driven energy demand chain framework and the service-based approach from a local authority perspective can however be accounted for in simple ways. Confusion regarding the energy system framing can be reduced with proper briefing, while training in input-output methodology could resolve the issues with uptake. It is therefore possible to overcome barriers to the use of the service-driven energy demand chain framework beyond this thesis.

9.3.2 Shortcomings of the consumption-based energy service demand footprints

Despite the benefits of understanding the energy consumption associated with Great Britain's energy service demands, for different energy services, as well as the variation in energy service demands across space, there are shortcomings of the methodology and results utilised in this thesis. Great

Britain's energy service demands were examined at a local authority level as this is the lowest level of government in the UK with meaningful powers. However, local authorities are still areas of aggregated consumption.

The results in Chapter 5 show how energy service demands vary across space, but examining energy consumption at a local authority level may mask the variation in energy service demands within a local authority. This was demonstrated in Chapter 5 when the socioeconomic variables such as income and household size did not display strong relationships with energy service demands levels across Great Britain. Examining energy service demands at a local authority level may therefore lead to households exhibiting high or low energy service demand levels within local authorities being overlooked when considering local authority level energy consumption.

Additionally, the methodology underpinning the modelling work in Chapter 5 has disadvantages. The consumption-based energy service demands footprints in Chapter 5 are generated using the Living Costs and Food survey, which focuses upon collecting household-level expenditure microdata across a national scale. Such data has been used successfully in the past to generate footprint profiles across income deciles and space, and can be scaled to a national-level using calculated scaling values representing the number of households of each survey's type in the UK (Owen and Barrett, 2020; Baltruszewicz, Steinberger, Ivanova, *et al.*, 2021).

Scaling and disaggregating sampled data comes with inherent risks of misrepresenting the energy footprints of each local authority in Great Britain. Households within the same output area classification, in different areas of the country, are unlikely to have identical consumption patterns, which means that despite efforts to reduce error through scaling, the energy service demand footprints produced in Chapter 5 are less accurate without specific locally-collected energy consumption data.

However, environmental footprints generated using input-output data are a well-regarded method of considering energy consumption across space. The footprints generated in Chapter 5 may contain an element of error, however they provide a representative view of energy consumption in different areas of Great Britain.

9.3.3 Disadvantages of a services-oriented approach to demand-side mitigation

Previous studies on the transition to a low energy demand society, such as Barrett *et al.*, (2022), examine the effect and evolution of different energy demand reduction strategies over time, examining the potential impact at 10 year intervals up to 2050. However, due to the available data on consumption-based energy demand reduction options, and the input-output methodology utilised in Chapter 6, the energy demand reduction strategies modelled in Chapter 6 could not demonstrate how energy demand reduction evolved in each local authority throughout Great Britain over time. The input-output methodology set out in Wood *et al.*, (2018) is therefore limited from projecting full energy demand reduction scenarios, and considering how the impact of energy demand reduction options encourages greater innovation and more radical options to be implemented and accepted over time. This may therefore lead to the underestimation of energy demand reduction potential across local authorities in Great Britain.

The input-output approach also models the effect of energy demand reduction options on aggregate groups of products and services, rather than individual responses, and cannot capture long-term trends which occur alongside energy demand reduction option implementation, but are not specifically modelled – e.g. shifting to active transport, and therefore healthier transport habits, may lead to households adopting healthier, more plant-based diets too (Wood *et al.*, 2018). Additionally, the method cannot assess non-linear responses to energy demand reduction measures such as economic of scale (Wood *et al.*, 2018).

There is also a limitation concerning the underlying acceptance rates used to generate the results of the strategies in Chapter 6, whereby there is a tension between the use of a universal acceptance rate in Chapter 6, and the capacity index analysis in Chapter 7. In Chapter 6 the acceptance of each measure is assumed to be the same across each Local Authority throughout Great Britain (Appendix 7). However, Chapter 7 demonstrates that each Local Authority has a different capacity index score, thus indicating that acceptance and uptake of each energy demand reduction measure in Chapter 6's strategies would not be universal across Great Britain. A universal acceptance rate was utilised to negate the need to generate local authority-specific acceptance rates and therefore reduce the complexity of the data required to model the strategies in Chapter 6. However, the shortcoming of this methodological choice was to potentially limit even greater variation of the results presented in Chapter 6. Future work modelling the potential of energy demand reduction strategies at a local authority-level should therefore consider generating and utilising locally-specific acceptance rates to improve the robustness of the results generated by the model, and therefore allow greater insight into the potential of measures and strategies on a local scale.

Beyond the methodology chosen in this thesis, the energy demand reduction strategies were designed based upon the avoid-shift-improve framework to demonstrate how energy demand reduction potential varied between an energy efficiency, a maintained service level, a reduced service level and a full consideration strategy. The potential of the service-based approach to consider a wide range of strategies which go beyond dividing measures based upon whether they improve, shift or avoid energy use, was not exploited in Chapter 6. For example, a strategy based upon current government plans could have been modelled, or a strategy based upon low cost measures. Additionally, only universal energy demand reduction strategies were considered when different approaches to energy demand reduction could have been modelled for different local authorities throughout Great Britain, which is important for considering energy demand reduction in the context of subsidiarity. The results in Chapter 6 are therefore limited by the scope of the thesis. However, there is therefore potential for future work to exploit these gaps and explore more strategies for energy demand reduction, and their effect upon the energy service demands of households in Great Britain.

9.3.4 Disadvantages of the capacity study for energy demand reduction

The capacity index scores, and subsequent correlation analysis in Chapter 7 was limited by inherent limitations of the work in Chapter 5 and Chapter 6, as well as the available local authority data for infrastructure levels and the number, and detail, of different socioeconomic variables. Capital is a complex concept, and the list of indicators that could have been included under each capital type is potentially endless, while the research in Chapter 7 did not consider the linkages between each capital type – i.e. Higher financial capital leading to higher physical capital.

Capacity analysis, using the capacity index method, is usually undertaken as part of adaptation studies, rather than mitigation studies. Therefore it is important to consider whether the use of a capacity index, and the consideration of the five type of capital model, achieved its purpose in this study.

Considering the initial research question in Section 1.2.4, the results in Chapter 7 clearly answered the second half of research question 4, “do high capacity index scores align with local authorities exhibiting high levels of energy service demands and energy demand reduction potential?” by comparing local authorities capacity index scores with the energy service demand and energy demand reduction results in Chapters 5 and 6 respectively. However, the first half of the research question: “what is the capacity of households to adopt each energy demand reduction strategy in Great Britain at local authority level?” is more complicated.

In the context of research question 4 (Section 1.2.4), based upon the analysed indicators, the results in Chapter 7 do indicate local authorities where households generally have higher capacity to adopt the strategies modelled in Chapter 6. For example, under financial capital, proportion of income spent on non-essential consumption indicates local authorities where households are not living at, or beyond, their means, meaning that, for example, a shift to a more expensive, plant-based diet is less likely to impact upon their wellbeing by compromising their financial capital. Similarly, proportion of owner-occupied housing, under physical capital, indicates local authorities where consumers are homeowners, and do not have to rely upon landlords to implement measures such as better thermal insulation, indicating higher adaptive capacity.

However, other capital types – e.g. natural capital – are limited by the choice of indicators. In this study, natural capital neglected consideration of natural resources required for the transition to a low energy demand society. Natural capital, under the five capital model, is generally approached using this framing. Considering natural capital in this way, at a local authority-level however would not have been appropriate for the study of the adaptive capacity of households within local authorities. The research in Chapter 7 was considering the adaptive capacity of households to adopt the full consideration strategy in Chapter 6, rather than the ability of the global supply chain to produce the level of infrastructure and products necessary for the transition. The use of population density as an indicator of natural capital therefore does not align with previous usage of the five capital model in capacity studies.

The ability of the global supply chain to cope with the potential transition set out in the full consideration strategy is important to consider however, and is neglected by this thesis. Future studies should examine the level of natural resources required for a low energy demand transition alongside population density, as different local authorities will require different levels of natural resources to build the infrastructure required under the full consideration strategy. Analysing this element of the demand-side transition would enhance the research undertaken in Chapter 7 to give a more complete picture of the adaptive capacity of local authorities, and the households within them, to adopt the full consideration strategy. However, calculating the level of natural resources required for the transition was beyond the scope of this thesis.

As with Chapter 5 and Chapter 6, the use of local authorities, rather than households may also mute the nuance of the capacity index scores in each of the local authorities in Great Britain. Focusing upon individual households, rather than local authorities, may yield different results which show that a full consideration strategy is appropriately implemented at a national-level in Great Britain, which is missed when focusing upon the aggregated area of a local authority.

