Integrating embodied emissions into climate change mitigation policy

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Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds
Sustainability Research Institute
School of Earth and Environment

February 2016

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Chapter 2 is a published paper: SCOTT, K. & BARRETT, J. 2015. An integration of net imported emissions into climate change targets. Environmental Science & Policy, 52, 150-157. I was responsible for research design, analysis and writing. John Barrett provided supervision and reviewed the paper.

Chapter 3 is a published paper: SCOTT K., DALY H., BARRETT J., STRACHAN N. (2015) National climate policy implications of mitigating embodied energy system emissions, *accepted on 26.1.16 in Climatic Change*. The paper was based on integrating two modelling approaches in collaboration with Hannah Daly and Neil Strachan at University College London (UCL). I undertook the analysis for one of the models (MRIO analysis) and Hannah was responsible for the analysis using the UK TIMES model. UCL lead on a preliminary paper describing the method and I lead a paper on the policy implications. I was responsible for the majority of the paper writing as well as framing the research questions. UCL co-authors were responsible for contributing text related to the methodology underlying the UK TIMES model. All co-authors offered advice and reviewed the paper.

Chapter 4 is a paper under review: SCOTT K., ROELICH K., OWEN A., BARRETT J. (2015) Addressing globally traded emissions through domestic consumption policies, *under review in Environmental Research Letters*. I took the lead on the paper and was responsible for the majority of the research framing, analysis and writing. The underlying input-output data was Provided by Anne Owen. Katy Roelich provided text for the policy discussion that I edited and John Barrett provided comments and discussion on the objectives of the paper.

Acknowledgements

Thank you to my primary supervisor John Barrett whose knowledge and insight into the vast area of climate mitigation I have extremely benefitted from. He has created a bright, encouraging and motivating research environment and has been a great support at every stage of my PhD. Thanks to my co-supervisor Julia Steinberger who provides constructive critical feedback that the PhD has undoubtedly benefitted from, and she encourages me to further develop my research career. I also want to thank Alice Bows-Larkin at Manchester University as this is where I originally started my PhD. She really took the time and attention to review and discuss everything I wrote and has continued to be encouraging since my move to Leeds University.

I was once told it takes a year to become familiar with a new complex model and so the collaboration with UCL to bring together our two modelling disciplines has made it possible to do a more thorough analysis in the time of the PhD. I think collaborations really expand your knowledge as a researcher and developing the model with Hannah Daly and Neil Strachan has definitely improved mine. My research group at Leeds university also has a great mix of skills and expertise and I have been able to discuss the very technical details of input-output models with Anne Owen and alternatively about climate change governance and policies with Katy Roelich. I always find our research group an open, approachable and knowledgeable team and I look forward to continue working with them.

I have found the Sustainability Research Institute to be a very enabling place to work. The research is very interdisciplinary and varied, the PhDs welcomed me from the start, the support staff have always been helpful and accommodating, the research groups provide a great foundation to share information and I have really enjoyed my time here.

Last but not least I must thank my family and friends who despite asking when I'm going to get a 'real' job make it easy to distract myself from my work and enjoy my life outside of it! A special thank you to Luis and my gran for their encouragement.

Abstract

International greenhouse gas emissions are typically monitored and regulated from a production perspective. This accounts for emissions produced directly by industries within a country's territory. International climate regulation centres around decarbonisation, negative emissions technologies and energy efficiency, none of which are aligned in practice with a two degree future. Given the remaining emissions gap between limiting temperature rise to two degrees (or lower) and existing climate mitigation pledges, mitigation policies must be constantly reviewed.

Materials act as a carrier of industrial energy that allows, through trade, the transfer of emissions between producers and consumers. Despite continual increases in aggregate consumption, industrialised countries have managed to stabilise their production emissions, partially from increasing imports from developing countries. For example, 20% of emissions growth in countries without climate targets under the Kyoto Protocol can be attributed to products exported for final consumption in countries with climate targets, who are not assigned any responsibility for reducing them. However international policies continue to prioritise production-related measures that reduce the carbon intensity of energy supply or reduce direct energy consumption. Reducing absolute demand for materials and products, which embody emissions, is absent from national climate policy packages in high-consuming developed countries. In this context, 'sufficiency' is seen as politically unpopular and often framed by companies and governments as denying consumers' basic rights or by describing consumers unwilling to change their behaviours. Yet evidence suggests consumption patterns are instead heavily influenced by ingrained social practices, locked in by powerful marketing corporations.

I investigate how the implementation of embodied emissions would redefine existing climate targets and policies, and explore further opportunities for resource consumption policies in climate mitigation. This is within the context of existing UK climate targets, however I also argue that the targets need to be reframed as they, in themselves, are not aligned with the international climate objective of preventing two degrees or lower temperature rise. I examine how the integration of embodied emissions would alter the UK's 2050 climate target and mitigation policies, how the UK's energy supply system might adapt when mitigating for emissions embodied in fuels and energy technologies, and the additional emissions scope of extending energy efficiency policies to include emissions embodied in resource use in the EU.

I conclude that resource consumption policies increase the policy portfolio of energy dominant mitigation strategies and can contribute to bridging the remaining emissions gap. However, the tools and targets used to devise this evidence base are limited, and need further validation. I propose complementing mandatory production emissions accounting with mandatory consumption-based accounts. Their use in policy would ensure actions in one country do not result in a shift in production impacts to another and increases the policies available to meeting climate targets, particularly in combination with resource efficiency policies. In the discussion I

make the case that the foundation of such a framework already exists and outline possible steps for implementation.

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Abbreviations

CBDR	Common But Differentiated Responsibilities
CBDR-RC	Common But Differentiated Responsibilities and Respective Capabilities
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CDM	Clean Development Mechanism
CO_2	Carbon dioxide
COP	Conference of Parties
DECC	Department for Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DMC	Domestic material consumption
EE-MRIO	Environmentally extended multi-region input-output
EKC	Environmental Kuznets Curve
ESME	Energy System Modelling Environment
ESOMs	Energy System Optimisation Models
ETP	Energy Technology Perspectives
ETS	Emissions Trading Scheme
EU	European Union
FEC	Final energy consumption
GDP	Gross domestic product
GHG	Greenhouse gases
Gt	Gigatonne
GtC	Gigatonnes of carbon
IEA	International Energy Agency
IEF	Indirect emissions factor
IMF	international Monetary Fund
INDCs	Intended Nationally Determined Contributions
IO	Input-output
IOA	Input-output analysis
IPCC	Intergovernmental Panel on Climate Change

MRIO	Multi-region input-output
Mt	Megatonne
n.e.c.	Not elsewhere classified
NGO	Non-Government Organisation
NPISH	Non-profit institutions serving households
OBR	Office for Budget Responsibility
OECD	Organisation for Economic Co-operation and Development
ONS	Office for National Statistics
PEC	Primary energy consumption
PEP	Primary energy production
PJ	Petajoule
RCP	Representative Concentration Pathway
SIC	Standard Industrial Classification
TCRE	Transient climate response to emissions
UCL	University College London
UKTM	UK TIMES energy system model
UNFCCC	United Nations Committee on Climate Change
WTO	World Trade Organisation

1 Introduction

Despite international agreement by 195 countries to reduce greenhouse gas emissions consistent with limiting global temperature rise to two degrees Celsius (UNFCCC, 2010), global greenhouse gas emissions continue to rise. National territorial emissions inventories are submitted annually to the UNFCCC to monitor progress. These report the volume of emissions released directly from production sectors within a country, incentivising countries to reduce end-of-pipe emissions generated within their territories. However, this accounting procedure underplays the role consumption has on rising emissions. This thesis investigates an alternative but complementary approach for national emissions accounting, target setting and policy making: a consumption-based accounting approach. Consumption emissions are the sum of emissions generated globally to produce products (goods and services) consumed in a country, also termed embodied emissions (Munksgaard and Pedersen, 2001, Peters and Hertwich, 2008a, Peters, 2008). Conceptually they are equal to territorial emissions plus emissions generated abroad to produce imports minus emissions generated domestically to produce exports. Changes to consumption therefore have the ability to reduce emissions generated outside a nation's territory from import production, creating potential policy applications that would not arise from a territorial accounting approach.

The problem of climate change is mounting, having arguably transgressed the boundaries for operating within two degrees of temperature rise (Rockstrom et al., 2009, Steffen et al., 2015). There is a well-established scientific foundation to inform climate policy so as to prevent warming of greater than two degrees, however climate change is proving difficult to mitigate, due largely to the complexity and multiplicity of actors involved. I have chosen to focus on the integration of embodied emissions into climate mitigation policy because it offers policy additionality, has been suggested as a compromise to break the climate impasse (Grasso and Roberts, 2014), and prevents countries shifting their emissions burden abroad. Whilst there has been a considerable amount of research reporting the consumption impacts of a region or organisation, developing and refining the models and methods , and to a lesser extent on quantifying the emissions saving potential of altering consumption patterns; there has been little empirical work on how its implementation would affect existing national climate policies and targets. This thesis attempts to move away from tracing the consumption-driven climate impacts of regions, to focusing on the solutions.

1.1 A consumption perspective of climate mitigation

A global deal on climate change is seen as an essential tool in reducing emissions, and this is being negotiated at the national level, with countries or regional groupings pledging individual action plans. It was the aim of the 21st Conference of Parties (COP 21) of the UNFCCC in

December 2015 to reach a global agreement on how to meet the internationally agreed two degree climate objective. The analysis in this thesis was completed before countries began submitting their most recent climate pledges, known as Intended Nationally Determined Contributions (INDCs), that were negotiated at the COP 21. Therefore, most of the text refers to the pre-existing pledges and policies. However, early indications suggest there still remains a considerable gap between targets and actions pledged and carbon budgets for a two degree future (Gütschow et al., 2015) and pledges are yet to mention embodied emissions. Therefore the analysis remains relevant to the ongoing debate.

In this section I review the literature on climate mitigation from a consumption perspective. The structure of the review is summarised in Figure 1. I identify the scientific evidence on emissions budgets and trajectories to prevent dangerous climate change; explore the drivers of rising global emissions which provide the leverage for reducing their impact; outline the strengths and limitations of consumption-based accounting from a governance perspective; describe the availability of data and methods from a practical standpoint; and present evidence of the effectiveness of potential consumption-based climate policies.

Figure 1: Overview of literature review

1. Target setting and climate governance
- Budgets and pathways
- Evolution of climate governance
- Global actors and cooperation

2. Analysis of emissions drivers
- Energy and the economy
- Consumption
- International trade

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- Limitations
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- Information and government-led
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1.1.1 Target setting and climate governance

Based on climate science, this section identifies the speed of the low carbon transition required and the adequacy of current mitigation policies to achieve this goal, finding that there remains a considerable disconnect between science and policy.

1.1.1.1 Carbon budgets and mitigation pathways

Climate science gives us a good indication of atmospheric limits to avoid more than two degrees of warming. Global temperature rises are approximately proportional to an increase in cumulative carbon emissions, but not end-point targets where emission pathways to reach a 2050 reduction target can differ (Gillett et al., 2013). The linear response of climate as a function of cumulative emissions is termed transient climate response to emissions (TCRE), and is defined as the global mean surface temperature change per 1000GtC emitted to the atmosphere. The TCRE is likely to be in the range of 0.8 degrees to 2.5 degrees per 1000 GtC, factoring in uncertainty and holding true only until temperatures peak and for smoothly varying cumulative emissions (i.e. not disruptive change) (Collins et al., 2013). By directly relating warming to emissions it can be used to calculate the cumulative emissions consistent with two degrees of warming (Allen et al., 2009, Meinshausen et al., 2009), providing a scientific basis to inform 21st century emission pathways (Collins et al., 2013).

The uncertainty associated with the TCRE means that probabilities are attached to budgets for limiting the warming caused by anthropogenic CO_2 emissions to less than 2^{o}C. To have a 66% probability (the highest probability considered) of not exceeding two degrees of temperature rise, the IPCC calculated that 790 GtC of greenhouse gases (GHG) can be emitted between 1880 and 2100. In 2011 approximately 515 ± 85 GtC had already been emitted since the 1860-1880 baseline, limiting future emissions (from 2011) of between 275 and 385 GtC to 2100 depending on the probability accepted. Including a 10% contribution from land-use change, we are currently emitting between 10-11 GtC annually. If an equivalent amount continues to be emitted annually the budget could be exhausted as early as 2038, however Meinshausen et al. (2009) shows that this could be as early as 2024 if less risk is accepted (they measure an 80% probability of not exceeding 2 degrees). Anderson and Bows (2011) suggest that 2 degrees should form a threshold level where probabilities of exceeding 2 degrees are replaced with prevention of 2 degrees of warming, but warn that the viability of this is rapidly diminishing.

In recognition of the relationship between cumulative emissions and temperature rise, emission trajectories need to be derived from concentrations of accumulated GHGs in the atmosphere, as was done in the latest round of IPCC scenarios (Peters et al., 2013). They are referred to as Representative Concentration Pathways (RCPs) and are particularly relevant to informing climate mitigation budgets as they have for the first time included a strong mitigation pathway consistent with the long term climate policy objective of not exceeding 2 degrees (RCP 2.6).

To be aligned with RCP 2.6, the IPCC suggest global emissions need to peak by 2020 whilst sustaining 2015 emissions levels until then, sustain around 3% annual reductions thereafter, and if delayed, achieve negative carbon emissions by withdrawing carbon from the atmosphere by 2070 (Peters et al., 2013). However, the uncertainty and expense of these technologies are widely cited and to be successful have a politically and economically contentious road ahead (Watson et al., 2014). If we assume that negative carbon technologies will not be available then emissions would need to peak earlier or the annual reduction would need to be steeper. Trajectories (i.e. emissions peaks and reduction rates) have been differentiated between regions to reflect stages of economic growth and allow room for less developed economies to grow (Bows and Barrett, 2010, Anderson and Bows, 2011, Raupach et al., 2014). Delaying peak emissions however will only lead to higher mitigation rates in the future at higher costs. Without the technologies available to withdraw atmospheric carbon, Raupach et al. (2014) demonstrate the need for stronger global annual reduction rates of 7% to have a 66% chance of not exceeding two degrees. When differentiating across countries based on per emissions per capita, mitigation rates exceed 15% in some developed countries, whilst being nearly zero in some of the world's low-income countries. Anderson and Bows (2011) reach similar conclusions, suggesting reduction rates of between 6 and 8% in less developed countries, and up to 11% in developed countries.

1.1.1.2 Climate governance

Early environmental regulation in the Global North in the 1960s addressed visible environmental problems (McManus, 2009), concentrated on regulating the quality of localised impacts to environmental media such as air, soil and water, independent of market objectives (Hey, 2005). Concern about the ability of regulated industries to compete in markets with unregulated ones saw a weakening of government intervention and a reduction in the legislative and regulatory burdens for businesses in the 1980s. Regulation was replaced with market incentives with the aim of motivating business to cost-effectively innovate. As trade has been liberalised patterns of trade specialisation have resulted, to some degree, in less developed countries producing carbon intensive goods for export to developed countries (Gasim, 2015). There has been a shift from legislating localised impacts to international agreements protecting global commons and regulating internationally important resources whilst recognising the development needs of millions living in poverty. Governance has moved from a first-come first-served basis, to principles of burden-sharing, questioning whether countries that have contributed least to the cumulative problem should be treated the same as those who have contributed the most.

Since 1992, 195 nations have signed an international treaty under the United Nations Framework Convention on Climate Change (UNFCCC) agreeing to limit climate change and its impacts, but with differentiated responsibilities to reflect development needs, termed Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC). Within this parties endorsed a target requiring climate policy to limit warming to two degrees above pre-industrial levels in the Copenhagen Accord (UNFCCC, 2010). This overall objective has not yet been matched with a global agreement on emission reduction targets and cross-country responsibilities.