Similarly, the complexity of capital, and the need to draw boundaries for each capital type when considering which indicators to examine, leads to limitations of the results in Chapter 7. Future work can however build upon these results drawing in more indicators under each capital type, and undertaking micro-level capacity analysis to identify the variation in household ability to adopt a full consideration strategy The results in Chapter 7 therefore give a good, initial indication of the adaptive capacity of each local authority throughout Great Britian which can be built upon in the future.

Additionally, while it was beyond the scope of the thesis, Chapter 7 did not examine bespoke energy demand reduction strategies for different areas of Great Britain. Therefore, while a universal full consideration strategy appears to be inappropriate for implementation in Great Britain due to the lack of correlation between modelled energy demand reduction levels and areas of higher capacity index scores, a set of non-universal approaches have not been considered and may generate similar results.

9.4 Future work

Energy demand reduction in Great Britain will remain a pressing concern as the transition to a net-zero society continues over the 21st century. Bringing about effective, equitable energy demand reduction is one of the most significant challenges of our time, with large shifts in technology, increases in infrastructure, and shifts in behaviour and practices necessary for a sustainable, 1.5 °C future. Going forward, the work generated in this thesis can contribute to achieving this future.

The work in this thesis has quantified the levels of household energy service demands, and demonstrated that under a full consideration strategy, energy demand reduction can be undertaken in Great Britain to a level which is in-line with the levels necessary for a 1.5°C future (Masson-Delmotte *et al.*, 2018). Additionally, the research on capacity index scores at a local authority level demonstrate that capacity to adopt energy demand reduction strategies across different types of capital is similar throughout Great Britain. However, the research in Chapter 7 demonstrated that energy demand reduction under a universal full consideration strategy does not necessarily target areas of Great Britain with different levels of capacity to adopt energy demand reduction strategies, and that a bespoke, disaggregated approach to energy demand reduction may be appropriate across different areas of Great Britain due to differing present-day levels of energy service demands and capacity index scores.

The research throughout the thesis has advocated the need to go beyond energy efficiency, with the need for an increased focus upon the ‘avoid’ and ‘shift’ columns of the ‘avoid-shift-improve’ framework, in particular Chapter 6 which demonstrates the potential of a ‘full consideration’ strategy to reduce energy demand as opposed to an energy efficiency-only strategy. A scale-up of ambition by all actors is needed for the full consideration strategy to be realised however.

The scale-up of ambition requires buy-in from all actors involved with the demand-side transition, including national and local governments, utility providers, companies managing the supply chain of goods and services and individual households. Current strategies and behaviours adopted by all actors reinforce current unsustainable lifestyle practices at present. The national governent therefore needs to consider energy demand reduction measures beyond energy efficiency and encourage the uptake of new technologies, such as heat pumps and battery-electric vehicles, and alternative lifestyle practices, such as plant-based diets. Utility companies need to shift to greater levels of renewable electricity production, and phase-out fossil fuels, while companies providing goods and services to consumers need to consider more sustainable product standards and alter their business strategies towards making better use of the circular and sharing economies. Local authorities and individual households are more ambitious than other actors in the supply chain, however they often lack the funding to undertake more ambitious demand-side action themselves, and encourage others to undertake similar actions.

The research in this thesis acts as a guide for local authorities on the average household energy service footprint, as well as the potential effect of different energy demand reduction measures upon households, in their locality. For the work in this thesis to be translated into bespoke, local policy actions, each local authority will need to build upon the analysis presented in this thesis to determine the potential of implementing different energy demand reduction strategies in different local authorities throughout Great Britain. A disaggregated approach to energy demand reduction may speed-up the mitigation process and allow local authority specific energy demand reduction strategies to be implemented that do not compromise the wellbeing of households to be set out.

At present, the analysis in this thesis demonstrates that at a local-level, there is great potential for energy demand reduction in households across Great Britain. However, local authorities only have limited powers which govern certain areas of the demand-side transition. For the research in this thesis to be translated into bespoke policy actions, local authorities must draw together local partners to facilitate the demand-side transition in their locality, put pressure on the national UK government to increase policy ambition and to devolve more funding to enact ambitious local policies, while also working collaboratively with other, nearby local authorities to address cross-boundary issues such as households commuting from one local authority to another – e.g. from Guildford to London.

While beyond the scope of this thesis, more work also needs to be done on the devolution of powers to local authorities for demand-side energy policy. This work must consider whether powers should be devolved, what form they should take or whether funding should be set aside for local authorities to enact demand-side policy within their current power set. The Labour party is calling for more devolution to regional and local government in the UK, therefore the form and extent of these powers needs to be considered before the next General Election in 2024, when this policy promise may be enacted (Labour, 2022).

Building upon the work in this thesis is important for the transition to net-zero, through understanding whether the energy demand reduction potential of universal strategies varies in different areas of Great Britain, designing local authority specific energy demand reduction strategies and identifying the powers local authorities may need to make further cuts to energy consumption, which doesn't compromise wellbeing, across Great Britain. It is hoped that by setting out this work, and identifying that universal demand-side policies in Great Britain may be effective, but inequitable, in different areas of the country, that more work will be undertaken in this area in order to accelerate an effective and equitable transition to a low energy demand society.

10 Appendix

Appendix 1 Concordance Matrix weightings used to calculate energy service footprints in Chapter 5.

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
1.1.1.1 Rice	0	0	0	0	0	1	0	0	0
1.1.1.2 Bread	0	0	0	0	0	1	0	0	0
1.1.1.3 Other breads and cereals	0	0	0	0	0	1	0	0	0
1.1.2 Pasta products	0	0	0	0	0	1	0	0	0
1.1.3.1 Buns, crispbread and biscuits	0	0	0	0	0	1	0	0	0
1.1.3.2 Cakes and puddings	0	0	0	0	0	1	0	0	0
1.1.4 Pastry (savoury)	0	0	0	0	0	1	0	0	0
1.1.5 Beef (fresh, chilled or frozen)	0	0	0	0	0	1	0	0	0
1.1.6 Pork (fresh, chilled or frozen)	0	0	0	0	0	1	0	0	0
1.1.7 Lamb (fresh, chilled or frozen)	0	0	0	0	0	1	0	0	0
1.1.8 Poultry (fresh, chilled or frozen)	0	0	0	0	0	1	0	0	0
1.1.9 Bacon and ham	0	0	0	0	0	1	0	0	0
1.1.10.1 Sausages	0	0	0	0	0	1	0	0	0
1.1.10.2 Offal, pate etc.	0	0	0	0	0	1	0	0	0
1.1.10.3 Other preserved or processed meat and meat preparations	0	0	0	0	0	1	0	0	0
1.1.10.4 Other fresh, chilled or frozen edible meat	0	0	0	0	0	1	0	0	0
1.1.11.1 Fish (fresh, chilled or frozen)	0	0	0	0	0	1	0	0	0
1.1.11.2 Seafood, dried, smoked or salted fish	0	0	0	0	0	1	0	0	0
1.1.11.3 Other preserved or processed fish and seafood	0	0	0	0	0	1	0	0	0
1.1.12.1 Whole milk	0	0	0	0	0	1	0	0	0
1.1.12.2 Low fat milk	0	0	0	0	0	1	0	0	0
1.1.12.3 Preserved milk	0	0	0	0	0	1	0	0	0
1.1.13 Cheese and curd	0	0	0	0	0	1	0	0	0
1.1.14 Eggs	0	0	0	0	0	1	0	0	0
1.1.15.1 Other milk products	0	0	0	0	0	1	0	0	0
1.1.15.2 Yoghurt	0	0	0	0	0	1	0	0	0
1.1.16 Butter	0	0	0	0	0	1	0	0	0
1.1.17 Margarine and other vegetable fats and peanut butter	0	0	0	0	0	1	0	0	0
1.1.18.1 Olive oil	0	0	0	0	0	1	0	0	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
1.1.18.2 Edible oils and other animal fats	0	0	0	0	0	1	0	0	0
1.1.19.1 Citrus fruits	0	0	0	0	0	1	0	0	0
1.1.19.2 Bananas	0	0	0	0	0	1	0	0	0
1.1.19.3 Apples	0	0	0	0	0	1	0	0	0
1.1.19.4 Pears	0	0	0	0	0	1	0	0	0
1.1.19.5 Stone fruits	0	0	0	0	0	1	0	0	0
1.1.19.6 Berries	0	0	0	0	0	1	0	0	0
1.1.20 Other fresh, chilled or frozen fruits	0	0	0	0	0	1	0	0	0
1.1.21 Dried fruit and nuts	0	0	0	0	0	1	0	0	0
1.1.22 Preserved fruit and fruit based products	0	0	0	0	0	1	0	0	0
1.1.23.1 Leaf and stem vegetables	0	0	0	0	0	1	0	0	0
1.1.23.2 Cabbages	0	0	0	0	0	1	0	0	0
1.1.23.3 Vegetables grown for their fruit	0	0	0	0	0	1	0	0	0
1.1.23.4 Root crops, non-starchy bulbs and mushrooms	0	0	0	0	0	1	0	0	0
1.1.24 Dried vegetables	0	0	0	0	0	1	0	0	0
1.1.25 Other prepared or processed vegetables	0	0	0	0	0	1	0	0	0
1.1.26 Potatoes	0	0	0	0	0	1	0	0	0
1.1.27 Other tubers and products of tuber vegetables	0	0	0	0	0	1	0	0	0
1.1.28.1 Sugar	0	0	0	0	0	1	0	0	0
1.1.28.2 Other sugar products	0	0	0	0	0	1	0	0	0
1.1.29 Jams and marmalades	0	0	0	0	0	1	0	0	0
1.1.30 Chocolate	0	0	0	0	0	1	0	0	0
1.1.31 Confectionery products	0	0	0	0	0	1	0	0	0
1.1.32 Edible ices and ice cream	0	0	0	0	0	1	0	0	0
1.1.33.1 Sauces, condiments	0	0	0	0	0	1	0	0	0
1.1.33.2 Baker’s yeast, dessert preparations, soups	0	0	0	0	0	1	0	0	0
1.1.33.3 Salt, spices, herbs and other food products	0	0	0	0	0	1	0	0	0
1.2.1 Coffee	0	0	0	0	0	1	0	0	0
1.2.2 Tea	0	0	0	0	0	1	0	0	0
1.2.3 Cocoa and powdered chocolate	0	0	0	0	0	1	0	0	0
1.2.4 Fruit and vegetable juices	0	0	0	0	0	1	0	0	0
1.2.5 Mineral or spring waters	0	0	0	0	0	1	0	0	0
1.2.6 Soft drinks	0	0	0	0	0	1	0	0	0
2.1.1 Spirits and liqueurs	0	0	0	0	0	0	1	0	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
2.1.2.1 Wine from grape or other fruit	0	0	0	0	0	0	1	0	0
2.1.2.2 Fortified wine	0	0	0	0	0	0	1	0	0
2.1.2.3 Champagne and sparkling wines	0	0	0	0	0	0	1	0	0
2.1.3.1 Beer and lager	0	0	0	0	0	0	1	0	0
2.1.3.2 Ciders and Perry	0	0	0	0	0	0	1	0	0
2.1.4 Alcopops	0	0	0	0	0	0	1	0	0
2.2.1 Cigarettes	0	0	0	0	0	0	1	0	0
2.2.2.1 Cigars	0	0	0	0	0	0	1	0	0
2.2.2.2 Other tobacco	0	0	0	0	0	0	1	0	0
3.1.1 Men’s outer garments	0	0	0	0	0	0	0	1	0
3.1.2 Men’s under garments	0	0	0	0	0	0	0	1	0
3.1.3 Women’s outer garments	0	0	0	0	0	0	0	1	0
3.1.4 Women’s under garments	0	0	0	0	0	0	0	1	0
3.1.5 Boys outer garments	0	0	0	0	0	0	0	1	0
3.1.6 Girls outer garments	0	0	0	0	0	0	0	1	0
3.1.7 Infants outer garments	0	0	0	0	0	0	0	1	0
3.1.8 Children’s under garments	0	0	0	0	0	0	0	1	0
3.1.9.1 Men’s accessories	0	0	0	0	0	0	0	1	0
3.1.9.2 Women’s accessories	0	0	0	0	0	0	0	1	0
3.1.9.3 Children’s accessories	0	0	0	0	0	0	0	1	0
3.1.9.4 Protective head gear	0	0	0	0	0	0	0	1	0
3.1.10 Haberdashery, clothing materials and clothing hire	0	0	0	0	0	0	0	0.67	0.33
3.1.11.1 Dry cleaners and dyeing	0	0	0	0	0	0	0	0.5	0.5
3.1.11.2 Laundry, laundrettes	0	0.5	0	0	0	0	0	0	0.5
3.2.1 Footwear for men	0	0	0	0	0	0	0	1	0
3.2.2 Footwear for women	0	0	0	0	0	0	0	1	0
3.2.3 Footwear for children and infants	0	0	0	0	0	0	0	1	0
3.2.4 Repair and hire of footwear	0	0	0	0	0	0	0	1	0
4.1.1 Actual rentals	0	1	0	0	0	0	0	0	0
4.1.2 Imputed rent	0	1	0	0	0	0	0	0	0
4.2.1 Central heating repairs	1	0	0	0	0	0	0	0	0
4.2.2 House maintenance	0	1	0	0	0	0	0	0	0
4.2.3 Paint, wallpaper, timber	0	1	0	0	0	0	0	0	0
4.2.4 Equipment hire, small materials	0	1	0	0	0	0	0	0	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
4.3.1 Water charges	0	1	0	0	0	0	0	0	0
4.3.2 Other regular housing payments incl. service charge for rent	0	0.5	0	0	0	0	0	0	0.5
4.3.3 Refuse collection including skip hire	0	0.5	0	0	0	0	0	0	0.5
5.1.1.1 Furniture	0	1	0	0	0	0	0	0	0
5.1.1.2 Fancy/decorative goods	0	1	0	0	0	0	0	0	0
5.1.1.3 Garden furniture	0	1	0	0	0	0	0	0	0
5.1.2.1 Soft floor coverings	0	1	0	0	0	0	0	0	0
5.1.2.2 Hard floor coverings	0	1	0	0	0	0	0	0	0
5.2.1 Bedroom textiles including duvets and pillows	0	0	0	0	0	0	0	1	0
5.2.2 Other household textiles, including cushions, towels, curtains	0	0	0	0	0	0	0	1	0
5.3.1 Gas cookers	0	0	0	0	0	1	0	0	0
5.3.2 Electric cookers, combined gas/electric cookers	0	0	0	0	0	1	0	0	0
5.3.3 Clothes washing machines and clothes drying machines	0	1	0	0	0	0	0	0	0
5.3.4 Refrigerators, freezers and fridge freezers	0	0	0	0	0	1	0	0	0
5.3.5 Other major electrical appliances e.g. dish washers, microwaves, vacuum cleaners, heaters	0	1	0	0	0	0	0	0	0
5.3.6 Fire extinguishers	0	1	0	0	0	0	0	0	0
5.3.7 Small electric household appliances	0	1	0	0	0	0	0	0	0
5.3.8 Spare parts for appliances and repairs	0	1	0	0	0	0	0	0	0
5.3.9 Rental/hire of major household appliances	0	0.5	0	0	0	0	0	0	0.5
5.4.1 Glassware, china, pottery, cutlery and silverware	0	1	0	0	0	0	0	0	0
5.4.2 Kitchen and domestic utensils	0	1	0	0	0	0	0	0	0
5.4.3 Repair of glassware, tableware and household utensils	0	1	0	0	0	0	0	0	0
5.4.4 Storage and other durable household articles	0	1	0	0	0	0	0	0	0
5.5.1 Electrical tools	0	1	0	0	0	0	0	0	0
5.5.2 Garden tools, equipment and accessories	0	1	0	0	0	0	0	0	0
5.5.3 Small tools	0	1	0	0	0	0	0	0	0
5.5.4 Door, electrical and other fittings	0	1	0	0	0	0	0	0	0
5.5.5 Electrical consumables	0	0.5	0	0	0	0	0	0.5	0
5.6.1.1 Detergents, washing-up liquid, washing powder	0	0.5	0	0	0	0	0	0.5	0
5.6.1.2 Disinfectants, polishes, other cleaning materials, some pest controls	0	0.5	0	0	0	0	0	0.5	0
5.6.2.1 Kitchen disposables	0	0.5	0	0	0	0	0	0.5	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
5.6.2.2 Household hardware and appliances, matches	0	0.5	0	0	0	0	0	0.5	0
5.6.2.3 Kitchen gloves, cloths etc.	0	0.5	0	0	0	0	0	0.5	0
5.6.2.4 Pins, needles, tape measures, nails, nuts and bolts	0	0.5	0	0	0	0	0	0.5	0
5.6.3.1 Domestic services including cleaners, gardeners, au pairs	0	0.5	0	0	0	0	0	0	0.5
5.6.3.2 Carpet cleaning , ironing service and window cleaner	0	0.5	0	0	0	0	0	0	0.5
5.6.3.3 Hire/repair of household furniture and furnishings	0	0.5	0	0	0	0	0	0	0.5
6.1.1.1 NHS prescription charges and payments	0	0	0	0	0	0	0	0	1
6.1.1.2 Medicines and medical goods (not NHS)	0	0	0	0	0	0	0	0	1
6.1.1.3 Other medical products	0	0	0	0	0	0	0	0	1
6.1.1.4 Non-optical appliances and equipment	0	0	0	0	0	0	0	0	1
6.1.2.1 Purchase of spectacles, lenses, prescription sunglasses	0	0	0	0	0	0	0	0	1
6.1.2.2 Accessories/repairs to spectacles/lenses	0	0	0	0	0	0	0	0	1
6.2.1.1 NHS medical, optical, dental and medical auxiliary services	0	0	0	0	0	0	0	0	1
6.2.1.2 Private medical, optical, dental and auxiliary services	0	0	0	0	0	0	0	0	1
6.2.1.3 Other services	0	0	0	0	0	0	0	0	1
6.2.2 In-patient hospital services	0	0	0	0	0	0	0	0	1
7.1.1.1 New cars/vans outright purchase	0	0	1	0	0	0	0	0	0
7.1.1.2 New cars/vans loan/HP purchase	0	0	1	0	0	0	0	0	0
7.1.2.1 Second-hand cars/vans outright purchase	0	0	1	0	0	0	0	0	0
7.1.2.2 Second-hand cars/vans loan/HP purchase	0	0	1	0	0	0	0	0	0
7.1.3.1 Outright purchase of new or second-hand motorcycles	0	0	1	0	0	0	0	0	0
7.1.3.2 Loan/HP purchase of new or second-hand motor cycles	0	0	1	0	0	0	0	0	0
7.1.3.3 Purchase of bicycles and other vehicles	0	0	1	0	0	0	0	0	0
7.2.1.1 Can/van accessories and fittings	0	0	1	0	0	0	0	0	0
7.2.1.2 Car/van spare parts	0	0	1	0	0	0	0	0	0
7.2.1.3 Motorcycle accessories and spare parts	0	0	1	0	0	0	0	0	0
7.2.1.4 Bicycle accessories and spare parts	0	0	1	0	0	0	0	0	0
7.2.2.1 Petrol	0	0	1	0	0	0	0	0	0
7.2.2.2 Diesel oil	0	0	1	0	0	0	0	0	0
7.2.2.3 Other motor oils	0	0	1	0	0	0	0	0	0
7.2.3.1 Car of van repairs, servicing and other work	0	0	1	0	0	0	0	0	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
7.2.3.2 Motor cycle repairs and servicing	0	0	1	0	0	0	0	0	0
7.2.4.1 Motoring organisation subscription	0	0	1	0	0	0	0	0	0
7.2.4.2 Garage rent other costs, car washing	0	0	1	0	0	0	0	0	0
7.2.4.3 Parking fees, tolls and permits	0	0	1	0	0	0	0	0	0
7.2.4.4 Driving lessons	0	0	1	0	0	0	0	0	0
7.2.4.5 Anti-freeze, battery water, cleaning materials	0	0	1	0	0	0	0	0	0
7.3.1.1 Rail and tube season tickets	0	0	0	1	0	0	0	0	0
7.3.1.2 Rail and tube other than season tickets	0	0	0	1	0	0	0	0	0
7.3.2.1 Bus and coach season tickets	0	0	0	1	0	0	0	0	0
7.3.2.2 Bus and coach other than season tickets	0	0	0	1	0	0	0	0	0
7.3.3.1 Combined fares other than season tickets	0	0	0	1	0	0	0	0	0
7.3.3.2 Combined fares season tickets	0	0	0	1	0	0	0	0	0
7.3.4.1 Air fares within UK	0	0	0	0	1	0	0	0	0
7.3.4.2 Air fares international	0	0	0	0	1	0	0	0	0
7.3.4.3 School travel	0	0	0	1	0	0	0	0	0
7.3.4.4 Taxis and hired cars with drivers	0	0	1	0	0	0	0	0	0
7.3.4.5 Other personal travel and transport services	0	0	1	0	0	0	0	0	0
7.3.4.6 Hire of self-drive cars, vans, bicycles	0	0	1	0	0	0	0	0	0
7.3.4.7 Car leasing	0	0	1	0	0	0	0	0	0
7.3.4.8 Water travel, ferries and season tickets	0	0	0	1	0	0	0	0	0
8.1 Postal services	0	0	0	0	0	0	0.5	0	0.5
8.2.1 Telephone purchase	0	0	0	0	0	0	1	0	0
8.2.2 Mobile phone purchase	0	0	0	0	0	0	1	0	0
8.2.3 Answering machine, fax machine purchase	0	0	0	0	0	0	1	0	0
8.3.1 Telephone account	0	0	0	0	0	0	1	0	0
8.3.2 Telephone coin and other payments	0	0	0	0	0	0	1	0	0
8.3.3 Mobile phone account	0	0	0	0	0	0	1	0	0
8.3.4 Mobile phone other payments	0	0	0	0	0	0	1	0	0
8.4 Internet subscription fees	0	0	0	0	0	0	1	0	0
9.1.1.1 Audio equipment, CD players incl. in car	0	0	0	0	0	0	1	0	0
9.1.1.2 Audio accessories e.g. tapes, CDs, headphones	0	0	0	0	0	0	1	0	0
9.1.2.1 Purchase of TV and digital decoder	0	0	0	0	0	0	1	0	0
9.1.2.2 Satellite dish purchase and installation	0	0	0	0	0	0	1	0	0
9.1.2.3 Cable TV connection	0	0	0	0	0	0	1	0	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
9.1.2.4 Video recorder	0	0	0	0	0	0	1	0	0
9.1.2.5 DVD player/recorder	0	0	0	0	0	0	1	0	0
9.1.2.6 Blank, pre-recorded video cassettes and DVDs	0	0	0	0	0	0	1	0	0
9.1.2.7 Personal computers, printers and calculators	0	0	0	0	0	0	1	0	0
9.1.2.8 Spare parts for TV, video, audio	0	0	0	0	0	0	1	0	0
9.1.2.9 Repair of AV	0	0	0	0	0	0	1	0	0
9.1.3.1 Photographic and cine equipment	0	0	0	0	0	0	1	0	0
9.1.3.2 Camera films	0	0	0	0	0	0	1	0	0
9.1.3.3 Optical instruments, binoculars, telescopes	0	0	0	0	0	0	1	0	0
9.2.1 Purchase of boats, trailers and horses	0	0	0	0	0	0	1	0	0
9.2.2 Purchase of caravans, mobile homes	0	0	0	0	0	0	1	0	0
9.2.3 Accessories for boats, horses, caravans and motorhomes	0	0	0	0	0	0	1	0	0
9.2.4 Musical instruments	0	0	0	0	0	0	1	0	0
9.2.5 Major durables for indoor recreation	0	0	0	0	0	0	1	0	0
9.2.6 Maintenance and repair or other major durables for recreation and culture	0	0	0	0	0	0	1	0	0
9.2.7 Purchase of motor caravan - outright purchase	0	0	0	0	0	0	1	0	0
9.2.8 Purchase of motor caravan - loan/HP	0	0	0	0	0	0	1	0	0
9.3.1 Games, toys and hobbies	0	0	0	0	0	0	1	0	0
9.3.2.1 Computer software and games cartridges	0	0	0	0	0	0	1	0	0
9.3.2.2 Console computer games	0	0	0	0	0	0	1	0	0
9.3.3 Equipment for sport, camping and open-air recreation	0	0	0	0	0	0	1	0	0
9.3.4.1 BBQ and swings	0	0	0	0	0	0	1	0	0
9.3.4.2 Plants, flowers, seeds, fertilisers, insecticides	0	0	0	0	0	0	1	0	0
9.3.4.3 Garden decorative	0	0	0	0	0	0	1	0	0
9.3.4.4 Artificial flowers, potpourri	0	0	0	0	0	0	1	0	0
9.3.5.1 Pet food	0	0	0	0	0	0	1	0	0
9.3.5.2 Pet purchase and accessories	0	0	0	0	0	0	1	0	0
9.3.5.3 Veterinary and other services for pets	0	0	0	0	0	0	1	0	0
9.4.1.1 Spectator sports - admission charges	0	0	0	0	0	0	1	0	0
9.4.1.2 Participant sports	0	0	0	0	0	0	1	0	0
9.4.1.3 Subscriptions to sports and social clubs	0	0	0	0	0	0	1	0	0
9.4.1.4 Hire of equipment for sport	0	0	0	0	0	0	1	0	0
9.4.1.5 Leisure class fees	0	0	0	0	0	0	1	0	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
9.4.2.1 Cinemas	0	0	0	0	0	0	1	0	0
9.4.2.2 Live entertainment, theatre, concerts, shows	0	0	0	0	0	0	1	0	0
9.4.2.3 Museums, zoological gardens, theme parks	0	0	0	0	0	0	1	0	0
9.4.3.1 TV licences	0	0	0	0	0	0	1	0	0
9.4.3.2 Satellite subscriptions	0	0	0	0	0	0	1	0	0
9.4.3.3 Rent for TV/Satellite/VCR	0	0	0	0	0	0	1	0	0
9.4.3.4 Cable subscriptions	0	0	0	0	0	0	1	0	0
9.4.3.5 TV slot meter payments	0	0	0	0	0	0	1	0	0
9.4.3.6 Video, cassette and CD hire	0	0	0	0	0	0	1	0	0
9.4.4.1 Admissions to clubs, dances. Discos, bingo	0	0	0	0	0	0	1	0	0
9.4.4.2 Social events and gatherings	0	0	0	0	0	0	1	0	0
9.4.4.3 Subscriptions for leisure activities	0	0	0	0	0	0	1	0	0
9.4.5 Development of film, photos	0	0	0	0	0	0	1	0	0
9.4.6.1 Football pools stakes	0	0	0	0	0	0	1	0	0
9.4.6.2 Bingo stakes	0	0	0	0	0	0	1	0	0
9.4.6.3 Lottery	0	0	0	0	0	0	1	0	0
9.4.6.4 Bookmaker, tote, other betting stakes	0	0	0	0	0	0	1	0	0
9.5.1 Books	0	0	0	0	0	0	1	0	0
9.5.2 Diaries, address books, cards etc.	0	0	0	0	0	0	1	0	0
9.5.3 Cards, calendars, posters and other printed matter	0	0	0	0	0	0	1	0	0
9.5.4 Newspapers	0	0	0	0	0	0	1	0	0
9.5.5 Magazines and periodicals	0	0	0	0	0	0	1	0	0
10.1 Education	0	0	0	0	0	0	0	0	1
10.2 Educational trips	0	0	0	0	0	0	0	0	1
11.1.1 Restaurant and café meals	0	0	0	0	0	0.5	0.5	0	0
11.1.2 Alcoholic beverages	0	0	0	0	0	0	1	0	0
11.1.3 Takeaway meals	0	0	0	0	0	0.5	0.5	0	0
11.1.4.1 Hot food and cold food	0	0	0	0	0	0.5	0.5	0	0
11.1.4.2 Confectionery	0	0	0	0	0	0.5	0.5	0	0
11.1.4.3 Ice cream	0	0	0	0	0	0.5	0.5	0	0
11.1.4.4 Soft drink	0	0	0	0	0	0.5	0.5	0	0
11.1.5 Contract catering	0	0	0	0	0	1	0	0	0
11.1.6.1 School meals	0	0	0	0	0	1	0	0	0
11.1.6.2 Meals bought in workplace	0	0	0	0	0	1	0	0	0