International negotiations were initiated in the early 1990's where parties were split into three main groups Table 1. Annex I parties have the strongest quantitative commitments and reporting obligations compared to non-Annex I parties which have qualitative obligations, more lenient reporting requirements and eligibility for financial and technological assistance (Depledge, 2009). Underpinning the UNFCCC are the Kyoto Protocol and Cancun Agreements. Countries known as Annex B are those Annex I countries that have ratified an emission reduction target under Annex B of the Kyoto Protocol. In addition to achieving Kyoto reductions (18% below 1990 levels by 2020) through domestic measures, the Protocol created a carbon market allowing countries to sell credits if they exceeded their targets, but also to receive credits for reducing emissions overseas. The carbon market is implemented through three market-based measures: International Emissions Trading allows countries to sell spare carbon units to those that are over their targets; the Clean Development Mechanism credits Annex B countries for emission reduction projects they implement in non-Annex B countries; and Joint Implementation credits Annex B countries for emission reduction projects they implement in other Annex B countries. Whilst the intention was that as emissions in non-Annex I parties grew they would take on the obligations of Annex I countries, the voluntary nature has failed to motivate such transitions (Depledge, 2009).

Table 1: UNFCCC party classification according to differing commitments

Classification	Definition	Example countries/ regions	Current commitment
Annex I	Industrialised OECD member countries and countries deemed to be economies in transition in 1992	EU, the Baltic States, Russia, North America, Australia, Japan etc.	Pledged quantified economy-wide emission reduction targets to 2020 (Cancun Agreements)
Annex B	Annex I countries with emission reduction commitments in Annex B of the Kyoto Protocol	Annex I excluding USA, Japan, Russia and New Zealand	Legally-binding emission reduction commitments (Kyoto Protocol)
Annex II	OECD members in Annex I excluding economies in transition	EU, North America, Australia	Provide financial resources for abatement in transition and developing economies
Non-Annex I	Countries deemed as developing in 1992 and recognised as being vulnerable to the adverse impacts of climate change	Asia, Central and South America, Middle East, Africa	Nationally appropriate mitigation actions with no legally-binding targets (Cancun Agreement)

Whilst the majority of countries in Annex I signed up to the initial Kyoto Protocol, the US, the second largest emitter worldwide, refused to ratify it on the basis that some high emitting nations were excluded (e.g. China) and that it would harm the US economy. Canada, Japan, New Zealand and Russia have since withdrawn from the second commitment from 2013 to 2020, deeming that the Protocol is ineffective without the inclusion of the highest emitters.

Alongside legally-binding Kyoto targets, Annex I countries have pledged quantified economy-wide reduction targets to 2020 documented in the Cancun Agreement (UNFCCC, 2011). Some participants, for example the EU, have said they will strengthen their reduction (from 20% to 30%), but only if a global agreement is reached where developed countries reduce by a comparable amount and developing countries contribute adequately according to their respective capabilities. Parties are not legally held to these, but it is anticipated they will underpin a legal emission reduction framework that was negotiated COP21 at the end of 2015. Whilst the Cancun Agreements are not restricted to Annex I countries, the divide between quantified targets and qualitative mitigation actions remain, with Annex I countries submitting quantified reduction targets for 2020 and non-Annex I countries implementing mitigation actions based not on absolute emission reductions but largely to gain technology and financial transfers from Annex I countries.

So far, climate policy has prioritised the deployment of low carbon energy technologies. From this perspective, emissions will depend on how effectively policy can enable the deployment of low carbon technologies (Chicco and Stephenson, 2012). Whilst deemed to be technically feasible and within the political scope of national governments, the risks and barriers to widespread technology deployment are frequently documented ((Bruckner et al., 2014) (Iyer et al., 2015, Luthra et al., 2014) (Kennedy and Basu, 2013) (Balcombe et al., 2013) (Eleftheriadis and Anagnostopoulou, 2015)). Commonly identified is their high upfront investment costs compared to the relatively long payback period. The current market-driven policy approach has been shown to be incapable of delivering the type of low carbon technology investment required over the necessary timescales (Bolton and Foxon, 2015), and industrialising countries do not seem to be avoiding fossil fuel lock-in, as was hoped (Unruh and Carrillo-Hermosilla, 2006). While low carbon technologies could technically provide all the energy needed for the continuing growth in consumption, this is proving to be a very expensive pathway with many barriers.

The IEA (2013) analysed the CO_2 impact of pre-COP 21 climate commitments and pledges, finding that even if fulfilled they fall far short of levels needed for a two degree future. 38 countries representing only 13% of global emissions have taken on binding emission targets to 2020 under the extended Kyoto protocol. Additionally, 43 countries representing a 36% share of 2010 global emissions have set themselves a mitigation target, and 48 countries making up a 42% share of global emissions have pledged actions to mitigate their emissions. Even if all these are achieved, the two degree target remains out of reach.

Despite the scientific evidence of the IPCC's Fifth Assessment Report, international mitigation policy within the UNFCCC remains descriptive when referring to a two degree target and fragmented in terms of implementation. A key challenge facing climate policy is therefore how to distribute the remaining global carbon budget between countries to form national mitigation strategies. Contraction and convergence frameworks have been proposed to distribute the global budget equitably across nations in accordance with every person having an equal right to carbon space, offering environmental benefits and addressing poverty alleviation simultaneously (Corfee-Morlot and Höhne, 2003). Several allocation schemes have been proposed, often discussed in the context of equity and political acceptability (for summaries refer to Winkler et al. (2002), Mattoo and Subramanian (2012) Kawase and Matsuoka (2013) and Pan et al. (2014)). Proposed allocations are governed by issues of historical responsibility for emissions generation, the ability to pay for abatement, responsibility for current emissions releases and equal entitlements for every citizen to atmospheric emissions space (Bows and

Barrett, 2010). Different fairness-based criteria favour and bias different countries, not only between developed and developing countries but also within developing countries (Winkler et al., 2002), making it difficult to come to a consensus.

1.1.1.3 Global cooperation

The atmosphere is characterised as a common-pool resource which has a limited carbon space, at least to minimise rising temperatures; is difficult to exclude or limit greenhouse gas emitters; and emissions from one actor limits the carbon space of others (Ostrom, 1999). Climate change has been described as a tragedy of the commons (Paavola, 2011, Stavins et al., 2014), first depicted by Hardin in 1968. Hardin depicts his hypothesis as a pasture open to all herdsmen. Each herdsman is expected to keep as many cattle as possible. As populations grow, for example by health improvements, the carrying capacity of the land is exceeded and cannot maintain increasing numbers of cattle. Each herdsman acts ‘rationally’ to maximise his own gain. As all the proceeds from the sale of an animal go to the individual farmer, yet the effects of overgrazing are shared amongst all herdsmen, the farmer is incentivised to keep adding to his own herd.

There are two implicit assumptions within Hardin’s analogy: there can be no technological solution to growing population demands on a planet with finite resources and ecological limits, and people act out of self-interest and not concern for the global good. In the case of the former, it is mathematically impossible to maximise for two variables: resource limits and a growing population. In the latter case it is assumed that the individual benefits received from the use of a resource outweigh the shared collective loss from over use or pollution. In this circumstance, Hardin concludes that regulations on access and use of the pasture in the form of private property rights (i.e. getting rid of the commons) would be needed to stop herdsman degrading the pasture, as without this they would continue profit seeking for themselves.

The assumption of self-interested actors seeking to maximise their immediate individual gains has been challenged by Elinor Ostrom in direct response to Hardin’s analogy (Ostrom, 1999). Moreover, the basic economic theory of utility-maximising individuals has been criticised in many fields of research (Levine et al., 2015). Actors do not necessarily act in self-interest, nor for purely economic gains (Cárdenas and Ostrom, 2004, Jackson, 2005). Rather trust and reciprocity can go some way to explaining the cooperation of individuals within a system, along with psychological, sociological and institutional influences, describing an individual with habitual behaviours and preferences, interacting with others around them, and operating within an institutional construct.

Whilst Ostrom argues communities can cooperate for the greater good without the need for external regulation (Ostrom, 2012, Ostrom, 1999), she and other scholars also recognise that the multiplicity of global actors contributing to climate change lends itself somewhat to the need for some form of external regulation (Ostrom, 2010). Ostrom depicts a theory of collective action where behaviours are characterised by human action, influenced by internal psychological and external sociological and institutional factors, and not purely individual reasoning. She promotes a polycentric system of governance where various actors across different spatial, temporal and institutional scales play some role in the process, as they understand the local context and need to be able to adapt within it, but recognising that with no clear atmospheric boundary, and a large, highly mobile and diverse population of emitters, there may be no alternative but to rely on centrally imposed rules to incentivise changes in behaviour (Ostrom et al., 2012). Relying exclusively on the latter however, she argues, is unlikely to create sufficient trust among actors that is essential to compliance (Ostrom, 2012), and those actors remaining unconvinced about the need to reduce emissions could continue to be or become free-riders (Ostrom, 2010).

1.1.2 Analysis of emissions drivers

Understanding the drivers of emissions puts the mitigation challenge into perspective. In quantifying the contribution of individual drivers it is possible to determine the rates of change required to reverse rising trends in emissions. For example, it gives analysts and policy makers the ability to quantify the required rates of efficiency improvements to offset growth in population and the economy to meet a given carbon budget.

1.1.2.1 Energy and the economy

GHG emissions, dominated by fossil fuel combustion, are often explained by patterns of economic growth. The literature is inconclusive as to whether energy is a prerequisite for economic growth, or economic growth drives energy demand, which will have implications for future policy development (Stern and Enflo, 2013). If GDP stimulates energy use, then energy supply wouldn't constrain economic growth, however if the reverse is true, limited energy could have negative impacts on economic growth (Kalimeris et al., 2014).

The conventional approach to understanding the energy-economy relationship is measured as the proportion of GDP spent on direct energy compared to capital and labour costs (Warr and Ayres, 2010, Ayres and Warr, 2005). Studies consistently show a relative decoupling of energy consumption from economic growth since the 1970s (Bithas and Kalimeris, 2013), explained by global processes of industrialisation and economic restructuring (Sorrell, 2015). As countries industrialise, in aggregate they shift to less energy-intensive production and restructure to produce higher value service-based products (Warr and Ayres, 2010). In comparison to the high costs of capital and labour, energy is deemed of little importance in driving economic growth, and is often depicted as being substitutable with capital (Daly, 2013).

However, Ayres and Warr (2005) demonstrate that the role of energy is greater than the payment made for it, describing it as the ‘engine for growth’. The conventional measure captures primary energy as a direct input to the production process, but not the efficiency with which primary energy is converted, or the dependence of other production processes for the physical output in the form of goods and services, coined as ‘useful work’. In other words, production outputs require not only direct energy inputs, but indirect inputs (goods and services) within which energy is embodied (Gasim, 2015, Wagner, 2010). For example, whilst capital in the form of fertiliser and irrigated water has to some extent replaced sunlight, soil nutrients and rain, they themselves embody energy and therefore are not a replacement for it (Daly, 2013). Given energy is the only source of useful work, it is indispensable for economic progress (Kalimeris et al., 2014, Warr and Ayres, 2010). Energy is therefore certainly a limiting factor to growth (Brown et al., 2011) and to sustain long-term growth it is necessary to increase energy supplies or increase the efficiency of energy into useful work (Warr and Ayres, 2010).

Energy consumption is not only correlated to economic growth but to other quality of life indicators such as health and education, as it takes energy to train doctors and teachers and build hospitals and schools (Brown et al., 2011), yet beyond a certain level of energy consumption the returns start to become diminished (Steinberger and Roberts, 2010). Feeding, clothing and maintaining a population necessitates energy, the amount of which is determined by the efficiency in which it is converted to useful work and the demand for goods and services. Bithas and Kalimeris (2013) show that improvements in the conversion of energy have been offset by increasing population and demand for goods. Steinberger and Roberts (2010) find that if global resources were equally distributed, current energy consumption would be sufficient to meet global human needs at high levels of human development. Despite uncertainty as to the direction of the causal effect between energy and economic growth, there is general agreement that energy is essential to growing economies and to stay within climatic limits, current trends in population and consumption growth cannot be sustained.

1.1.2.2 Consumption as a driver of emissions

Simplifying emissions growth into a linear function of economic output has been shown to give a poor understanding of emissions (Roberts et al., 2003). Candidate drivers of greenhouse gases include population, affluence, technology, institutions, culture, attitudes and beliefs (Rosa and Dietz, 2012, Dietz and Rosa, 1997, Lamb et al., 2014). There is a longstanding consensus in the literature that increasing consumption is the dominant factor when measured using the common Kaya identity, based on the earlier I-PAT equation, which looks at environmental impacts more broadly (credited to Ehrlich and Holdren in the 1970s). The Kaya identity decomposes overall changes in emissions into macro-level variables of population, affluence and technology as follows:

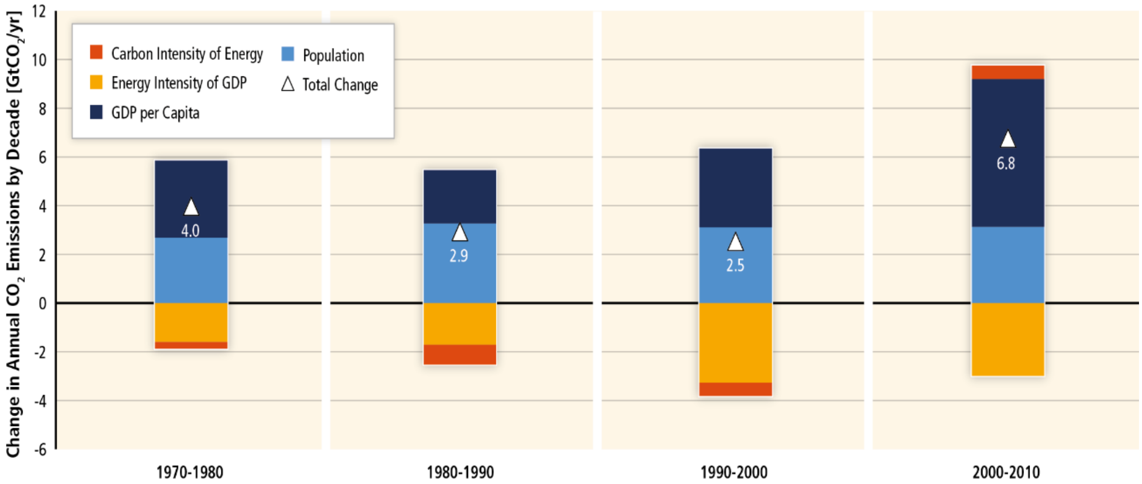
$$Emissions = Population \times \underbrace{\frac{GDP}{population}}_{Affluence} \times \underbrace{\underbrace{\frac{Energy}{GDP}}_{\substack{Energy\\intensity}} \times \underbrace{\frac{Emissions}{Energy}}_{\substack{Carbon\\intensity}}}_{Technology}$$

Affluence is expressed as GDP per capita and is indicative of income, and technology is expressed as the product of energy to produce GDP and the CO_2 intensity per unit of energy used. However, from a per capita perspective, only a minority of the population are responsible for the majority of impact (Chakravarty et al., 2009), and there is an uneven distribution in time (reflected by cumulative emissions),across regions (Raupach et al., 2007) and increasingly within regions (Chancel and Piketty, 2015).

Different regions and sectors contribute differently to global emissions. Asia for example is the only region to have nearly doubled the carbon intensity of its energy, compared to an improvement in the range of 5 to 25% for all other regions since 1970. In addition, Asia experienced the strongest economic growth averaging 5% per annum, compared to a global average of 1.8%. Transport and buildings are the dominant source of emissions in high-income countries; land-use change dominates in low income countries; and energy and industry in middle income countries (Blanco et al., 2014). Liddle and Lung (2010) found that affluence has twice the impact on CO_2 emissions from transport compared to population, yet for residential energy consumption population has a considerably greater impact. This seems consistent with transport dominating wealthy country emissions, and energy in middle-income countries. However, at the city level, urbanisation reduces the need for travel (Weisz and Steinberger, 2010), and hence different relationships exist at different spatial scales and for different activities. Furthermore, other localised incentives such as the quality of public transport and deterrents of car use play a role at this level (Weisz and Steinberger, 2010).