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
11.2.1 Holiday in the UK	0	0	0	0	0	0	1	0	0
11.2.2 Holiday abroad	0	0	0	0	0	0	1	0	0
11.2.3 Room hire	0	0	0	0	0	0	1	0	0
12.1.1 Hairdressing, beauty treatment	0	0	0	0	0	0	0.5	0	0.5
12.1.2 Toilet paper	0	0	0	0	0	0	0	1	0
12.1.3.1 Toiletries	0	0	0	0	0	0	0	1	0
12.1.3.2 Bar of soap, liquid soap, shower gel	0	0	0	0	0	0	0	1	0
12.1.3.3 Toilet requisites	0	0	0	0	0	0	0	1	0
12.1.4 Baby toiletries and accessories	0	0	0	0	0	0	0	1	0
12.1.5.1 Hair products	0	0	0	0	0	0	0	1	0
12.1.5.2 Cosmetics and related accessories	0	0	0	0	0	0	0	1	0
12.1.5.3 Electrical appliances for personal care	0	0	0	0	0	0	0	1	0
12.2.1.1 Jewellery clocks and watches and other personal effects	0	0	0	0	0	0	0	1	0
12.2.1.2 Leather and travel goods	0	0	0	0	0	0	0	1	0
12.2.1.3 Sunglasses	0	0	0	0	0	0	0	1	0
12.2.2.1 Baby equipment	0	0	0	0	0	0	0	1	0
12.2.2.2 Prams, pram accessories	0	0	0	0	0	0	0	1	0
12.2.2.3 Repairs to personal goods	0	0	0	0	0	0	0	1	0
12.3.1.1 Residential homes	0	0.5	0	0	0	0	0	0	0.5
12.3.1.2 Home help	0	0.5	0	0	0	0	0	0	0.5
12.3.1.3 Nursery, crèche, playschools	0	0	0	0	0	0	0	0	1
12.3.1.4 Child care payments	0	0	0	0	0	0	0	0	1
12.4.1.1 Structure insurance	0	0.5	0	0	0	0	0	0	0.5
12.4.1.2 Contents insurance	0	0.5	0	0	0	0	0	0	0.5
12.4.1.3 Insurance for household items	0	0	0	0	0	0	0	0.5	0.5
12.4.2 Medical insurance premiums	0	0	0	0	0	0	0	0	1
12.4.3.1 Vehicle insurance	0	0	0.5	0	0	0	0	0	0.5
12.4.3.2 Boat insurance	0	0	0	0	0	0	0.5	0	0.5
12.4.4 Non package holiday, other travel insurance	0	0	0	0	0	0	0.5	0	0.5
12.5.1.1 Moving and storage of furniture	0	0.5	0	0	0	0	0	0	0.5
12.5.1.2 Property transaction - purchase and sale	0	0.5	0	0	0	0	0	0	0.5
12.5.1.3 Property transaction - sale only	0	0.5	0	0	0	0	0	0	0.5
12.5.1.4 Property transaction - purchase only	0	0.5	0	0	0	0	0	0	0.5
12.5.1.5 Property transaction - other payments	0	0.5	0	0	0	0	0	0	0.5

COICOP Product Type and Code	Heating	Other Shelter	Personal Transport	Public Transport	Aerial Transport	Nutrition	R&C[1]	Consumer Goods	Services
12.5.2.1 Bank building society fees	0	0	0	0	0	0	0	0	1
12.5.2.2 Bank and post office counter charges	0	0	0	0	0	0	0	0	1
12.5.2.3 Credit card fees	0	0	0	0	0	0	0	0	1
12.5.3.1 Other professional fees	0	0	0	0	0	0	0	0	1
12.5.3.2 Legal fees	0	0	0	0	0	0	0	0	1
12.5.3.3 Funeral expenses	0	0	0	0	0	0	0	0	1
12.5.3.4 TU and professional organisations	0	0	0	0	0	0	0	0	1
12.5.3.5 Other payments for services	0	0	0	0	0	0	0	0	1

[1]Recreation & Communication

Appendix 2 ESD category sub-categories used to model EDR in Chapter 6

Energy Service Demand Category	Energy Service Demand Sub-Category
Heating	
	Heating
Other Shelter	
	Residential Services
	Rent & Maintenance
	Utilities
	Household Furnishings
	Household Consumables
	Shelter Finances
Personal Transport	
	Vehicle Purchase
	Vehicle Use
	Vehicle maintenance & Running costs
	Cycling
	Taxis
Public Transport	
	Bus Travel
	Rail Travel
	Other Travel
Aerial Transport	
	Air Travel
Nutrition	
	Cereal Products
	Meat Products
	Dairy Products & Eggs
	Oils, Spreads & fats
	Fruit & Vegetables
	Sugar, Confectionary & Desserts
	Non-Alcoholic Beverages
	Food Eaten Outside of Household
	Food Preparation
Recreation & Communication	
	Alcohol & Tobacco
	Holidays
	Information & Communication Services
	Audio-Visual & Gaming
	Hobbies & Recreational Goods
	Garden Products & Pets
	Recreational Services
	Takeaway Food
Consumer Goods	
	Clothing & Footwear
	Household Consumables
	Hygiene Products
	Personal Goods
Services	
	Domestic & Personal Services
	Health Services
	Education Services
	Financial Services
	Communication Services

Appendix 3 The number of LCFSs, from the 2015/16, 2016/17 and 2017/18 LCFSs, by OAC supergroup, group and subgroup.