Overall improvements in energy intensities have not been enough to offset growing consumer demands of an increasing population (Figure 2). The contribution of economic growth rose sharply in the last decade (IPCC, 2014). The global financial crisis in 2009 had only short-lived effects, with emissions rebounding back to record highs the following year (Peters et al., 2012b). Population is expected to continue to grow in most regions alongside the promotion of economic growth (Rosa and Dietz, 2012), resulting in higher purchasing powers which will need to be met with greater rates of efficiency improvements if lifestyles and consumption levels remain unaddressed. However, contradictory to the widely held view that increased affluence leads to reduced environmental impacts beyond a certain level of wealth, defined by the Environmental Kuznets Curve (EKC), this has not been shown to be the case for greenhouse gas emissions (Rosa and Dietz, 2012, Dietz et al., 2007), particularly in countries rich in fossil fuel resources (Burke, 2010, Burke, 2012).

Figure 2: Decadal decomposition of global CO_2 emissions by four drivers (IPCC, 2014)



When considering emissions per capita, inequalities in regional contributions become even more striking. Per capita emissions of the highest income countries are almost ten times that of the lowest income countries (Blanco et al., 2014, Chancel and Piketty, 2015). Emissions per capita are growing in emerging economies in Asia, yet remain at two thirds of OECD countries. Evidence has shown however that there is a general trend towards Western consumption patterns in less developed economies (Rosa and Dietz, 2012, Dietz and Rosa, 1997). As wealth accumulates, the number of households increases, and hence the heating, cooling, lighting and energy service requirements increase, complicated by a range of additional demographic factors such as age structure and urbanisation (Dietz et al., 2007, Liddle and Lung, 2010).

International diversity and temporal dynamics makes driver-based analyses challenging (Lamb et al., 2014). To enable the quantification of drivers to increasing emissions, variables have had to be simplified and therefore are often investigated at the macro level. However, underlying trends in population, affluence and technology are a complex set of influential variables. It is this complex set of drivers that explains in much more detail the sectoral and regional divergences, which are much harder to quantify and therefore lack systematic assessment (Rosa and Dietz, 2012, Roberts et al., 2003). Different behavioural models have developed to understand why people consume and what internal and external factors shape and constrain choices and actions of individuals and organisations (Røpke, 1999, Jackson, 2005). These better describe the internal psychological and external societal influences on people's behaviours and why pro-environmental attitudes are not necessarily reflected in sustainable behaviours.

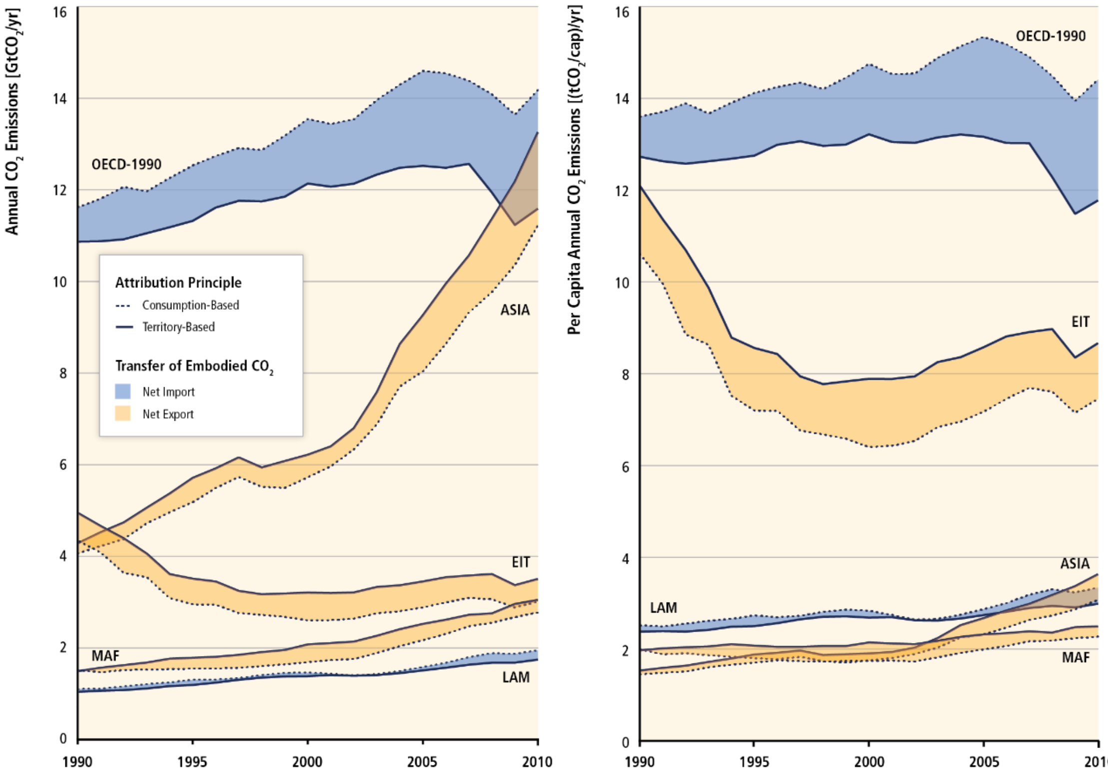
1.1.2.3 International trade and carbon leakage

Many low income countries have been subject to the 'resource curse' where they have not been able to diversify their export economies beyond natural resources with little processing, which dampens economic growth and does not incentivise investment in human capital and innovation (Murshed and Serino, 2011) . The liberalisation of trade, starting in the late 1970s, has enabled high-income countries to take advantage of cost competitive pricing, and shift low skill, labour intensive industries, e.g. clothing, textiles and manufactured hardware, to less developed countries (Mair et al.). High income countries tend to get more favourable terms of trade (Jorgenson, 2012), and falling costs in communication and coordination activities means that various stages of production do not need to be in close proximity, opening them up to global competition (Timmer et al., 2013). Western Europe is shifting towards more high-skilled service-based workers as manufacturing becomes more global (Timmer et al., 2013). Less developed countries have turned to export production as a means to stimulate economic growth and attract direct foreign investment (Jorgenson, 2012). Whilst overall the global economy has expanded, most notably in China, trade between developed and less developed countries has become increasingly ecologically unequal (Jorgenson and Clark, 2012). As a result of globalisation, high income countries are able to partially externalise their environmental impacts through the 'vertical flow of exports' (Jorgenson, 2012).

An increase in the volume and structure of international trade has enabled production activities, and their emissions, to be transferred outside the country of consumption (Peters et al., 2011), referred to as carbon leakage (Peters and Hertwich, 2008a). Between 1990, the benchmark year for emission reduction targets, and 2008, global CO_2 emissions from export production grew at an average 4.3% a year, faster than economic and population growth (Peters et al., 2011). Net emissions transfers from non-Annex B countries (without climate targets) to Annex B countries (with legally-binding targets) via trade grew by 1.2 Gt CO_2 (17% a year), whilst reductions within Annex B territories reduced by only 0.3 Gt CO_2 (2%) (Peters et al., 2011). Kanemoto et al. (2014) found that up to 30% of global emissions are linked to export production. They confirm that trade is undermining Kyoto targets, calculating that the amount of burden-shifting abroad from Annex B countries is greater than their Kyoto-sized targets.

A consumption-based emissions accounting perspective, which is adjusted for trade, often changes the rank of a country in terms of their contribution to global emissions. Territorial emissions from non-OECD Asian countries (includes China and India) more than tripled in two decades between 1990 and 2010, overtaking OECD countries in 2009 (left chart in Figure 3). Consumption emissions (territorial + imports – exports) remain overall higher in OECD countries. 20% percent of emissions growth in non-Annex B countries can be attributed to increased demand for products in Annex B countries, 25% of which are emitted in China (Blanco et al., 2014). Per capita territorial emissions (right chart in Figure 3) in OECD countries are three times those for non-OECD Asia, and OECD per capita consumption emissions are a factor five higher.

Figure 3: Territorial-based versus consumption-based emissions in five world regions, from 1990 to 2010 (Blanco et al., 2014)



The left panel presents total emissions, the right panel per capita emissions. The blue areas indicate that a region is a net importer of embodied CO_2 emissions. The yellow area indicates a region is a net exporter of embodied CO_2. OECD-1990 = OECD countries in 1990; EIT = economies in transition; LAM = Latin America and the Caribbean; MAF = Middle East and Africa; Asia = non-OECD Asia

1.1.3 Consumption-based emissions accounting

A growing body of research is concerned with emissions embodied in consumption (Munksgaard and Pedersen, 2001, Peters and Hertwich, 2008a, Wiedmann, 2009, Davis and Caldeira, 2010, Barrett et al., 2013), which is gaining policy relevance as nations consider their roles in global emissions reductions. In this section I consider the motivations for consumption accounting in international negotiations, and the robustness of accounting methods.

1.1.3.1 The motivation

There is an ethical argument that consumers should take responsibility for what they consume (Kokoni and Skea, 2013, Vetőné Mózner, 2013). Some propose that much of the pressure on climate change is a direct consequence of affluence and unsustainable consumption practices in industrialised countries (Steininger et al., 2014, Grasso and Roberts, 2014), which drive production. There have also been suggestions that both consumers and producers should share responsibilities, because whilst producers bear the environmental costs, they generate jobs and income from production (Ferng, 2003, Lenzen et al., 2007, Vetőné Mózner, 2013). Annex I countries can be seen as having taken out an ecological debt as they have generated nearly 60%

of the global cumulative emissions to develop their economies, whilst diminishing the carbon space for other countries to follow a similar development pathway (Ward and Mahowald, 2014). A number of authors suggest that attributing emissions reductions based on cumulative consumption accounting could address issues of inequality and fairness (Peters and Hertwich, 2008a, Raupach et al., 2014) and hence be more politically acceptable to developing countries. Also, big emitters like the U.S. could be more accepting of mitigation requirements if their polluting counterparts (i.e. China) were also subject to mitigation targets.

Practically, Peters et al. (2011) and Kanemoto et al. (2014) have shown that despite reporting success in bringing down their territorial emissions, when adjusted for net trade, most developed countries have resulted in increased global emissions driven by their consumption. These countries have more capacity, most often determined by their ability to pay, to mitigate emissions (Baer et al., 2007). It is therefore more economically and emissions effective for high-income countries to be attributed greater mitigation responsibility. This also adheres to the principle of Common but Differentiated Responsibility and Respective Capacities (CBDR-RC) written into the UNFCCC (Wiedmann, 2009), which acknowledges the different capabilities and responsibilities of individual countries in addressing climate change.

Consumption accounting increases information available to policy makers to design policy tools and analyse the probable effects of different consumer changes/ policies (Wiedmann, 2009, Steen-Olsen et al., 2014). In considering supply chains, the domination of energy production and energy intensive producers is replaced by resource intensive procurers, such as public services and manufactured goods. A consumption approach brings to the forefront different points of leverage that include the emissions of traded products that are not captured under territorial accounting (Barrett et al., 2013). This does not advocate only consumer-oriented measures, but it both increases the policy mechanisms available and would ensure policies cannot report reducing emissions by shifting them elsewhere. By putting pressure on greening up supply chains, developing countries would be encouraged to implement energy efficiency improvement strategies to reduce the carbon embodied in their exports in order to safeguard their access to foreign markets. However, this would require support in the form of technology and or finance to give developing countries the capacity to compete on the world market, which could be in the form of targeted technology transfers between trading partners for example (Wiedmann, 2009).

1.1.3.2 Arguments against implementation

Consumption accounting would require the greenhouse gas content of traded products to be recorded which is more methodologically and empirically challenging than compiling production accounts. Product supply chains have become increasingly complex since the liberalisation of trade, and can span several countries. The compilation of consumption accounts requires a standard monitoring, reporting and verification process to ensure transparency and enable cooperation between countries to comply with consumption accounting procedures.

The data requirements are larger, requiring global trade data between countries to be recorded in a common classification, currency and in basic prices (i.e. with the effect of inflation and distorting taxes and subsidies on prices removed, so the transactions represent physical quantities and not price effects). Additional administrative duties will put further pressure on developing countries that already require support to compile their production inventories. Currently global trade data sets are prone to assumptions where data is limited (Wiedmann, 2009), or where recorded exports of one country do not tally with recorded imports from that country. The results have added uncertainty to production based measures, yet the additional uncertainty has been shown to be less significant than that inherent in production accounts (Peters et al., 2012a).

Implementing regulation on the carbon content of products could impact on the comparative advantage of developing countries, whose export revenues would be reduced unless they met the specification at a cost. Carbon and energy intensive exports have been shown to be an important factor in economic growth and industrialisation (Chang et al., 2013, Xia et al., 2015, Sheridan, 2014, Helm et al., 2012), and the welfare effects could be unevenly felt by developing economies specialising in export production (Sakai, 2013). Discriminating against carbon intensive imports could be in breach of World Trade Organisation (WTO) agreements (Helm et al., 2012) which do not allow discrimination between similar domestic and foreign products. If environmental concerns allowed the differentiation of products based on their embodied carbon, export-intensive economies might instead meet their consumer demands increasingly by domestic means, and with more carbon intensive economies such measures could actually indirectly increase global emissions (Jakob and Marschinski, 2013). However, the outcome on global trade is uncertain and will depend on the ability of countries to diversify their production.

1.1.3.3 Methods and uncertainty

At the macro level multi-region input-output (MRIO) analysis is a well-established method to re-allocate emissions associated with production activities to the final demand of products (Wiedmann, 2009, Steen-Olsen et al., 2014). In the 1930s Wassily Leontief developed a series of linear equations that describe how producing a single unit of final demand requires inputs from all sectors of the economy. The economic framework was later extended to include a vector of ‘externalities’ which measured tonnes of pollution per unit of final consumption (e.g. CO_2/ £) (Miller and Blair, 2009), and to incorporate imports and exports (Wiedmann, 2009). The different sectors of an economy not only require natural resources in order to produce different goods and services, but they also generate several by-products (e.g. pollution and waste) during their production processes. Calculations could then determine how pollution originating from producing sectors in one country could be reallocated to final consumers in another country.

In essence, inverting a global trade matrix showing monetary transactions between intermediate sectors and final consumers, termed the Leontief inverse after its inventor, can identify the direct effects that occur in a specific sector within a region and the indirect effects that take place throughout the global supply chain in other regions derived by an additional unit spent either on finished domestic or imported goods. Pre-multiplying the Leontief inverse by a vector of carbon intensities (i.e. CO_2/total output) produces a matrix indicating how the sum of emissions created directly and indirectly by an additional unit of final demand. Post multiplying this by a vector of final demand identifies the amount of emissions that is emitted upstream throughout the supply chain for a country or regions composition and level of spend. The results from MRIO databases can be used at a variety of scales from national level consumption accounting, to sector level footprints down to identifying the contribution of a particular sector, from a particular country in a good's production chain (Peters, 2010b).

In the last five years, several MRIO databases with an emissions extension have been developed, described in Table 2. Limitations in the availability, consistency and quality of global trade data has meant tables are constructed using various approaches (Inomata and Owen, 2014). The MRIO databases differ in their geographical, sectoral and temporal coverage. Eora has the longest annual time series from 1990 to 2012 and the largest geographical scope covering 186 world regions. EXIOBASE uses the most detailed sector classification, displaying each region's economy in 163 production sectors.

Table 2: EE-MRIO models

Model	Sector coverage	Country coverage	Years available	Potential updates	Reference(s)
Eora	Varies by country from 26 to 515 sectors[1]	187	1990 – 2012	Annual updates with 2 year time lag	(Lenzen et al., 2012, Lenzen et al., 2013)
GTAP	57	129 (yr '07); 113 (yr '04); 87 (yr '01)	2001, 2004, 2007	3 year intervals with a 4 year time lag	(Narayanan et al., 2012, Peters et al., 2011)
EXIOBASE	163	44 (EU27, 16 others + ROW)	2000, 2007	Funding dependent	(Tukker et al., 2013, Wood et al., 2015)
WIOD	35 industries, 59 products	41 (27 EU, 13 others + RoW)	1995 – 2011	Funding dependent	(Dietzenbacher et al., 2013)

Understanding uncertainties in the data gives an indication of the robustness of outcomes (Inomata and Owen, 2014) for use in designing and evaluating policies. Environmentally extended-MRIO analysis relies on the compilation of secondary economic, environmental and trade data into a MRIO framework. As shown by Peters et al. (2012a) different results across

[1] The original database has heterogeneous country sector classification systems, however a harmonised 26 sector model is available

different models and studies can be attributed to the use of different production emissions data sources, different definitions of consumption and different economic and trade structures (supported by (Lenzen et al., 2010, Wiedmann et al., 2008, Wilting, 2012)).There are many ways in which the data can be assembled and adjusted (Inomata and Owen, 2014) and each alteration to the original source data introduces a layer of uncertainty. National economic data needs to be converted into a common currency and monetary transactions converted into basic prices. This requires price conversion statistics and taxes and subsidies to be re-distributed from a product to a value added sector. Where national data are missing, estimations are required such as the use of a representative average. MRIO tables must also adhere to a number of properties such as inputs must equal outputs and the sum of value added must equal the sum of the final demand. If these conditions are not met in the raw data, then the table is subjected to a number of balancing iterations until a table is produced that satisfies these constraints. Balancing methods vary and there are numerous techniques for table construction which leads to uncertainty in the final result.