OAC Supergroup	Total	OAC Group	Total	OAC Subgroup	Total
1: Rural Residents	1754				
		1A: Farming communities	550		
				1A1: Rural workers and families	88
				1A2: Established farming communities	201
				1A3: Agricultural communities	169
				1A4: Older farming communities	92
		1B: Rural tenants	972		
				1B1: Rural life	363
				1B2: Rural white-collar workers	380
				1B3: Ageing rural flat tenants	229
		1C: Ageing rural dwellers	232		
				1C1: Rural employment and retirees	70
				1C2: Renting rural retirement	72
				1C3: Detached rural retirement	90
2: Cosmopolitans	566				
		2A: Students around campus	108		
				2A1: Student communal living	16
				2A2: Student digs	27
				2A3: Students and professionals	65
		2B: Inner city students	112		
				2B1: Students and commuters	44
				2B2: Multicultural student neighbourhood	68
		2C: Comfortable cosmopolitan	203		
				2C1: Migrant families	111
				2C2: Migrant commuters	49
				2C3: Professional service cosmopolitans	43
		2D: Aspiring and affluent	143		
				2D1: Urban cultural mix	62
				2D2: Highly-qualified quaternary workers	32
				2D3: EU white-collar workers	49
3: Ethnicity Central	529				
		3A: Ethnic family life	215		
				3A1: Established renting families	120
				3A2: Young families and students	95
		3B: Endeavouring Ethnic Mix	114		

OAC Supergroup	Total	OAC Group	Total	OAC Subgroup	Total
				3B1: Striving service workers	50
				3B2: Bangladeshi mixed employment	34
				3B3: Multi-ethnic professional service workers	30
		3C: Ethnic dynamics	57		
				3C1: Constrained neighbourhoods	46
				3C2: Constrained commuters	11
		3D: Aspirational techies	143		
				3D1: New EU tech workers	36
				3D2: Established tech workers	42
				3D3: Old EU tech workers	65
4:Multicultural Metropolitans	1462				
		4A: Rented family living	639		
				4A1: Social renting young families	277
				4A2: Private renting new arrivals	226
				4A3: Commuters with young families	136
		4B: Challenged Asian terraces	414		
				4B1: Asian terraces and flats	252
				4B2: Pakistani communities	162
		4C: Asian traits	409		
				4C1: Achieving minorities	152
				4C2: Multicultural new arrivals	111
				4C3: Inner city ethnic mix	146
5: Urbanites	2778				
		5A: Urban professionals and families	1585		
				5A1: White professionals	596
				5A2: Multi-ethnic professionals with families	516
				5A3: Families in terraces and flats	473
		5B: Ageing urban living	1193		
				5B1: Delayed retirement	321
				5B2: Communal retirement	273
				5B3: Self-sufficient retirement	599
6:Suburbanites	3323				
		6A: Suburban achievers	1336		
				6A1: Indian tech achievers	251
				6A2: Comfortable suburbia	281
				6A3: Detached retirement living	494

OAC Supergroup	Total	OAC Group	Total	OAC Subgroup	Total
				6A4: Ageing in suburbia	310
		6B: Semi-detached suburbia	1987		
				6B1: Multi-ethnic suburbia	267
				6B2: White suburban communities	773
				6B3: Semi-detached ageing	550
				6B4: Older workers and retirement	397
7: Constrained City Dwellers	1239				
		7A: Challenged diversity	535		
				7A1: Transitional Eastern European neighbourhood	104
				7A2: Hampered aspiration	180
				7A3: Multi-ethnic hardship	251
		7B: Constrained flat dwellers	145		
				7B1: Eastern European communities	39
				7B2: Deprived neighbourhoods	46
				7B3: Endeavouring flat dwellers	60
		7C: White communities	408		
				7C1: Challenged transitionaries	119
				7C2: Constrained young families	141
				7C3: Outer city hardship	148
		7D: Ageing city dwellers	151		
				7D1: Ageing communities and families	56
				7D2: Retired independent city dwellers	36
				7D3: Retired communal city dwellers	45
				7D4: Retired city hardship	14
8: Hard-Pressed Living	2716				
		8A: Industrious communities	751		
				8A1: Industrious transitions	461
				8A2: Industrious hardship	290
		8B: Challenged terraced workers	444		
				8B1: Deprived blue-collar terraces	263
				8B2: Hard pressed rented terraces	181
		8C: Hard pressed ageing workers	819		
				8C1: Ageing industrious workers	393
				8C2: Ageing rural industry workers	190
				8C3: Renting hard-pressed workers	236
		8D: Migration and churn	702		

OAC Supergroup	Total	OAC Group	Total	OAC Subgroup	Total
				8D1: Young hard-pressed families	264
				8D2: Hard-pressed ethnic mix	301
				8D3: Hard-Pressed European Settlers	137

Appendix 4 Median carbon dioxide (CO_2) potential per capita by consumption-based policy option from Ivanova *et al.*, (2020), conversion factors from CO_2 to EDR potential in tonnes of oil equivalent (toe) per capita, and EDR potential in toe per capita.

Policy Option	CO_2 Potential (tCO_2 per capita)	Conversion Factor	EDR Potential (toe per capita)
Better thermal insulation	0.19	3.58	0.05
Better use of appliances	0.04	4.48	0.01
Car-pooling/sharing	0.34	7.25	0.05
Eat out eco-friendly	0.31	3.22	0.10
Energy and material efficiency (Transport)	0.13	3.39	0.04
Energy and material efficiency (Other Consumption)	0.03	4.81	0.01
Fewer appliances	0.03	4.93	0.01
Fewer purchases/durable items	0.07	4.85	0.01
Food sufficiency	0.13	3.66	0.04
Food waste management	0.03	3.66	0.01
Food waste reduction	0.26	3.66	0.07
Fuel efficient driving	0.21	7.25	0.03
Heat pump	0.79	3.58	0.22
Hot water saving	0.16	3.58	0.04
Improved cooking equipment	0.65	3.97	0.16
Less animal products	0.16	3.78	0.04
Less car transport	0.77	7.25	0.11
Less energy use (clothing)	0.04	4.48	0.01
Less living space/co-housing	0.27	3.58	0.08
Less packaging	0.16	3.66	0.04
Less paper	0.01	4.26	0.00
Less processed food/ alcohol	0.09	3.97	0.02
Less textiles	0.04	5.96	0.01
Less transport by air	0.44	2.94	0.15
Live car-free	2.07	7.25	0.29
Lower room temperature	0.09	3.58	0.03
Mediterranean and similar	0.38	3.66	0.10
More efficient appliances	0.06	4.48	0.01
No pets	0.35	3.74	0.09
Nutrition guidelines diet	0.23	3.66	0.06
One less flight (long return)	1.68	3.04	0.55
One less flight (medium return)	0.61	3.04	0.20
Organic food	0.40	3.56	0.11
Partial shift to dairy/plants/fish	0.17	3.78	0.05
Passive house	0.60	3.58	0.17
Produce own food	0.36	3.66	0.10
Produce renewable electricity	0.57	4.59	0.13
Recycle	0.01	5.01	0.00
Recycled materials	0.01	5.01	0.00
Refurbishment and renovation	0.89	3.58	0.25
Regional/local food	0.36	3.66	0.10
Renewable electricity	1.60	4.59	0.35
Renewable-based heating	0.64	3.58	0.18
Seasonal/ fresh food	0.21	3.66	0.06
Service/sharing economy	0.33	4.64	0.07
Shift to a smaller car	0.30	7.25	0.04
Shift to active transport	0.40	7.25	0.05
Shift to BEV	1.95	7.25	0.27
Shift to FCV	-0.33	7.25	-0.05
Shift to lower carbon meats	0.43	4.20	0.12
Shift to PHEV/HEV	0.45	7.25	0.06
Shift to public transport	0.98	7.25	0.14
Smart metering	0.10	4.59	0.02
Sustainable diet (unspecified)	0.54	3.68	0.15
Telecommuting	0.34	7.25	0.05

Policy Option	CO_2 Potential (tCO_2 per capita)	Conversion Factor	EDR Potential (toe per capita)
Vegan diet	0.80	3.78	0.21
Vegetarian diet	0.49	4.20	0.12
Walk instead of bus	0.08	1.65	0.05

Appendix 5 Energy demand reduction measures included within each of the three strategies modelled in Chapter 6.