In addition, the aggregation of economic sectors introduces uncertainty. Firms are grouped into broader economic sectors, each representing a weighted average of the characteristics of the firms within them (Steen-Olsen et al., 2014). Steen-Olsen et al. (2014) show that this is more problematic for environmental analyses, as industries within a sector can exhibit different emissions profiles with an order of magnitude difference. For example, a carbon intensity is often applied to the agricultural sector when calculating consumption emissions. This aggregated sector includes a wide range of crops, animals, practices and so forth. However, cattle farming is considerably more carbon intensive than other types of agriculture. The choice of aggregation can therefore lead to different impact results. Grouping data together that exhibit very different emission intensities will lead to calculations containing more uncertainty.

Whilst national-level trends in consumption emissions reported across different MRIO models are consistent within 10%, results by country and sector are more varied (Moran and Wood, 2014). In a comparison of the main databases, Owen et al. (2014) find that differences in national consumption emissions accounts across the models are largely explained by differences in total global emissions from different data sources, differences in the trade structures, and differences in total final demand. Peters et al. (2012a) found that consumption-based emissions are broadly consistent across studies and MRIO databases, despite some differences in the model compilation, and that the difference didn't necessarily translate into uncertainty but were a result of several data sources and definitions of consumption (see Table 3). Variation in the territorial emissions accounts, and the attribution of these emissions to countries and sectors, before entering the IO calculations, was found to be much larger than the variation in economic and trade input data. Transport and energy intensive sectors exhibited the most variation in results along with small trade dependant countries and countries with poor data quality.

Table 3: Average percentage variation between consumption-based emission accounts (adapted from Peters et al. (2012a))

Input data/ assumptions	Average percentage variation
Territorial emission accounting source	30% (between countries)
Definition of consumption	21%
Economic and trade input data	5%

1.1.3.4 Quantifying material and product flows

Using IOA, emissions associated with resource flows are calculated according to the magnitude of economic transactions between sectors, which does not distinguish between quantity and price components. IO models can separate costs from quantities (Davar, 1993), which is useful to investigate the effect of prices on the system, for example simulating the price effects of pollution abatement or rising energy costs. However, price homogeneity allows us to investigate supply and demand in one system.

Homogeneity of prices holds true within sectors, but not across sectors. For example, the physical quantity of emissions from steel production are attributed to steel procurers based on the relative costs intermediate purchasers and consumers pay, and the physical quantity of emissions from electricity production are attributed separately to energy users based on the value of transactions between the energy sector and intermediate and final consumers. Therefore, emissions from steel remain allocated to users of steel and so on. The common price assumption means you can't decompose whether different procurers paid a different amount for a unit of production output, meaning that if sectors paid a higher price for steel or energy, they would be allocated disproportionately more emissions from the production of that good. In reality, larger resource-intensive firms will generally agree a lower price per unit for resources than smaller firms. This is not a problem in IOA where firms producing similar outputs, regardless of size, are aggregated into an average sector, and hence will average out the price disparity. For commodities with relatively fixed prices (found more in oligopolistic markets) this is less of a problem compared to commodities with many more competitive global suppliers or those that are more volatile due to e.g. supply shortages or geopolitical concerns. Merciai and Heijungs (2014) argue that the assumption that purchasers pay the same price for an aggregate commodity can violate material flow balances. Material usage would be under estimated for those paying a lower than average price, and opposite for those paying a higher than average price.

Economy-wide material flow analysis (MFA) builds on early concepts of material and energy balancing. It considers how materials are extracted from the natural system, transformed into products and finally put back into the natural system as an output i.e. waste. There are different methods for resource accounting based on mass balances and impact assessments that can trace materials through the macro economy or along micro product supply chains (Mancini et al., 2015). In the UK, Allwood and Cullen (2012) and Cullen et al. (2012) have calculated the emissions impacts of material flows of steel and aluminum in detail, but data is limited to a few materials and is not collected as standard practice making it time-consuming to collect. Therefore, MFA tends to be subject to similar aggregation limitations to IOA, for example bulk materials are often grouped together regardless of the environmental impact of each material (e.g. Giljum et al. (2014b) and Schaffartzik et al. (2014)) and more detailed studies focus on tracing one material flow or product (e.g. Müller et al. (2011) and Pauliuk et al. (2012)) which does not provide an economy-wide perspective relevant for e.g. assessing economy-wide climate targets.

There have been attempts to produce physical input-output tables (Hubacek and Giljum, 2003, Konijn et al., 1997), which are directly comparable to monetary IOA except inter-industry trade is represented in physical units (e.g. material weights). However these tend to be at a more aggregated sector, resource and impact level and are not done annually and therefore are available for a handful of years only (Hoekstra and van den Bergh, 2006). Probably due to the complexity and lack of data for collating them, these are not readily available for use.

Sectoral carbon intensities, which are a function of emissions and economic output, are first calculated before promulgating through the economy to the final consumer. If prices are high and less of a good is purchased as a result, the carbon intensity will be lower, which will equal out the effect of the high price on emissions, and vice versa, albeit that some of the change will reflect an improvement in the carbon intensity of production and not just a price change. Carbon intensities represented in IOA are not solely a measure of efficiency due to a number of other economic factors such as price changes and inflation. Improvements in the physical efficiency of a process would require the use of physical data such as emissions (gCO_2e)/ energy use (kWh). Majeau-Bettez et al. (2016) argue that the problem remains the aggregation of sectors with different environmental profiles. Two sectors may purchase quite different products within this, however, the emissions apportioned to them reflect the average of the sector and not the specific product they are purchasing. Majeau-Bettez et al. (2016) suggest the limitations would not necessarily reduce using physical flow tables, which remain at a highly aggregated level, including the aggregation of products and processes with different physical inputs. Therefore, I conclude that despite these limitations, IOA traces producer-consumer linkages with the most detail and uses data that is published annually in national economic accounts and environmental inventories.

1.1.4 Consumption policies

There are different levels of implementation of consumption-based accounting in practice, and the degree to which it becomes integrated in policy-making will determine the scope of policy instruments required. If consumption accounting were to be used as a mechanism for attributing responsibility for greenhouse gas mitigation only, then the focus would be on establishing robust consumption-based measures. However, to target traded emissions, consumption accounting would need to be accompanied by a set of policy mechanisms addressing demand, trade and business supply chains, which I focus on in this section. There is evidence of embodied or life cycle emissions being applied in an informative capacity to guide policy, but applications with a direct link to specific policy instruments are rare (Kokoni and Skea, 2013). When demand is considered, much of it relates to energy efficiency improvements and not an absolute reduction in demand, and it is not integrated with non-technological innovations such as behavioural drivers, business models and policies (Hannon and Skea, 2014).

Chapter 15 of Working Groups III's contribution to the IPCC fifth assessment report provides an assessment of the performance of policies and measures in both developed and developing countries (Stavins et al., 2014). However, the assessment is at the sectoral level, e.g. energy, transport and industry, failing to identify policy instruments that specifically address emissions traded between countries. Table 4 provides a summary of such policy instruments referenced in the literature that directly or indirectly address these. References are given in the discussion that follows. There will be other options not well established in the literature and this summary should not be viewed as a definitive list of policies that can influence consumption.

Table 4: Summary of policy instruments addressing internationally traded emissions

Policy instruments	Specific measures addressing traded emissions
Economic instruments or market-based approaches	Emissions credits under the CDM Carbon border tax adjustments Industrial emissions trading schemes
Regulatory approaches	Product or process standards Public procurement buying standards (considered under government procurement) Mandatory carbon labelling
Information Initiatives	Carbon labelling Carbon calculators
Government procurement and provision of public goods and services	Removal of institutional barriers Public procurement buying standards
Voluntary actions	Bilateral trade agreements e.g. technological, information and economic transfers Consideration of embodied emissions
Non-climate	Resource efficiency (e.g. product longevity) Reduce consumption (e.g. work less)

1.1.4.1 Economic and regulatory policies

Under economic instruments or market-based approaches, the Kyoto Protocol Clean Development Mechanism (CDM) has provided a tool with which Annex I countries can claim carbon credits from implementing projects abroad. Developed economies are relatively clean, and therefore face higher marginal costs for reducing emissions than in less developed economies. Two thirds of the lowest-cost abatement opportunities currently lie in developing countries (Harris and Symons, 2012). Incentivising investment in cleaner and more efficient production systems in developing countries, by being able to claim carbon credits for example, has the advantage of presenting the international community with additional mitigation options at lower costs (although this excludes them as options for the eventuality that all countries are assigned reduction targets). Whilst the CDM has been a cost-effective means to reduce emissions for industrialised countries, and in some cases, although not all, generated income or led to a positive technology transfer (Stavins et al., 2014), it does not extend the volume of global emissions that are capped and limits cheaper options for developing countries in the future. Spash (2010) argues that offsets are essentially an excuse to increase emissions, particularly when sinks which have individual characteristics and storage capacities are used to offset the emissions. Also, the degree to which the addition of renewable energy has managed to displace fossil fuels has been shown to be modest, and when controlled for demand York (2012) found the introduction of one unit of renewable energy displaced on average only a quarter of a unit of fossil-based energy.

Carbon border taxes have been proposed as a measure that could overcome competitiveness concerns, whereby imports are taxed at the emissions price of the regulating region and emission payments for exports to non-regulating countries are rebated (Bohringer et al., 2012a, Bohringer et al., 2012b, Bohringer et al., 2014, Bednar-Friedl et al., 2012). However, by penalising exporting economies, border tax adjustments have been found to intensify regional inequalities and may be in breach of world trade agreements (Atkinson et al., 2011, Bohringer, 2014, Li et al., 2013). China, the world's largest exporter of emissions, could suffer substantial losses, estimated to be as much as 4% of its GDP (Qi et al., 2014). The distributional impacts could be reduced if tariff revenues were redirected towards the exporting countries (Bohringer et al., 2012a), and low carbon technology transfers from regulated to unregulated regions enabled developing countries to compete by producing carbon equivalent products. However, the implementation of standards does not necessarily achieve immediate results, as Williams et al. (2016) have shown through the introduction of Western European building energy standards.

Springmann (2012) concluded, however, that an equivalent emission reduction could be achieved by linking emissions trading schemes (ETS), whereby emissions are capped and carbon allowances within this bought and sold between sectors, across Annex I countries. Such an approach would yield greater welfare benefits for non-Annex I countries and would have more political traction than implementing carbon tariffs on energy-intensive goods imported from non-Annex I countries. Carbon pricing in the form of an ETS is only in effect in some countries or regions, and generous emissions allowances and exemptions for many energy-intensive industries have deemed them largely environmentally ineffective (Gawel et al., 2014). Sector coverage would need to be extended, or the charge applied to lifecycle emissions (Kokoni and Skea, 2013), to capture more emissions and, in the longer term, these could link to emissions trading schemes in non-Annex I countries (Springmann, 2012). China, for example, is currently preparing for the launch of its nationwide emissions trading scheme in 2016, while South Korea has already done so since January 2015 (Liu et al., 2015, Hübler et al., 2014). No Scheme in practice is currently premised on a two degree level of ambition.

Industries in countries with stronger emission reduction commitments claim that implementation of a carbon price could put them at a comparative disadvantage to those industries in countries where there was no carbon price. If these industries chose to relocate to non-Annex B countries to take advantage of cheaper production costs, this would lead to an overall increase in global emissions as these emissions become outside the scope of reduction targets, and countries with weaker environmental regulations tend to have higher carbon intensities of production. However Peters (2010b) shows that implementation of the EU ETS has not resulted in the relocation of industry outside the EU[2]. Chan et al. (2013) support this, concluding that that concerns over carbon leakage, job loss and industry competitiveness were unsubstantiated.

Domestic performance standards have already been successful in reducing emissions in the operation of vehicles, buildings, and appliances (Somanathan et al., 2014). By ensuring that only those products within a specified energy performance bracket are sold on the market, regulated standards ensure a certain level of energy efficiency. This is already implemented through European policies including the EU Ecolabel and Eco-design directive without imposing a tax on imported goods. Performance standards can play a key role, particularly when consumers have limited knowledge or influence over product choice, like for example when renting a house, in which case tenants have limited influence over the products in it. Whilst existing standards relate to operational energy efficiency addressing mainly production emissions (e.g. gas combusted to heat a home), methods for carbon footprinting have been developed into standards to enable calculation of the embodied emissions of products (Vasan et al., 2014, Suh and Huppes, 2005, Finnveden et al., 2009), which are not restricted to operational emissions. Taking the example of buildings, a lot of research shows that emissions embodied in building fabrics are becoming an increasing proportion of building-related emissions and there are options such as material substitution and optimisation to reduce embodied emissions (Miller et al., 2015, Ibn-Mohammed et al., 2013, Moncaster and Symons, 2013, Dixit et al., 2012, Iddon and Firth, 2013). Similarly, non-energy related products such as financial services produce few

[2] However, there were also generous subsidies provided to EU industry

direct emissions and are therefore largely neglected in climate policy, yet have a high embodied content (Suh, 2006). In the UK, on average 50% of consumption-related emissions are generated abroad (Barrett et al., 2013), indicating the potential for resource consumption measures to mitigate emissions outside the UK.

The emissions effectiveness of efficiency measures however can be diminished by what are termed rebound effects (Sorrell, 2015). These refer to an economic response to a resource efficiency measure. Rebound effects can be direct; for example if a car is more fuel efficient the owner can drive further for the same original cost, offsetting any energy savings. They can also be indirect; for example the savings from fuel costs of a more efficient car could be spent on other goods, which require energy to produce. And finally, a reduction in fuel demand could reduce fuel prices and increase fuel consumption in other parts of the economy. As Sorrell (2015) points out, these are extremely difficult to calculate but the best available evidence suggests that they are higher than previously thought and can offset or eliminate savings from energy efficiency by more than 50% (Blanco et al., 2014) in the absence of policies to compensate for the rebound.

1.1.4.2 Information and government-led policies

As far as informational instruments are concerned, carbon footprints have been used to label products and develop carbon calculators in the hope that they will incentivise consumers to purchase and adopt greener products and lifestyles (Birnik, 2013, Padgett et al., 2008). They have also been suggested to create positive competition between companies to strive for a better carbon label, including companies outside the consuming country (Cohen and Vandenbergh, 2012). The evidence for information as a standalone mechanism to reduce emissions is inconclusive (Cohen and Vandenbergh, 2012), with some suggesting it has limited impact (Isenhour and Feng, 2014) unless used in combination with other measures such as obligatory standards (Somanathan et al., 2014). However, it is argued in the literature that the standardisation of product footprinting needs to be improved to move from the voluntary reporting of embodied emissions to enable the regulation of embodied performance standards (Wu et al., 2014). Standards would also need to comply with trade regulations that prohibit discrimination against the import of similar products, which could be a contentious issue if only some countries were subject to greener standards (Cohen and Vandenbergh, 2012).

The government has a double role to play in addressing consumption policies. Firstly it needs to set the policy framework to remove the institutional barriers, such as investment cycles, cultural and social norms and habitual consumer practices (Moreno et al., 2014). There also exist some internal political-institutional barriers (Langlois-Bertrand et al., 2015). Langlois-Bertrand et al. (2015) categorise these, at least for energy efficiency, as a lack of political backing, for example related to vested interests; differing interests by government departments having partial authority over energy efficiency; and a lack of policy coordination. Secondly, public procurement accounts for 17% of the OECD countries GDP, meaning governments can use this high purchasing power to influence production and consumption trends (Testa et al., 2014). By exercising buying standards and specifying green criteria systematically in public tenders, governments can provide a stimulus for eco-innovation along product supply chains (Testa et al., 2014, Alvarez and Rubio, 2015, Michelsen and de Boer, 2009, Uyarra et al., 2014, Bratt et al., 2013). This requires organisational resources, and hence the political support for it, clear guidelines and training, standardised accounting methods, and increased cooperation with suppliers.

1.1.4.3 Voluntary and non-climate policies

Voluntary agreements can at least be a starting point to engage with international suppliers. For example, Sweden set up a Centre for Environmental Technology (CENTEC) at their Embassy in Beijing, promoting and facilitating exchange of 'envirotech' in public and private sectors (Isenhour and Feng, 2014). By providing cooperative technology assistance, Sweden is able to influence the carbon intensity of its imports and indirectly introduce consideration of embodied emissions into bilateral policymaking without placing a domestic restriction on imports. The host country is able to benefit from the efficiency improvement, which should also improve economic growth (Parrado and De Cian, 2014). However, this in turn could negate the intended emissions reduction by increasing consumption in the host country, and therefore does not guarantee an absolute reduction in global emissions.

With non-climate actions, greenhouse gas mitigation from changing consumption has received little attention in climate policy literature (Girod et al., 2014), with the exception of residential energy efficiency, despite consumption being the main driver of global emissions. Ecological limits necessitate a reduction in aggregate consumption (Heindl and Kanschik, 2016), which is often referred to as sufficiency in climate discourse. Sufficiency however would need to be framed within a social justice context where an acceptable minimum level of consumption to fulfil basic needs is defined. However, sufficiency is deemed unpopular on the grounds that it violates people's freedom of choice and therefore efficiency is generally pursued as a policy agenda, albeit on the periphery itself. Girod et al. (2014) suggest that reduced consumption addresses carbon leakage as it reduces embodied emissions, and as it affects domestic and imported products equally it has a lower effect on international competitiveness. There is a growing body of literature to show that reduced consumption, through mechanisms such as working less, does not necessarily mean reduced quality of life (Knight et al., 2013). Girod et al. (2014) show the potential of consumer changes in food, shelter, mobility, goods and services to make a significant contribution to the international two degree target. Consumption considers not only energy demand, but demand for material goods and services which can have a high embodied impact. For example, Barrett and Scott (2012) show the potential for resource efficiency measures to contribute to reducing consumption emissions. Strategies include material substitution (Giesekam et al., 2014a), product longevity (Bakker et al., 2014), product-service systems (Reim et al., 2015) for example and Multi-Utility Service Companies (Roelich et al., 2015b). Extending the scope of climate policy to other areas such as resource efficiency increases the coverage of emissions beyond those from a country's production, but will also need to address sufficiency to be aligned with two degree or lower climate targets. Research framing and contribution

This thesis applies consumption-based emissions accounting to national climate mitigation policy and target setting. It addresses consumption and growth, the main drivers of emissions; analyses progress towards meeting carbon budgets from a consumption perspective; shows how low carbon energy pathways would need to adapt when including embodied energy system emissions in climate targets; and presents additional policy opportunities as well as supplying efficient low carbon energy.

1.1.5 Contribution to the literature

The scientific evidence is clear on the need to devise climate targets based on cumulative carbon budgets, yet international negotiations continue to discuss end-point targets. Those targets in place are also not sufficient to achieve a two degree, or lower, future. There is agreement in the literature that consumption is the main driver of greenhouse gas emissions, and that international trade distorts territorial emissions inventories. I reviewed studies that looked at different principles, mainly around justice and equity, to apportion the remaining carbon budgets to nations. However, if there were the political motivation for consumption accounting, this would require increased data collection and monitoring procedures, presenting additional administrative burdens, particularly for developing countries. Publications on consumption-based accounting methods have considerably increased in the last eight or so years, focusing on advancing the methods and presenting consumption emissions results, but with less applications to refining climate policies. While low carbon technologies have been cited as feasibly providing all the energy needed for the continuing growth in consumption, this is proving to be an expensive pathway with many barriers, and is yet aligned in practice with anywhere near a two degree future. Therefore, further attention is required to reduce energy demand through a range of additional policies. I found examples of policy instruments that when supported with technology and financial transfers could address traded emissions without disproportionately impacting the welfare of less developed countries. However, there has been little empirical work on how the implementation of consumption-based accounting would affect existing national climate policies and targets.

I build on the growing body of literature on consumption accounting by linking climate science directly to policy. I analyse how the integration of emissions embodied in trade would redefine climate targets and policies for three applications: 2050 climate change targets, energy supply pathways, and energy efficiency product standards. I focus on policies decided at the national and supra-national level (UK and EU), and not how these translate into local level decision-making and planning. The first two applications are analysed for the UK, however the latter is conducted at the European level as it relates to product and resource efficiency policy which is designed more at this level. I align the analyses with a carbon budgetary approach by measuring cumulative emissions alongside progress towards meeting end-point targets. The contribution of UK mitigation compared to global efforts is measured, placing the UK within the global context. This thesis both quantifies the additional reach of specific policies in terms of emissions coverage and demonstrates its applicability to devising policies where countries cannot transfer their emissions burden abroad. In doing so, it advances the application of consumption-based accounting beyond a diagnosis of the problem of carbon leakage.

In addition to its policy-oriented contribution to the literature, the thesis makes two methodological contributions. Firstly, high level IPCC scenarios have been extended to include emissions embodied in trade, calculating the most detailed projections to date of consumption-based emissions (Chapter 2). Secondly, in collaboration with energy system modellers at University College London (UCL)[3], we have developed a novel methodology by extending an energy system optimisation model to include traded emissions as a criterion in energy technology selection to meet a specified emissions budget (Chapter 3).

1.1.6 UK and EU case studies

The UK has committed to reducing its production emissions to 20% of 1990 levels by 2050, on a downward trajectory defined by five-year cumulative carbon budgets. As noted by Anderson and Bows (2011), the wording around UK climate targets in policy documents, such as the UK's Carbon Plan, is qualitatively clear on the need to <u>prevent dangerous climate change</u> and <u>not exceed two degrees</u>, however such efforts do not extend in practice. Going back to 2007, when the UK target was set at a 60%, not 80% reduction, Anderson and Bows (2007) suggested to have even a 30% chance of not exceeding two degrees would translate into a 70% and 90% reduction in 1990 emissions by 2030 and 2050 respectively. It was first thought that 2 degrees represented an acceptable level of damage limitation, however, the impacts associated with 2 degrees have been revised upwards representing a threshold between 'dangerous' and 'extremely dangerous' climate change and according to Anderson and Bows (2011) should represent a threshold level. However, despite the scientific evidence base, UK targets are based on a 50% probability of exceeding 2 degrees on the premise that "the global danger zone starts above about 2^0C, and that global policy should aim to keep central estimates of temperature increases below this danger zone" (CCC, 2008).

The global emissions budget based on IPCC evidence (Stocker et al., 2013) from 1870 to 2100 is 2900 $GtCO_2$, assuming a 66% probability of limiting temperature rise[4]. 1,891 Mt was emitted before 2011, leaving 1,009 Mt of remaining carbon space. If the global budget was apportioned on an equal per capita basis determined by today's population the UK's cumulative carbon budget from 2011 would be in the region of 9Gt, and even less if 2 degrees was taken as a

[3] Hannah Daly (Research fellow) and Neil Strachan (Professor)

[4] The highest probability measured

threshold limit or assuming 2050 population estimates in which the UK is anticipated to have a diminishing share of the global population. Based on different fairness based criteria of increasing equity, Raupach et al. (2014) estimate a remaining carbon space of between 7 and 12 Gt for the UK[5]. However, based on UK climate policy, assuming cumulative emissions aligned with existing carbon budgets and then cumulative emissions associated with a downward trajectory to meeting the UK's 80% emissions reduction target, the UK would produce 14.7 $GtCO_2e$ from 2011. This is 60% higher than the IPCC's scientific base. Given the evidence for 2 degrees, and moreover the latest negotiations in Paris which indicate limiting temperature rise to 1.5 degrees, the UK's target arguably needs considerable reframing. Whilst recongising the shortfalls in the targets set by the UK government, I aim to investigate a deviation from the existing climate policy landscape and therefore from here on in refer to existing targets, and not arguably required more ambitious targets.

As a Member State of the EU it is accountable to EU legislation and its regional targets and pledges under the UNFCCC. The three headline targets of EU energy and climate policy are to increase the share of renewable energy sources to 20%, to increase energy efficiency by 20% and to decrease CO_2 emissions by 20% by 2020. Furthermore, the EU has the objective of reducing greenhouse gas emissions by 80-95% by 2050 compared to 1990. UK climate policy, documented in its Carbon Plan (2011), is based on reducing production emissions by sectors, focusing on a low carbon energy transition away from fossil fuels. EU climate policy is centred on the EU Emissions Trading Scheme (EU ETS) and Directives addressing the energy efficiency of buildings and products. The EU ETS sets a limit on absolute industry emissions (representing 40% of EU production emissions), which reduces over time, and allocates industries a certain number of carbon allowances, each equivalent to one tonne of carbon. These are then traded between industries depending on individual mitigation efforts, putting a price on carbon. Industries which introduce fewer mitigation measures need to buy additional allowances from those who have carbon to spare. The intention is that a carbon price will encourage industries to innovate emissions abatement measures.

1.1.7 Research questions, methods and academic outputs

The overall objective of this thesis is to determine how climate policy would change when embodied emissions are integrated into climate mitigation targets using the UK and EU as representative case studies of Annex I nations. Three overarching research questions are proposed, each corresponding to a chapter of analysis and standalone peer-reviewed publication, outlined in

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[5] Raupach et al. derive budgets for Europe which I assign to the UK based on the UKs share of current population

Table **5**. Research aims for each question are presented in each paper. The discussion brings together these analyses to consider how the focus of climate mitigation policy would shift with the integration of embodied emissions, to what extent consumption-based emission accounting could be implemented, at what scale, and under which policy mechanisms.

This thesis includes papers in which I am the primary author, and I have also referenced relevant co-authored papers in Table 6. In Afionis et al. (*submitted*) we provide a political perspective on what has helped consumption-based emissions accounting gain stature in international discussions on climate mitigation on the one hand, but has hindered its widespread adoption on the other. In Daly et al. (2015) we developed the methodology that enables us to explore the policy implications of accounting for embodied emissions in devising energy pathways. In Barrett and Scott (2012) we explored the mitigation potential of resource efficiency strategies for meeting UK climate targets. Finally, in Holland et al. (2015) we explored the implications of energy demand on freshwater consumption, recognising that energy policy does not only affect greenhouse gas emissions, but a range of other environmental and social impacts.

Table 5: Research questions, corresponding methods and academic outputs

Research question	Study focus	Method	Data sources	Output
How would the integration of embodied greenhouse gas emissions alter UK climate change mitigation policies?	Trade and sector analysis of UK consumption emissions based on existing international climate pledges	MRIO and scenario analysis	Eora EE-MRIO database with greenhouse gas emissions extension, Committee on Climate Change's scenario for UK emissions to 2050, International Energy Agency scenarios of global energy use to 2050	*Chapter 2* Article published: SCOTT, K. & BARRETT, J. 2015. An integration of net imported emissions into climate change targets. *Environmental Science & Policy,* 52**,** 150-157.
How would the UK's low carbon energy transition adapt when mitigating embodied emissions, not just operational emissions from energy supply?	Analysis of UK national energy 2050 pathways to meet existing carbon targets when including traded emissions embodied in UK energy supply emissions	Integration of MRIO analysis with an energy system optimisation model (ESOM)	UK MRIO model with UKTM-UCL ESOM	*Chapter 3* Article accepted (26.1.16): SCOTT, K., DALY, H. E., BARRETT, J. R. & STRACHAN, N. National climate policy implications of mitigating embodied energy system emissions, *Climatic Change*.
What is the additional emissions scope of energy efficiency policy when embodied emissions are included?	Analysis of additional reach of EU climate policy when addressing emissions embodied in resource use	MRIO and product group analysis	Exiobase EE-MRIO database with greenhouse gas emissions extension	*Chapter 4* Article under review (18.12.15): SCOTT, K., ROELICH, K., OWEN, A. AND BARRETT, J. Addressing globally traded emissions through domestic consumption policies, *submitted to Environmental Research Letters*.

Table 6: Relevant co-authored papers

AFIONIS, S., SAKAI, M., SCOTT, K., BARRETT, J. AND GOULDSON, A. (2015) Consumption-based carbon accounting: Does it have a future? *Submitted to WIREs Climate Change (undergoing revisions)*
DALY, H. E., SCOTT, K., STRACHAN, N. & BARRETT, J. R. 2015. The indirect CO2 emission implications of energy system pathways: Linking IO and TIMES models for the UK. *Environmental Science & Technology*, 49, 10701-10709.
BARRETT, J. & SCOTT, K. 2012. Link between climate change and resource efficiency. *Global Environmental Change,* 22, 299-307.
HOLLAND, R. A., SCOTT, K. A., FLÖRKE, M., BROWN, G., EWERS, R. M., FARMER, E., KAPOS, V., MUGGERIDGE, A., SCHARLEMANN, J. P. W., TAYLOR, G., BARRETT, J. & EIGENBROD, F. 2015. Global impacts of energy demand on the freshwater resources of nations. *Proceedings of the National Academy of Sciences*, 112, E6707-E6716.

1.1.8 Summary of papers

The first paper (Chapter 2) extends well established territorial decarbonisation scenarios from the IPCC's RCPs (Stocker et al., 2013) and the IEA's Energy Technology Perspectives (International Energy Agency, 2012) to include trade. While the IPCC provided a detailed analysis of the embodied emissions of trade as part of the assessment of past drivers, the literature was not available to consider future projections within the scenario analysis. I calculate current and projected trajectories of UK consumption-based emissions in which international emissions are based on committed climate policies, and compare these to the UK's production emissions trajectory as defined by its carbon budgets.

Given the priority of energy policy, the second paper (Chapter 3) uses an established energy system optimisation model featured in the UK Carbon Plan, which has been extended to include emissions embodied in energy infrastructure, some of which occur outside the UK. In its original form, it generates cost optimal energy technology pathways based on combustion emissions from energy supply to meet UK energy service demands within a given emissions constraint. The analysis looks at the implications of mitigating embodied emissions within energy policy, in terms of both potential changes to the energy system pathways and first versus second best policy options.

The third paper (Chapter 4) analyses the emissions associated with resource consumption in the EU. The premise is that a greater integration of resource efficiency within climate mitigation policy can deliver additional emissions reductions, currently reliant on the deployment of renewable energy technologies and energy efficiency measures. Instead of considering a broad range of resource efficiency strategies, the paper measures how a simple extension of EU energy efficiency Directives to include emissions embodied in a product, and not just its operational performance, can increase the scope of emissions captured by existing EU policies.

1.1.9 Thesis structure and overview of chapters

The academic outputs presented in

Table **5** provide three chapters of analysis (Chapters 2 – 4). Chapter 5 summarises the main conclusions and policy implications of each analysis, presents the limitations of the study, discusses why and how to integrate embodied emissions into climate mitigation policy and suggests a pragmatic proposal for its implementation, including future research needs.

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2 An integration of net imported emissions into climate change targets

*This chapter is the author accepted manuscript of: SCOTT, K. & BARRETT, J. 2015. An integration of net imported emissions into climate change targets. Environmental Science & Policy, 52***,** *150-157.*

Abstract

There is an international divide between net emissions importers and net emissions exporters, with industrialised nations mainly falling into the former and emerging economies the latter. Integrating emissions transfers into climate policy, so as not to disadvantage export-intensive countries, has been suggested to increase participation in international emissions reduction commitments. Consumption-based scenarios are presented for the UK identifying the geographic and sectorial source of emissions to meet future consumer demands given the current international climate policy landscape. The analysis is applied to the UK yet the discussion is applicable to international climate policy; assigning national responsibility for global emissions reductions; and extending the mitigation potential for net importing countries. Two trajectories for UK consumption emissions are calculated in which (1) international reduction targets are consistent with those pledged today equating to four degrees of temperature rise and (2) international reduction targets achieve a two degree future. By 2050 it is estimated that UK consumption emissions are 40% to 260% greater than UK territorial emissions depending on the strength of global reduction measures, and assuming the UK meets its 80% reduction in 1990 emissions by 2050 target. Cumulative emissions are presented alongside emissions trajectories, recognising that temperature rise is directly related to every tonne of carbon emitted. Whilst this paper argues that the current UK emissions targets underestimate the UK's contribution to global mitigation for two degrees, it shows how expanding the focus of policy towards consumption introduces new opportunities for reduction strategies at scale. The paper advocates the implementation of consumption-based emissions accounting which reveals underexploited policy interventions and increases the potential to break down barriers that exist between industrialised and emerging economies in international climate policy.