Policy Option	Energy Efficiency	Maintained Service Levels	Reduced Service Levels	Full Consideration
Better thermal insulation	X	X		X
Better use of appliances	X	X		X
Car-pooling/sharing		X		X
Eat out eco-friendly		X		X
Energy and material efficiency (Transport)	X	X		X
Energy and material efficiency (Other Consumption)	X	X		X
Fewer appliances			X	X
Fewer purchases/durable items			X	X
Food sufficiency			X	X
Food waste management	X	X		X
Food waste reduction			X	X
Fuel efficient driving	X	X		X
Heat pump		X		X
Hot water saving			X	X
Improved cooking equipment	X	X		X
Less animal products			X	X
Less car transport			X	X
Less energy use (clothing)			X	X
Less living space/co-housing			X	X
Less packaging			X	X
Less paper			X	X
Less processed food/ alcohol			X	X
Less textiles			X	X
Less transport by air			X	X
Live car-free			X	X
Lower room temperature			X	X
Mediterranean and similar		X		X
More efficient appliances	X	X		X
No pets			X	X
Nutrition guidelines diet			X	X
One less flight (long return)			X	X
One less flight (medium return)			X	X
Organic food		X		X
Partial shift to dairy/plants/fish		X		X
Passive house			X	X
Produce own food		X		X
Produce renewable electricity		X		X
Recycle	X	X		X
Recycled materials		X		X
Refurbishment and renovation	X	X		X
Regional/local food		X		X

Policy Option	Energy Efficiency	Maintained Service Levels	Reduced Service Levels	Full Consideration
Renewable electricity		X		X
Renewable-based heating		X		X
Seasonal/ fresh food	X	X		X
Service/sharing economy			X	X
Shift to a smaller car	X	X		X
Shift to active transport		X		X
Shift to BEV	X	X		X
Shift to FCV	X	X		X
Shift to lower carbon meats		X		X
Shift to PHEV/HEV	X	X		X
Shift to public transport		X		X
Smart metering			X	X
Sustainable diet (unspecified)		X		X
Telecommuting			X	X
Vegan diet		X		X
Vegetarian diet		X		X
Walk instead of bus		X		X

Appendix 6 Assumptions of each energy demand reduction option (Median)

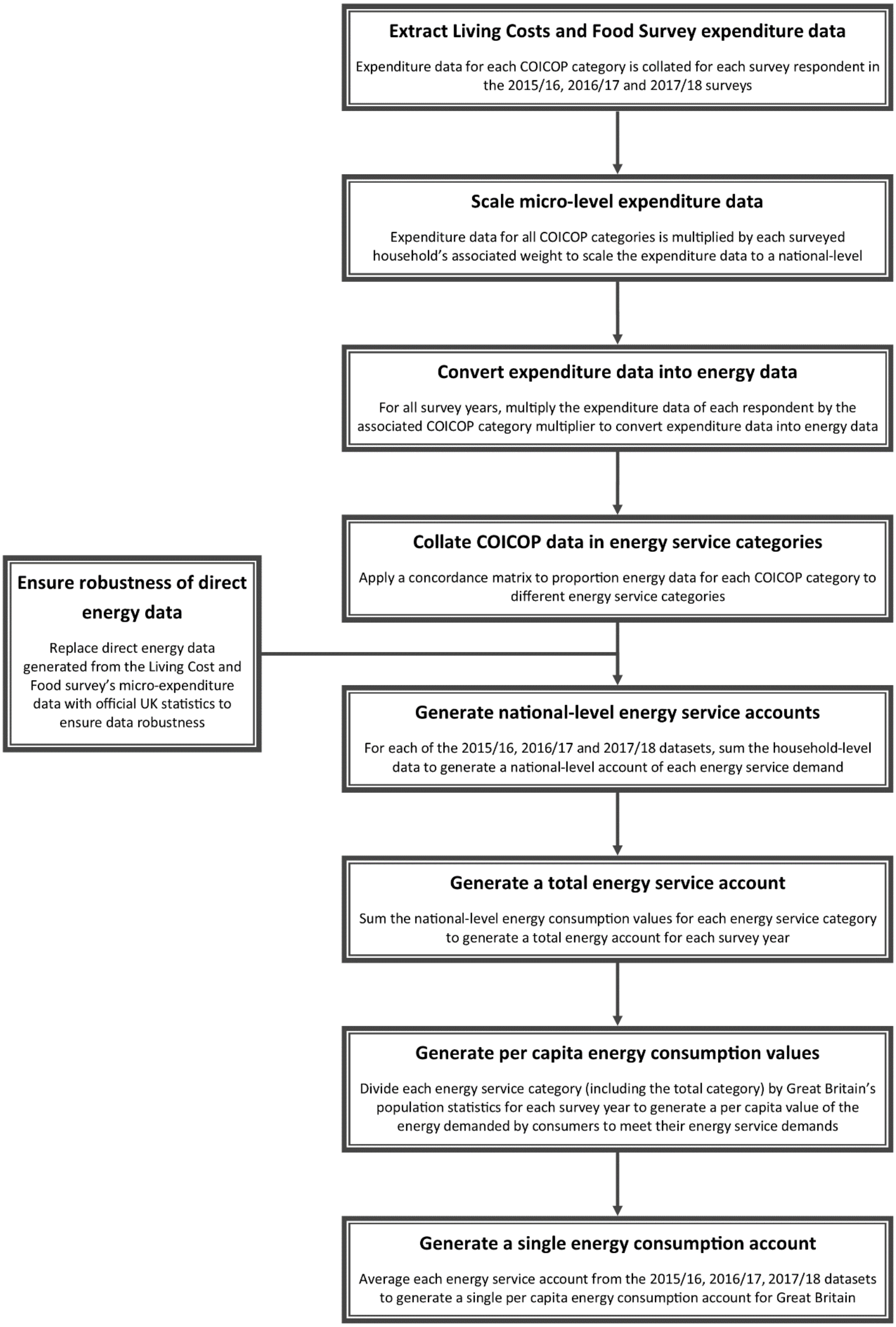
Energy Demand Reduction Option	Assumptions of each energy demand reduction option
Better thermal insulation	All households install cavity wall insulation (Sköld *et al.*, 2018)
Better use of appliances	Electronic devices are turned off instead of onto standby (Moran *et al.*, 2018)
Car-pooling/sharing	All households become car-club members (Wadud *et al.*, 2016)
Eat out eco-friendly	More plant-based foods in canteens and restaurants are eaten by households (Sköld *et al.*, 2018)
Energy and material efficiency (Transport)	Fossil-fuel vehicle fuel becomes more efficient (Sköld *et al.*, 2018)
Energy and material efficiency (Other Consumption)	Household purchase 30% more eco-labelled products (Sköld *et al.*, 2018)
Fewer appliances	Households give up some appliances (Sköld *et al.*, 2018)
Fewer purchases/durable items	Households buy 30% less furniture (Sköld *et al.*, 2018)
Food sufficiency	Households balance their energy intake through food (Hallström *et al.*, 2015)
Food waste management	Unavoidable food waste is managed properly – e.g. Composting fertiliser or animal feed (Moran *et al.*, 2018)
Food waste reduction	Avoidable food waste is reduced across all food products (Heller and Keoleian, 2015)
Fuel efficient driving	All households adopt eco-driving techniques (Sköld *et al.*, 2018)
Heat pump	All households install a heat pump (Sköld *et al.*, 2018)
Hot water saving	All households reduce their hot water usage (Akenji *et al.*, 2019)
Improved cooking equipment	Food production by all households becomes more efficient (Akenji *et al.*, 2019)
Less animal products	All households reduce their red and white meat consumption (Nelson *et al.*, 2016)
Less car transport	All households reduce motorised vehicle travel by 30% (Sköld *et al.*, 2018)
Less energy use (clothing)	All households wash clothes at lower temperatures (Moran *et al.*, 2018)
Less living space/co-housing	All households reduce their living space by 10% (Akenji *et al.*, 2019)
Less packaging	All households stop buying beverages in plastic and cans (Sköld *et al.*, 2018)
Less paper	All households reduce printing by only printing essential documents (Lekve Bjelle *et al.*, 2018)
Less processed food/ alcohol	All households give up ready meals (Sköld *et al.*, 2018)
Less textiles	All households buy 30% of clothes second hand (Sköld *et al.*, 2018)
Less transport by air	All households take 50% fewer domestic and inter-European (Sköld *et al.*, 2018)
Live car-free	All households live car-free (Wynes and Nicholas, 2017)
Lower room temperature	All households lower heated room temperature 2°C (Akenji *et al.*, 2019)
Mediterranean and similar	All households reduce their consumption of meat and dairy products by 30% (Song *et al.*, 2017)
More efficient appliances	All households upgrade home appliances to A +++ (Sköld *et al.*, 2018)
No pets	No households own a dog (Wynes and Nicholas, 2017)
Nutrition guidelines diet	All households follow the recommendations in the Dietary Approaches to Stop Hypertension diet (Nelson *et al.*, 2016)
One less flight (long return)	Households avoid transatlantic return flights (Wynes and Nicholas, 2017)
One less flight (medium return)	Households avoid return flights under 1,697km each way (Wynes and Nicholas, 2017)
Organic food	All households only buy organic food (Vita *et al.*, 2019)
Partial shift to dairy/plants/fish	19% reduction in energy intensive meat consumption by all households (Girod *et al.*, 2014)
Passive house	All households adopt passive house energy efficiency standards (Vita *et al.*, 2019)
Produce own food	All households produce their own food (Sköld *et al.*, 2018)
Produce renewable electricity	All households produce electricity (Sköld *et al.*, 2018)
Recycle	Households recycle clothing (Lekve Bjelle *et al.*, 2018)
Recycled materials	Households purchase toilet paper made from recycle material (Moran *et al.*, 2018)
Refurbishment and renovation	Old housing is replaced by new, energy efficient housing (Girod *et al.*, 2014)
Regional/local food	Households increase purchases of locally produced food by 30% (Sköld *et al.*, 2018)
Renewable electricity	Household electricity is supplied from tidal or waves generation (Amponsah *et al.*, 2014)