Key words: consumption emissions; emissions transfers; emissions targets; climate policy; scenario analysis

2.1 Introduction

Drastic cuts in emissions are needed to achieve the global climate objective of limiting temperature rise to two degrees. The IPCC 5th Assessment report presents the latest scientific evidence on the relationship between emissions and temperature rise (Stocker et al., 2013). The report shows that global temperature rises are approximately proportional to an increase in cumulative carbon emissions, and not simply end-point targets for 2050, given that emission pathways can differ (Gillett et al., 2013). This has major implications for the way climate change targets are implemented. Contributions to climate policy literature have illustrated the need to replace end-point targets with cumulative carbon budgets (Anderson et al., 2008, Anderson and Bows, 2011, Anderson and Bows, 2012, Meinshausen et al., 2009, Peters et al., 2013, Gillett et al., 2013, Chicco and Stephenson, 2012). Cumulative emissions will depend on the interplay of technology and policy development, and how effective policy can enable the deployment of low carbon technologies (Chicco and Stephenson, 2012).

Reaching global agreement on how much responsibility should be assigned across regions is being contested in international climate negotiations, creating somewhat of a climate 'impasse' (Grasso and Roberts, 2014). Currently greenhouse gas emissions reductions are by-and-large governed by a pledged-based system of end-point targets benchmarked against territorial emissions in a handful of regions implemented under the Kyoto Protocol and Cancun Agreements; however these commitments alone equate to in the region of four degrees of warming (International Energy Agency, 2012). Industrialised countries, termed Annex I parties[1], have the strongest quantitative commitments and reporting obligations compared to emerging and developing economies, non-Annex I parties[2], which have qualitative obligations, more lenient reporting requirements and eligibility for financial and technological assistance (Depledge, 2009). Countries are often referred to as Annex B and these are the Annex I countries that have ratified an emissions reduction target under Annex B of the Kyoto Protocol, which in its second phase accounts for less than 15% of global emissions (Grubb, 2013).

In contrast to territorial emissions accounting, research papers in the last five-to-ten years have calculated countries' consumption-based emissions accounts: the emissions embodied in a country's final consumption regardless of where they are produced (for example Davis and Caldeira (2010) and Hertwich and Peters (2009)). Studies show that industrialised countries tend to be net importers of emissions whereas emerging and less developed countries tend to be net emissions exporters. In the first round of Kyoto targets the emissions saved were completely offset by net emissions transfers from non-Annex B to Annex B countries (Peters et al., 2011, Kanemoto et al., 2014), referred to as carbon leakage. However, there has been little debate on the use of different system boundaries for international emissions reporting (Peters and Hertwich, 2008a), and efforts to incorporate consumption impacts into international negotiations have been marginalised (Isenhour and Feng, 2014). Some now advocate that net

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[1] industrialised OECD member countries and countries deemed to be economies in transition in 1992

[2] Those deemed as developing in 1992 and recognised as being vulnerable to the adverse impacts of climate change.

emissions importers should take on responsibility for the ‘additional’ imported emissions generated outside their territories (Singer et al., 2014).

Studies have shown on the grounds of equity that industrialised countries should take on more responsibility than is currently assigned to mitigate global carbon emissions (Steininger et al., 2014, Grasso and Roberts, 2014, Raupach et al., 2014, Athanasiou et al., 2014, Pan et al., 2014). Athanasiou et al. (2014) even suggest that emissions reductions in Annex I countries should be greater than the emissions generated within these countries, meaning they need to take responsibility for reducing emissions in non-Annex I countries. What has not been explicitly analysed in the literature is distributional trends in consumption emissions and whether trends in net traded emissions are likely to continue within existing climate change frameworks.

The UK for example has an 80% emissions reduction target on 1990 territorial emissions by 2050, to be achieved through implementation of its Carbon Plan (HM Government, 2011), and has interim five year carbon budgets (set four terms in advance) to try to ensure a reduction in cumulative emissions towards meeting the end-point target. It is unclear however how much of the UK’s cumulative consumption-based emissions would continue to sit outside the UK in the country of origin, complicating their inclusion in reduction targets. A few studies have shown for highly aggregated global regions what consumption-based emissions trajectories are needed to meet carbon budgets for two degrees, without considering what they are likely to be given existing climate polices (Bows and Barrett, 2010, Springmann, 2014). Both references provide high-level regional analysis without disaggregated trade and sectorial details. To help inform the evidence gap this paper analyses the corresponding cumulative emissions of implementation of international climate policies from a national consumption perspective. The paper poses four research questions:

1. Within the existing international climate policy framework, will the UK continue to be a net importer of emissions to 2050?
2. In which regions and sectors will UK consumption-driven emissions be emitted in 2050?
3. What is the cumulative impact of UK consumption emissions to 2050?
4. How can climate policy respond to achieve a reduction in the cumulative global emissions caused by UK consumption?

The paper is the most comprehensive analysis to date of consumption-based pathways at the country and sector level. It extends well established territorial decarbonisation scenarios from the IPCC’s representative concentration pathways (Stocker et al., 2013) and the IEA’s Energy Technology Perspectives (International Energy Agency, 2012) to include trade. While the IPCC provided a detailed analysis of the embodied emissions of trade as part of the assessment of past drivers, the literature was not available to consider future projections within the scenario analysis. This paper is one of the first to provide a detailed analysis of the future emissions embodied in trade within the context of the IPCC’s detailed analysis of territorial emissions.

Whilst providing this detailed consumption-based emissions pathways for the UK, the results are also discussed in the context of domestic and international climate policy and the feasibility of achieving a two degree future.

2.2 Method for determining consumption-based emissions trajectories for the UK (2010-2050)

Territorial emissions are published annually in the UK by DECC (Department for Energy and Climate Change), and the UK is one of a handful of countries to publish consumption-based emissions from 1990 to 2013 (Defra, 2015, Barrett et al., 2013). National consumption-based emissions are equal to territorial emissions minus emissions generated to produce exports (consumed elsewhere) plus emissions generated elsewhere to produce imports, and are calculated using multi-region input-output models. UK consumer demand will not just induce production in the UK economy but will induce global production activities, resulting in emissions being released outside of its territory. Consumption-based accounts lag a few years behind the release of territorial emissions therefore at the time of this research 2010 was the latest year available.

In this paper consumption-based emissions are projected at five year intervals from 2010 to 2050. The modelling framework is built on collaboration between the authors and the UK Committee on Climate Change (CCC) who were investigating emissions associated with future UK consumption patterns, documented in the CCC's report *Reducing the UK's carbon footprint and managing competitiveness risks* (CCC, 2013). In addition this paper presents territorial emissions alongside consumption-based emissions for comparison and the cumulative impacts of the scenarios are calculated based on the direct relationship between temperature rise and carbon emissions (Gillett et al., 2013).

2.2.1 Input-output analysis

Environmentally-extended multi-region input-output analysis (EE-MRIOA) can evaluate the emission impacts embodied in goods and services traded between nations and is recognised as the most appropriate tool to estimate consumption-based emissions accounts at the national and supra-national level (Peters, 2010a, Wiedmann, 2009, Peters et al., 2012a). EE-MRIOA reallocates production emissions, which are point source emissions from sectors within a country's territory, to the destination country of the final consumer through complex international trade flows (Peters, 2008). Direct household emissions for heating and transport are added onto the account as they are not allocated to an industry sector.

Using input-output analysis, consumption emissions (F) are given by $F = f_x L y$, where f_x is the direct carbon intensity of production sectors, L is the effect of trade transactions (known as the Leontief Inverse), and y is the volume and composition of final consumption. Carbon intensities for production sectors (f_x) are calculated by dividing direct sector emissions (f) by the sector's economic output (*X*). The Leontief inverse (*L*) calculates the ratio of upstream requirements (i.e. goods and services) to produce each sectors finished products. When multiplied by the vector of carbon intensities it provides carbon intensities for final products which includes the direct and indirect emissions produced along product supply chains to the point of purchase, referred to as total carbon intensities. Multiplying the total carbon intensities for domestic and imported products by a country's final demand for domestic and imported products (*y*) determines the emissions released globally in the production of goods and services consumed in a nation – its consumption-based emissions account.

2.2.2 Scenarios and projections

Two main scenarios are presented, providing different representative trajectories for UK consumption-based emissions to 2050 in which (1) international efforts don't go beyond those currently implemented equating to four degrees of warming, and (2) global production emissions reduce in line with carbon budgets for a two degree future. These scenarios will differ in their emissions embodied in UK imports.

The input-output framework is used to link international and UK emissions reductions with growth in UK final demand via global trade transactions to calculate the UK's consumption-based emissions from 2010 to 2050. 110 productive sectors are modelled within the UK and their trade with 26 sectors in seven global regions outside the UK to meet UK demand are modelled: OECD Europe (excluding UK), non-European OECD, Russia, China, India, Rest of Asia and Rest of World. Each variable in the input-output model described in section 2.2.1 is projected at five year intervals from 2010 to 2050 to generate two consumption based emissions trajectories. Emissions at five year intervals are then interpolated to estimate cumulative emissions from 2010 to 2050. Projections for UK territorial emissions are produced separately to projections for international emissions (f_{UK} and $f_{overseas}$). The assumptions for each variable are summarised in Table 7 and described in more detail in Appendices 6.1 to 6.6. The resulting consumption-based emissions trajectories are compared to the UK territorial target to determine the distance from the territorial target to achieve a two degree future. The results section presents two representative trajectories for UK consumption-based emissions to 2050, broken down by sector and import share, and from a cumulative perspective.

Table 7: Summary of UK consumption emissions projections (more detail is provided in Appendices 6.1 - 6.6)

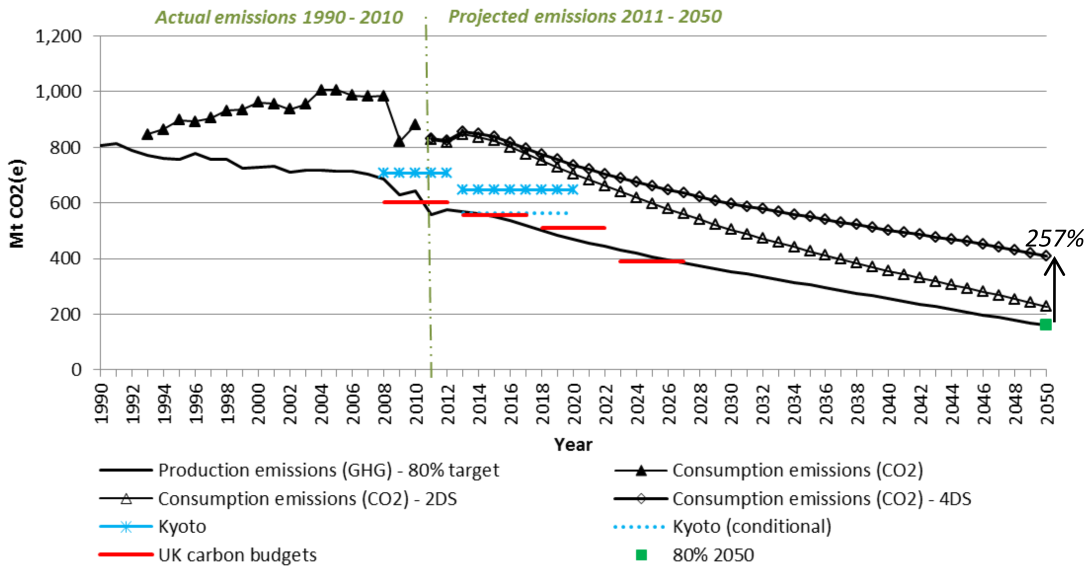
Consumption emissions variable	Summary of scenario assumptions 2010 to 2050
UK production emissions trajectory (f_{UK})	UK production emissions are reduced 80% from 1990 levels by 2050 following the "Barriers in industry" scenario defined by the CCC (pg. 46: CCC (2012)).
International production emissions trajectories ($f_{overseas}$)	This is where the two and four degree scenarios are distinguished. (1) Only currently pledged emissions reductions are achieved consistent with four degrees of temperature rise, and (2) global emissions are reduced from 2010 to 2050 to have a 66% probability of limiting temperature rise to two degrees.
Direct carbon intensities of production sectors (f_X)	Production emissions are divided by projected economic output to describe the carbon intensity of production sectors. The Office for Budget Responsibility (OBR) projections were used to project UK annual economic growth rates and IMF (International Monetary Fund) and other sources were used to project economic output in the seven trading regions. Both scenarios achieve improvements in carbon production intensities.
Global trade transactions (L)	Global trade transactions between sectors and countries destined for UK consumers are taken from the Eora database developed at the University of Sydney (Lenzen et al., 2012, Lenzen et al., 2013). The share of product inputs along product supply chains are assumed to remain constant, however sales to final consumers change which reflects changes in the structure of the global economy.
UK final demand (y)	The level of UK final demand grows in line with trends over the past 20 years, with demand for domestic and imported products increasing at an average annual growth rate of 1.9% and 2.75% respectively.

2.3 Results

Traded emissions results are limited to CO_2 only due to data availability of global emissions; however the UK production emissions are expressed in CO_2e to benchmark against national targets. UK consumption-based emissions have grown 16% from 1993 to 2010, with imported emissions from outside European OECD countries rising nearly 60%. Looking forward to 2050, implementation of domestic and international mitigation policies drives absolute emissions associated with the UK down. Figure 4 shows results for UK production and consumption emissions. The two trajectories for consumption emissions represent the two scenarios which consider (1) only the current Cancun Agreements consistent with four degrees of temperature rise (line with diamonds) are implemented, and (2) imports are produced in a world where global mitigation is compatible with limiting warming to two degrees (line with triangles). The UK has already complied with the first round of Kyoto targets set under the UNFCCC and is well underway to comply with the second phase target.

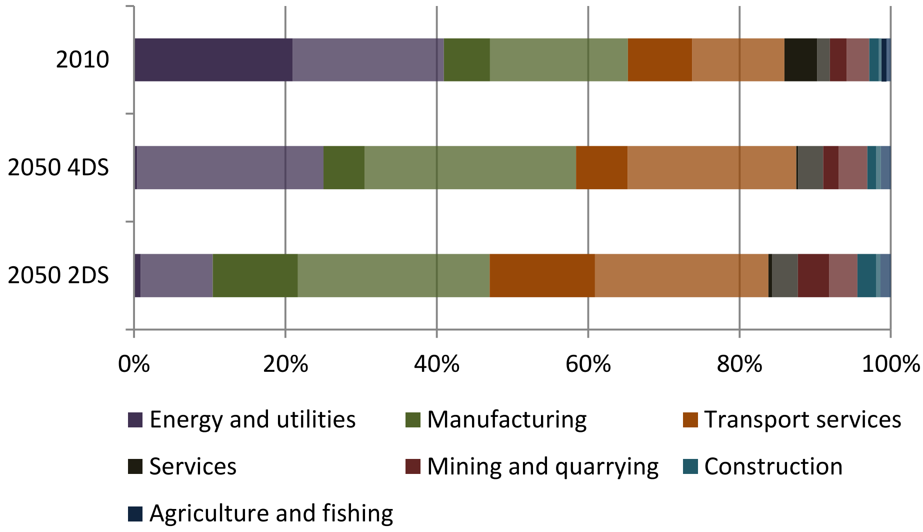
The success of the UK in achieving its reduction targets is offset by emissions generated in other regions to meet UK demand. Even with strong global mitigation the UK could continue to be a net importer of emissions in 2050 with consumption emissions estimated to be 43% higher than the 80% reduction target, increasing to two and a half times the target (257%) if only current internationally-pledged reductions were implemented (see Figure 4).

Figure 4: Emissions trajectory for the UK to 2050 (UK production emissions are in Mt CO_2e and import emissions are in Mt CO_2)



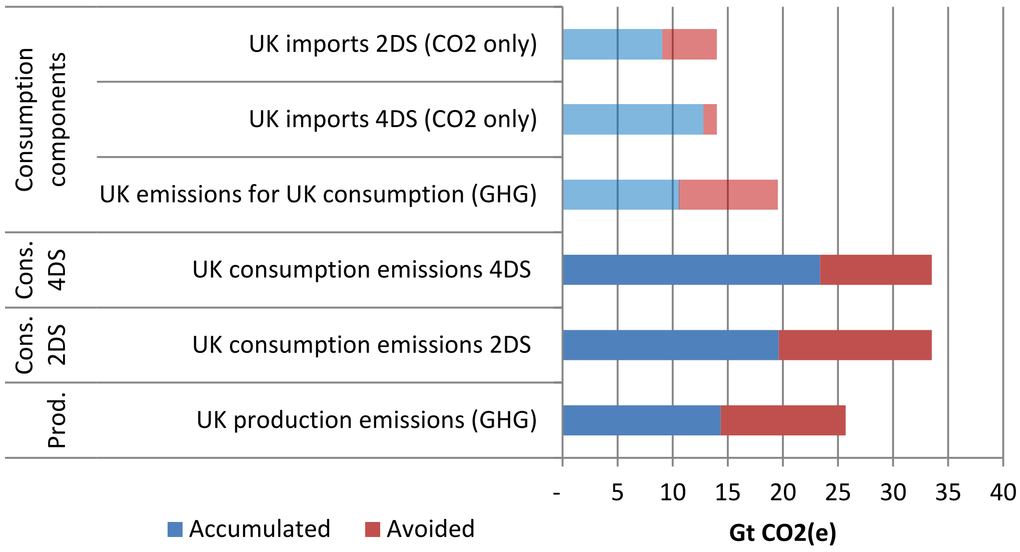
If strong international abatement efforts towards a two degree future are achieved, emissions generated in the energy sector become a tenth of what they are in 2010, changing the sector profiles considerably by 2050. Emissions generated in the global energy sector are anticipated to contribute an 11% share to UK consumption-based emissions in 2050 compared to 41% today. The share of emissions is shifted to manufacturing and transport services, where there are more barriers to technology deployment, each estimated to represent nearly a 40% share by 2050. If countries fail to achieve the required reductions, current international emission reduction commitments would mean the share of UK imported emissions climbs to nearly 80% (the transparent colours in Figure 5), with a higher share of the increase in imported emissions being produced in non-Annex I countries.

Figure 5: Share of UK consumption emissions by sector of origin in 2010 and 2050 under a two and four degree scenario. Sectors are disaggregated by their domestic and overseas location with the second transparent colour segment representing the overseas proportion.



The sum of the bars in Figure 6 show the cumulative emissions between 2010 and 2050 (blue bars) compared to a baseline situation whereby it is assumed 2010 emission remained constant at 2010 levels to 2050 to give a measure of avoided cumulative emissions (red bars). From a production perspective over 25 $GtCO_2e$ would have been generated by UK industries and just over 11 Gt (44%) would be avoided by meeting the 80% reduction target. From a consumption perspective 33.5 $GtCO_2(e)$ would have been generated, 42% from industries overseas. Only about 10 Gt (30%) would be avoided in a four degree future, compared to 14 Gt (41%) in a two degree future. Imported emissions add more than 9 Gt CO_2 to the cumulative account, and a further 4 Gt CO_2 without a global deal to strengthen current emission reduction commitments.

Figure 6: Accumulated and avoided emissions for scenarios from a production and consumption perspective from 2010 to 2050. Avoided emissions are equal to the cumulative emissions from 2011 to 2050 if emissions stabilised at 2010 level minus the cumulative emissions in the two and four degree futures.



2.4 Discussion and policy recommendations

The results of this analysis emphasise that unilateral climate policies can be hampered by carbon leakage. Half of the UK's cumulative consumption-based emissions sit outside the UK in the country of origin, and increasingly within non-Annex I countries, which is of mounting concern without their inclusion in international reduction targets. We illustrate how net imported emissions could increase UK production emissions in the region of 40% to nearly 260% depending on the strength of international mitigation efforts in 2050. This assumes compliance of UK carbon budgets and currently pledged emission targets; however recent analysis raises concerns for whether UK policy is even enough to achieve its fourth carbon budget (CCC, 2014).

Without a global cap on emissions, different policy measures have been proposed to prevent carbon leakage from making unilateral policies ineffective. One of the most widely discussed options is carbon border adjustments where the carbon content of imported products from non-regulated (or weaker regulated) regions is taxed at the emissions price of the regulating region and emission payments for exports to non-regulating countries are rebated (Bohringer et al., 2012a, Bohringer et al., 2012b, Bohringer et al., 2014, Bednar-Friedl et al., 2012). Whilst generally but not exclusively thought of as being the most effective means of cutting leakage, they have been found to intensify regional inequalities by penalising the high exporting countries and may be in breach world trade agreements (Atkinson et al., 2011, Bohringer, 2014, Li et al., 2013). The distributional impacts could be reduced if tariff revenues were redirected towards the exporting countries (Bohringer et al., 2012a), and low carbon technology transfers from regulated to unregulated regions enabled developing countries to compete by producing carbon equivalent products. The discussion below identifies options for the UK, and other industrialised nations, for mitigating emissions embodied in their imports, without unfairly taxing export economies.

2.4.1 Revising the UK's emissions reduction target

From a consumption perspective the UK generates more emissions abroad than it statutes for. This is not an argument to cease trade to the UK as this in itself would not necessarily reduce global emissions (Jakob and Marschinski, 2013), but to extend the scope of emission reductions to reflect the UK's position as an industrialised global consumer. With industrialised nations secured into a legally-binding mitigation framework, strengthening their commitments by extending their carbon budget framework to include net emissions embodied in trade could make reduction targets for high-exporting (less industrialised) economies more palatable. To demonstrate the scale of such an initiative, it is estimated that in 2050 the UK drives an additional volume of emissions of between 68 to 251 CO_2 outside its territory depending on global mitigation efforts. Subtracting these figures from the existing 2050 target of 160 Mt CO_2e would result in the UK target being reduced to at least 91 Mt CO_2e (equating to an 89% reduction on 1990 territorial emissions, 805 Mt CO_2e), to having negative emissions of 92 Mt CO_2e by 2050.

2.4.2 Expanding the focus of climate policy

To achieve the same intended "climate outcome" of the existing territorial target, which is dependent on cumulative emissions, countries with high consumption-based emissions could be given tighter carbon budgets. There are three broad options in which to achieve greater reductions without taxing exporters: (1) strengthen reduction efforts within the national territory, (2) reduce emissions in countries outside one's territory, and (3) reduce and/or alter resource consumption; of which there are benefits and disadvantages of each.

2.4.2.1 Increasing domestic emissions reductions

The UK could strengthen its domestic reduction efforts, however the assumptions employed in the scenarios for global and UK production emissions trajectories are heavily reliant on decarbonisation and technology innovation and deployment. It is assumed the technologies are available and cost effective to mitigate for two degrees. Whilst deemed to be technically feasible and within the political scope of national governments, there are risks and barriers to widespread technology deployment (Bruckner et al., 2014) and the transition into practice has not had a promising start. Although the UK met the first round of Kyoto targets and its first carbon budget, the evidence suggests this is mainly due to the exclusion of international aviation and shipping[3], the economic recession, and generous carbon allowances under the EU ETS. For

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[3] Whilst not in the UK's officially reported territorial emissions, these are included in the 80% reduction trajectory modelled in Figure 4. This is termed production emissions, not

example less than 1% of the 7% reduction in UK territorial emission reductions in 2011 is attributable to climate policy (CCC, 2014). The under ambitious allocation of allowances in the EU ETS coupled with reduced shares of GDP being spent on energy-related research (Bowen and Rydge, 2011) has meant there is less incentive to innovate and the share of energy consumption from renewable sources remains marginal compared to fossil fuels at 4% of UK energy consumption (DECC, 2013). With annual emissions reduction rates of more than four times the global average (1.2%) needed to 2050, and a diminishing global carbon budget, there is a need to look at alternative reduction options.

Edenhofer et al. (2015b) argue that unilateral policies can be effective with the implementation of a national carbon price. This would allow countries to select the policies that work most efficiently for them, and could pave the way to a global dynamic hybrid climate regime. Even though they acknowledge that a national carbon price will not in itself meet the required global emissions gap, evidence has shown that other countries are likely to reciprocate the more ambitious efforts of the lead country (enabled through for example shared experiences and technology spill over). These more flexible bottom-up unilateral policies could be coordinated into an international framework that is gradually scaled up over time by countries pledging to increase their effort conditional on policy support or more ambitious targets in other countries. Edenhofer et al. (2015b) provide examples of linking regional trading schemes, investing in joint research and development initiatives and technology cooperation aiming to harmonise high standards.

2.4.2.2 Strengthening effort-sharing agreements

National efforts could be strengthened by effort-sharing agreements linked to climate targets. As alluded to in the previous paragraph, this includes the transfer of finance, knowledge, abatement technologies and so forth and therefore allows the UK to take on more responsibility than what is defined by its territorial emissions. This was partly the intention of the Clean Development Mechanism (CDM) which was set up under the UNFCCC to allow countries with reduction targets to gain carbon credits for implementing or financing carbon reduction projects outside their territory; recognising however in theory that the process needs to also ensure it benefits the host population (Mathur et al., 2014). According to Edenhofer et al. (2015b), strong leadership and technology spillover can promote actions in other regions, and it can enable emissions intensive consumer countries to negate additional emissions outside of their political jurisdiction. Whilst this can be argued on the grounds of improved equity, whereby net emissions importing countries with higher economic capacity take on responsibility for the impact of their consumption-intensive lifestyles, CDM projects have not necessarily had the

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territorial, to identify that emissions from aviation and shipping are included. If these additional emissions were included in the territorial account the first carbon budget would have been exceeded by 2.5%.

intended transferal benefits for the host nation (Costa et al., 2013); they have been unevenly distributed across countries (Rahman and Kirkman, 2015); and it has been hard to prove that the emissions reductions wouldn't have occurred without the CDM (Erickson et al., 2014). Therefore this needs to be corrected for such policies to be effective.

2.4.2.3 Reducing consumption

Greenhouse gas mitigation from changing consumption has received little attention in climate policy literature (Girod et al., 2014), with the exception of residential energy efficiency. Consumption changes can increase mitigation options beyond decarbonisation. Bruckner et al. (2014) suggest more aggressive energy demand reductions are needed to meet international climate objectives. Girod et al. (2014) show the potential of consumer changes in food, shelter, mobility, goods and services to make a significant contribution to the international two degree target. Currently UK policy influencing consumption deals primarily with the energy consumption of products, stemming from three EU Directives: EU Eco-Design Directive, EU Energy Labelling Directive and the EU Ecolabel Scheme (a voluntary measure). Yet there is also untapped potential for resource efficiency strategies that deal with material and product demand to drive emission reductions upstream, including those generated in its trading partners (Barrett et al., 2013).

Barrett and Scott (2012) show the potential for demand-side strategies applied to non-energy related goods and services[4] to contribute to reducing UK consumer emissions. Strategies can be adopted by both producers such as lean production and green procurement, and households such as changing household's behaviours towards using products for longer and shifting to service-based consumption instead of ownership, for example joining a car club. They estimated savings of up to 28% in the non-energy sectors. These would influence emissions from sectors that under strong decarbonisation and electrification become the most significant source of emissions: transport services and manufacturing.

However, developing countries are dependent on export markets to generate economic growth to develop their infrastructure and increase their living standards. Whilst there is a considerable body of work on degrowth and its implications for developed economies, it has been hard to find how reduced consumption in developed economies or border taxes on developing countries' exports would impact welfare (Li and Zhang, 2012) and further exacerbate global inequalities.

[4] The study excluded emissions reductions from energy and transport

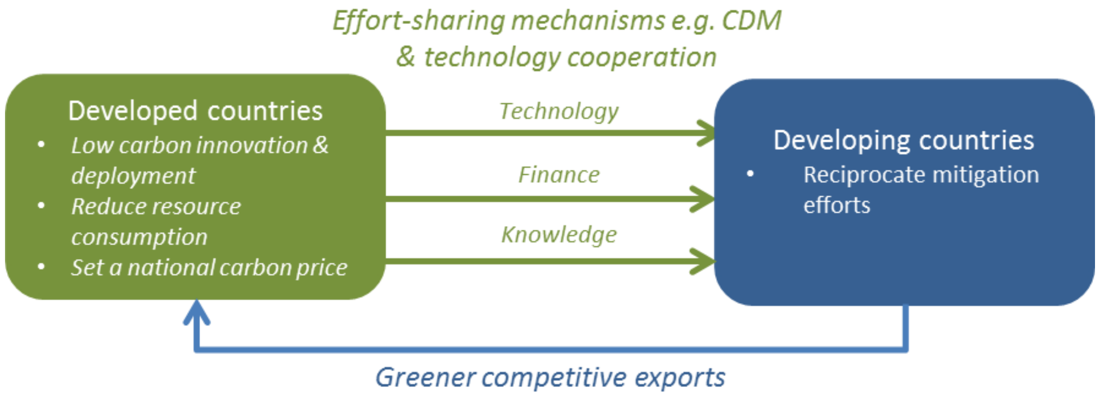
2.5 Conclusions

This paper presents evidence on the regional and sectorial distributional trends in UK consumption-driven emissions given existing international climate change frameworks from 2010 to 2050. It argues through an analysis of imported emissions, that current UK emissions targets underestimate the UK's contribution to global mitigation for two degrees. In this research paper two scenarios were investigated that project UK consumption-based emissions to 2050. These consider emissions embodied in UK imports and discount emissions embodied in exports which are assigned to the purchasing country. A few studies have shown for highly aggregated global regions the consumption-based emissions trajectories that would be required to meet carbon budgets for two degrees. These are not based on current reduction targets and or pledges, nor do they indicate how emissions will shift between sectors. This paper investigates national representative pathways for UK consumption-based emissions given (1) current international emissions reductions pledges and (2) strong global mitigation efforts aligned with two degrees, implemented mainly through country-wide energy measures and carbon capture and storage. Further analysis testing the sensitivity of the scenario assumptions would increase confidence in the results.

The UK is likely to remain a net importer of emissions. The origin of emissions shifts from energy production to transport and manufacturing, which are harder to mitigate. Under the scenarios for two and four degrees, UK consumption is anticipated to generate 20 to 24 Gt cumulative CO_2 between 2010 and 2050, compared to 14 Gt CO_2e from a production perspective. It is estimated that in the region of 46% to 55% would be emitted outside UK political jurisdiction. These percentages are higher when looking at the 2050 end-point only (46% to 76%). Whilst researchers have argued for industrialised countries to take stronger steps to mitigate global emissions on the basis of historic cumulative emissions, present consumption emissions and financial capacity, this paper shows that these distributional issues could prevail even with global mitigation for two degrees, at least this has been found to be the case in the UK.

Global mitigation requires immediate and unprecedented reductions in carbon intensities and strong international collaboration, particularly towards countries with less financial and technical capabilities. Current territorial policies in developed countries such as the UK are most probably inadequate to deal with the emissions released globally in the production of goods for their consumption. To meet cumulative budgets, the literature suggests that industrialised countries are likely to need to increase their annual rate of carbon reactions; more effectively transfer technology, finance and knowledge to non-Annex I countries; and reduce their demand for products (see Figure 7). In doing so (and somewhat relying on other Annex I countries take similar actions), evidence suggests this will enable non Annex-I countries to reciprocate emissions reductions without risking their economic development by retaining a certain degree of competitive edge. Such unilateral policies and agreements can harness a more flexible international climate change framework that is scaled up in time.

Figure 7: A climate policy framework for reducing net imported emissions



Whilst the analysis supports the finding that a mitigation framework based on consumption emissions would benefit net exporters in terms of emissions reduction, because a share of its export emissions will be the responsibility of the final consuming country, the policy responses from net importers could have economic implications for the exporting countries. Further research however is needed on the regional economic and social consequences of reducing consumption, particularly in developing economies, so as not to impede their development.