Energy Demand Reduction Option	Assumptions of each energy demand reduction option
Renewable-based heating	Household heating is shifted to solar thermal heating (Amponsah *et al.*, 2014)
Seasonal/ fresh food	Households buy fresh products instead of tinned or frozen produce (Sköld *et al.*, 2018)
Service/sharing economy	Households increase community service usage (Vita *et al.*, 2019)
Shift to a smaller car	Size of car is reduced by all households (Moran *et al.*, 2018)
Shift to active transport	Commuting is undertaken by bikes or e-bikes (Akenji *et al.*, 2019)
Shift to BEV	All cars are replaced by battery-electric vehicles (Marmiroli *et al.*, 2018)
Shift to FCV	Diesel cars are replaced by hydrogen fuel cell vehicles (Hao *et al.*, 2018)
Shift to lower carbon meats	A like-for-like substitution of meat for lower carbon meat alternatives (Clune *et al.*, 2017)
Shift to PHEV/HEV	Diesel cars are replaced by plug-in hybrid electric vehicles (Wolfram and Hertwich, 2019)
Shift to public transport	All car travel is shifted to rail transport – Regional or metro trains (Ivanova *et al.*, 2018)
Smart metering	All households install a smart meter (Malmodin and Coroama, 2017)
Sustainable diet (unspecified)	Households adopt a sustainable diet (González *et al.* 2011)
Telecommuting	Distance to workplace is reduced by 20% distance (Akenji *et al.*, 2019)
Vegan diet	All households adopt a vegan diet (Hallström *et al*, 2015)
Vegetarian diet	All households adopt a vegetarian diet (Hallström *et al.*, 2015)
Walk instead of bus	Public transport journeys under 9.4km are walked (Lekve Bjelle *et al.*, 2018)

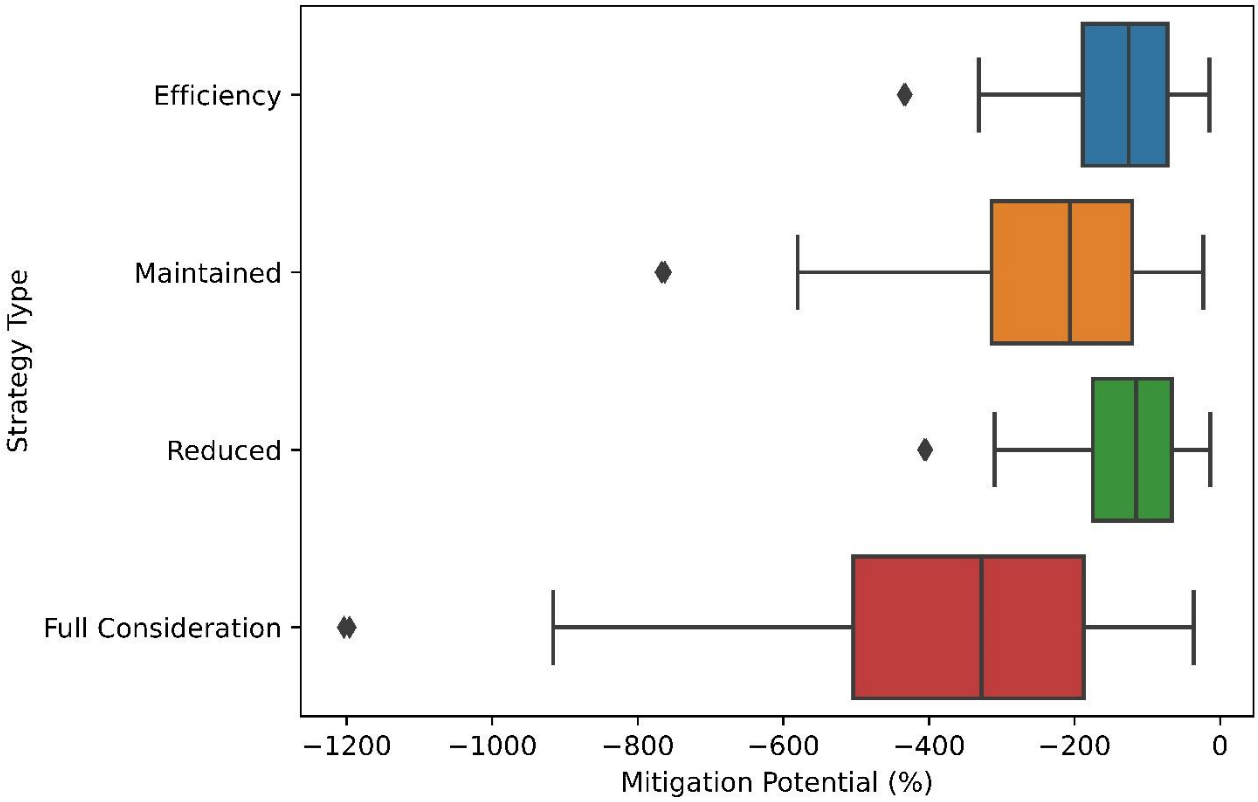
Appendix 7 Energy demand reduction potential and the estimated acceptance rate of each option modelled in the four energy demand reduction strategies in Chapter 6.

Energy Demand Reduction Option	Mitigation Potential (toe per capita)	Acceptance Rate
Better thermal insulation	0.05	45.4%
Better use of appliances	0.01	59.1%
Car-pooling/sharing	0.05	50.9%
Eat out eco-friendly	0.10	74.1%
Energy and material efficiency (Transport)	0.04	64.5%
Energy and material efficiency (Other Consumption)	0.01	67.9%
Fewer appliances	0.01	55.2%
Fewer purchases/durable items	0.01	63.1%
Food sufficiency	0.04	22.8%
Food waste management	0.01	45.1%
Food waste reduction	0.07	34.0%
Fuel efficient driving	0.03	83.9%
Heat pump	0.22	21.7%
Hot water saving	0.04	52.1%
Improved cooking equipment	0.16	57.0%
Less animal products	0.04	73.5%
Less car transport	0.11	58.9%
Less energy use (clothing)	0.01	52.4%
Less living space/co-housing	0.08	43.9%
Less packaging	0.04	92.1%
Less paper	0.00	92.1%
Less processed food/ alcohol	0.02	73.2%
Less textiles	0.01	58.8%
Less transport by air	0.15	17.8%
Live car-free	0.29	19.2%
Lower room temperature	0.03	66.1%
Mediterranean and similar	0.10	7.2%
More efficient appliances	0.01	70.3%
No pets	0.09	69.0%
Nutrition guidelines diet	0.06	12.3%
One less flight (long return)	0.55	21.3%
One less flight (medium return)	0.20	21.0%
Organic food	0.11	56.4%
Partial shift to dairy/plants/fish	0.05	33.2%
Passive house	0.17	26.9%
Produce own food	0.10	76.7%
Produce renewable electricity	0.13	28.8%
Recycle	0.00	96.3%
Recycled materials	0.00	71.5%
Refurbishment and renovation	0.25	30.9%
Regional/local food	0.10	73.9%
Renewable electricity	0.35	47.7%

Energy Demand Reduction Option	Mitigation Potential (toe per capita)	Acceptance Rate
Renewable-based heating	0.18	16.5%
Seasonal/ fresh food	0.06	68.8%
Service/sharing economy	0.07	58.2%
Shift to a smaller car	0.04	64.0%
Shift to active transport	0.05	20.0%
Shift to BEV	0.27	34.6%
Shift to FCV	-0.05	11.6%
Shift to lower carbon meats	0.12	18.6%
Shift to PHEV/HEV	0.06	11.8%
Shift to public transport	0.14	19.7%
Smart metering	0.02	56.0%
Sustainable diet (unspecified)	0.15	21.7%
Telecommuting	0.05	56.0%
Vegan diet	0.21	6.7%
Vegetarian diet	0.12	12.0%
Walk instead of bus	0.05	76.2%



Appendix 8 Key steps required to generate the national average Great Britain energy footprint of 2.47toe in Section 5.1 (Figure 5.1).



Appendix 9 Range of increase public transport ESDs under each of the four EDR strategies modelled in Chapter 6.

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