The conclusions of this paper need not be alarming for the policy community. International effort-sharing agreements in the form of the Clean Development Mechanism for example have shown to be environmentally effective (despite not achieving the desired level of technology transfers). Decarbonisation policy in the UK is well defined; yet changing the focus of policy towards consumption introduces new opportunities for reduction strategies at scale. Using consumption-based emissions accounting as a complementary tool to production accounting increases the levers available to policy makers with the potential to provide shorter-term measures whilst waiting for the wide deployment of low carbon technologies. With more systematic research on consumption-based policies on the rise, demand-side measures are a real contender to relieve pressure on large-scale reductions. Given the increasing share of imported emissions in the UK's account, and the political and technological uncertainty of decarbonisation, making consumption-based accounting mandatory gives us the greatest chance to be armed with responses faced with the increasing danger of climate change and could be the catalyst to unlock barriers in international negotiations.

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3 National climate policy implications of mitigating embodied energy system emissions

This chapter is the author accepted manuscript of: Scott K., Daly H., Barrett J., Strachan N. (2015) National climate policy implications of mitigating embodied energy system emissions, in press in Climatic Change

Abstract

Rapid cuts in greenhouse gas emissions require an almost complete transformation of the energy system to low carbon energy sources. Little consideration has been given to the potential adverse carbon consequences associated with the technology transition. This paper considers the embodied emissions that will occur to replace the UK's fossil fuel-reliant energy supply with low carbon sources. The analysis generates a number of representative scenarios where emissions embodied in energy systems are integrated within current national climate and energy policy objectives. The embodied emissions associated with a new low carbon energy system are lower than the emissions reduction associated with the low carbon energy sources, confirming that there is a carbon return on investment. However, even if the UK reaches its 2050 territorial climate target, it is estimated that by 2050 an additional 200 Mt CO_2 emissions are generated overseas (compared to 128 Mt generated within the UK) in the production of imported fuels and infrastructure components. The cost-optimal model results suggest that more electrification would need to occur, supported by nuclear energy, mainly in replacement of natural gas to mitigate these emissions. However, due to a number of deployment barriers, other policy interventions along the energy supply chain are likely needed, which are discussed alongside the model results. There could be more emphasis on an absolute reduction in energy demand to reduce the scale of change needed in supplying energy; new business models oriented towards performance and not sales; and existing trade schemes and international effort-sharing frameworks could be extended.

Key words: energy pathways, embodied emissions, energy systems, energy policy, climate mitigation

3.1 Introduction

The fifth assessment report of the IPCC (Bruckner et al., 2014) outlines the requirements for a fundamental transformation to a low carbon energy system, without delay (Luderer et al., 2013). Despite reducing operational combustion emissions, the building of a new and capital intensive low carbon energy infrastructure will release GHG emissions associated with its material requirements (and the mining of), construction, distribution, maintenance and decommissioning (Giesekam et al., 2014b, Müller et al., 2013), hereinafter referred to as embodied or indirect emissions[1]. Increasingly material requirements are being imported from emerging and less developed countries (Kanemoto et al., 2014, Peters et al., 2011, Peters and Hertwich, 2008b). For example, China's surge in manufacturing since the 1990s has seen its exports dominate global trade flows, becoming the world's largest exporter of emissions (Kanemoto et al., 2014). Within an energy context, trends in exported emissions from China to the developed world are likely to continue as China now dominates the global low carbon technologies market (Liu and Goldstein, 2013).

Little research has been conducted on the additional emissions generated by the infrastructure requirements of a global low carbon transition.. Beyond theoretical (Suh, 2004, Suh and Huppes, 2005, Suh et al., 2004) and applied (Wiedmann et al., 2011, Acquaye et al., 2011, Crawford, 2009) developments in life cycle impact assessments of energy technologies in the 2000s, there have been methodological contributions to improve our understanding of the environmental impacts of in-use and fixed capital stocks (e.g. buildings, infrastructure and products in which people derive a service) (Pauliuk and Müller, 2014, Pauliuk et al., 2015), and more specifically in terms of energy pathways (Hertwich et al., 2014, Hammond et al., 2013, Igos et al., 2015). These have not however been applied to understanding implications for revising and setting national and international climate policies when emissions transfers are accounted for in the energy system. These studies have assessed the life cycle environmental consequences of low carbon energy policies, but have not internalised embodied emissions in the calculation of low carbon energy pathways. Such results can be compared with reduction targets but do not suggest how the energy pathways would change when including the embodied energy system emissions in mitigation targets.

The uncertainties, risks and barriers to a low carbon technology transition are quite widely documented, with the diffusion of technologies limited by institutional, behavioural and social constraints (Iyer et al., 2015, Bruckner et al., 2014). Industrialising countries look like they are emerging along the same fossil fuel path as those before them (Unruh and Carrillo-Hermosilla, 2006), and governments that protect vested interests of powerful energy suppliers are likely to remain locked into carbon-intensive energy forms (Moe, 2010). The current economics-driven policy approach has been shown to be incapable of delivering the type of low carbon investment required over the necessary timescales (Bolton and Foxon, 2015).

The authors were the first to examine the emissions embodied in supplying energy by developing indirect emission factors for energy technologies and fuels with an input-output

[1] We define embodied emissions as the emissions generated along the energy supply chain up to the point of operation. This includes mining activities, fuel processing, electricity generation, emissions capture and fuel imports such as emissions from manufacturing mining drills, farming biomass, constructing power stations and manufacturing wind turbines

model and including them in an energy system model for the UK (Daly et al., 2015). In the analysis, indirect emissions in the generation of energy infrastructure and fuel processing are reallocated from the source industry to the component of the UK energy system in which they are embodied, to be considered in a model of cost-optimal technology and fuel selection, and included in an emissions constraint aligned with the UK's 2050 emission target. The UK has a legally-binding target to reduce 1990 emissions by 80% by 2050, and a series of interim carbon budgets aligned with this end-point. The study found that modelling only territorial emissions in the cost-optimal energy pathway lead to substantial international emissions transfers, and when required to mitigate embodied emissions generated abroad, the marginal cost of abatement more than doubled. Such outcomes are not just relevant for the UK, but contribute to the ongoing debate of accounting for traded emissions in international climate change negotiations. This paper builds upon that analysis and looks at the broader implications of accounting for emissions transfers in the UK energy system, both in terms of potential changes to the energy supply pathways and the UK's national energy and climate policy. This paper covers the following research questions:

1. How sizeable are the embodied emissions associated with the energy system in the UK required to deliver the 2050 emissions target?
2. What changes to energy sources and demand technologies are observed in a least-cost scenario, when emissions embodied in energy systems are considered in 2050 decarbonisation targets, and at what additional cost?
3. Is there evidence of alternative policy opportunities to reduce emissions embodied in an energy system beyond the technology solutions modelled, given the barriers and risks associated with low carbon energy technology solutions?

3.2 Method

Energy system optimisation models (ESOMs) are widely-used planning tools for regional, national and global energy systems, and are very highly detailed at the fuel and technology level. Well known examples include TIMES (Loulou et al., 2009), MESSAGE (Klaassen and Riahi, 2007) and OSEMOSYS (Howells et al., 2011). This paper uses the UK TIMES model (UKTM) (built in the TIMES framework (Loulou et al., 2004)), which has had a strong underpinning role in UK energy and climate policy development (Ekins et al., 2011). It portrays the UK energy system from fuel extraction and trading, through energy conversion, such as the production of electricity, hydrogen and biofuels, to final energy demand (Daly et al., 2015). Emissions from industry, transport and services are added to the energy sector emissions to add up to UK territorial emissions. UKTM generates cost optimal scenarios of the future composition of the UK energy system, which meets energy service demands, taking into account assumptions regarding the evolution of final demands, technology costs and attributes and resource availability.

Infrastructure requirements are defined as a cost to the system, representative of the physical flow of materials.

ESOMs have historically had a critical shortcoming: by counting emissions only at the point of combustion, they do not take into account the embodied impacts of energy pathways. By adding a value for indirect emissions, calculated using input-output analysis (Miller and Blair, 2009), to each component of the energy system, supply chain emissions become a criterion for technology selection. We use our novel methodology described in Daly et al. (2015) to integrate embodied emissions to all activities upstream of energy supply. Embodied emissions are generated using a top-down global trade model (the input-output model employed in Wiedmann et al. (2011)), which traces the interactions between the UK energy sector and all other sectors within and outside UK territory. Indirect emissions are added to the supply-side energy sources and technologies, and not to demand-side technologies such as household boilers and cars. This is aligned with current climate policy which largely influences supply-side technologies, the focus of this paper.

This paragraph summarises the novel methodology we developed in Daly et al. (2015) (also see Appendix 6.7), and the sections referenced here refer to sections in that article. Energy system technologies and fuel inputs in UKTM were aligned with an equivalent economic sector in the multi-region input-output model - MRIO (section 2.3.). For each relevant MRIO sector, an indirect or embodied emissions factor expressed in tCO_2 per £M was calculated for both the UK and a global average rest of world region (section 2.4). The embodied emissions were attributed to energy system technologies and traded fuels on the basis of installed capacity or fuel flow (section 2.4). The range of indirect emissions values for energy vectors are presented in Section 5 of Daly et al.'s supporting information. The volume of emissions reallocated from UK industry to the UK energy system as embodied emissions were subtracted from the UK industry emissions account (section 2.5.). Scenarios for future domestic and international emissions intensities and the import dependency of the UK economy were developed and run through UKTM (section 2.6.). Domestic embodied intensities were assumed to follow the same trajectory as the industry sector in UKTM. International embodied emissions intensities were assumed to decarbonise at the global average rate of 1% per year. Trade patterns are projected based on recent short-term trends. The paper also discussed some of the limitations and uncertainties of the approach which need further sensitivity analysis (section 4.2.), including country and sector aggregation, projection of global efficiency improvements and trade patterns, and the inclusion of emissions embodied in end-use technologies such as private vehicles household appliances.

3.2.1 Emissions boundary allocation

Our study focuses on energy supply as this dominates climate policy. Emissions in UKTM are constrained by UK cumulative carbon budgets which have been set to 2027 (HM Government, 2011) and then a cumulative carbon budget which is equivalent to the same total amount of emissions as a linear emission reduction meeting the 80% target by 2050, defined by the UK

Committee on Climate Change as the most 'cost effective path' (CCC, 2015a). To remain aligned with our previous scenarios in Daly et al. (2015) we describe the same 4 scenarios, however in the results comparisons are mainly drawn between S2 and S4. This is to understand how energy pathways would change when embodied emissions were included compared to the current approach where only combustion emissions are considered. The 4 scenarios are:

- **S1. No target**: the UK energy system is optimised on the basis of cost, with no emissions constraint. This represents a baseline scenario with no mitigation activities (however results focus on changes between S2-S4).
- **S2. Target – direct only**: combustion emissions in the UK energy system are optimised on the basis of cost, with total territorial CO_2 emissions between 2010 and 2050 constrained to meet an 80% reduction target on 1990 levels by 2050, representative of current UK policy.
- **S3. Target – Direct & UK emissions**: embodied energy system emissions from domestic industry are re-allocated to the energy system from the industry sector and included in the optimisation. As above, total territorial CO_2 emissions between 2010 and 2050 are constrained to meet an 80% reduction target.
- **S4. Target – All emissions**: international emissions are allocated to the UK energy system component in which they are embodied and included in the optimisation process. Territorial and imported CO_2 emissions minus emissions embodied in exports, between 2010 and 2050, are constrained to meet the carbon budget imposed by the 80% territorial target.

Each scenario generates the cost optimal technology mix to meet a specified demand for around 50 energy services (e.g. car kilometres, lighting and industrial heating) in the UK with increasing emissions to be mitigated. Energy service demands over the period will grow at different rates according to official government projections, with most increasing (e.g. international aviation doubles in the period) and some decreasing (some industrial demands, bus and domestic navigation). The scenarios are indicative of the changes to conventional energy pathways that consider territorial emissions only. We do not consider a comprehensive set of possible future pathways, and instead isolate the impact of including traded emissions. Hence, all other variables are held constant in the model. UKTM includes all greenhouse gases in the reduction targets; however the model only considers CO_2 in terms of energy sources and technology selection therefore the focus of the paper is CO_2 only. This analysis focuses on emissions pathways from 2010 (the latest year modelled which is used to represent current levels) to 2050.

3.3 Results

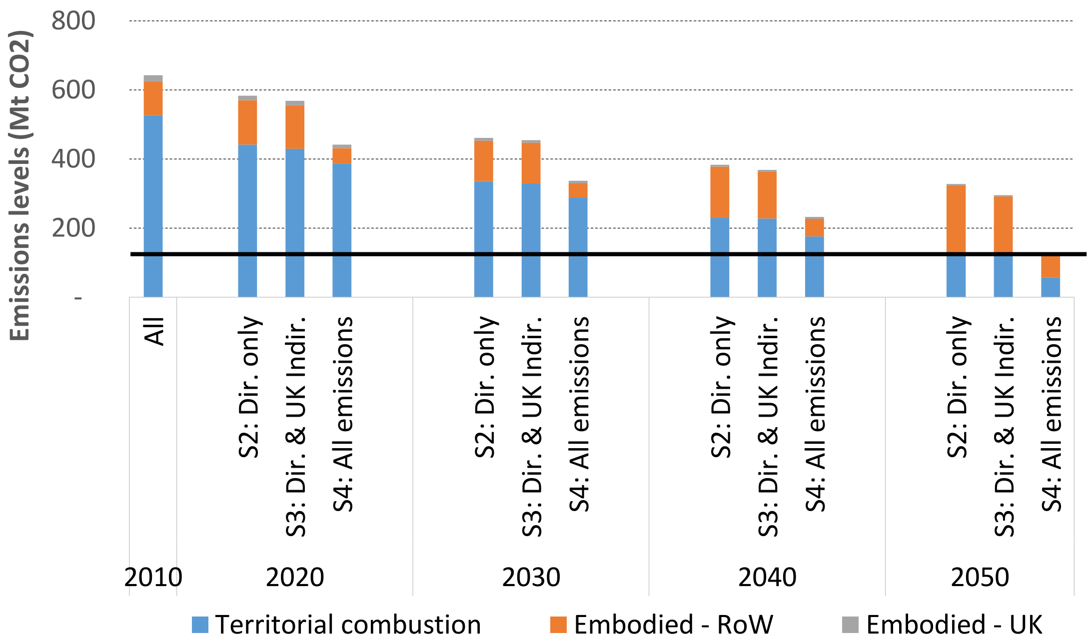
UKTM produces cost-optimal adjustments to energy supply vectors and technologies when embodied emissions are included in the UK's carbon budgets. Whilst we analyse one modelling exercise, a model run in isolation does not provide a complete policy assessment. Cost-optimisation alone cannot guarantee the desired emissions target due to governance, societal and technology barriers and future uncertainties. Therefore, in the discussion we consider the evidence for alternative policy options to those modelled here.

3.3.1 Embodied energy system emissions 2010 - 2050

Figure 8 shows the change in UK territorial combustion emissions and the additional indirect emissions embodied in the UK energy system under the three scenarios from 2010 to 2050. In 2010 UK territorial emissions were 527 Mt CO_2 and an additional 115 Mt CO_2 was embodied in the energy system. 85% of the embodied emissions were emitted outside the UK.

Constraining territorial combustion emissions only in the 2050 emissions reduction target of 80% (S2 in Figure 8), the current policy, reduces combustion emissions by 77% from 2010 to 2050. However overseas emissions more than double over the same time period, meaning that total emissions (including embodied emissions) are only reduced by around 50%. Energy service demand over this time period has increased across most categories, trade is on an upward trend and production efficiencies in the rest of the world progress at the global average of 1% per year. As embodied energy system emissions originating in other UK industries (e.g. from the manufacture of renewable energy technologies) represent less than a 3% share of energy system emissions in 2010, declining even further by 2050, their inclusion in targets makes little difference to the results (S3).

Figure 8: Combustion and embodied emissions when increasing mitigation from UK energy system emissions to include embodied emissions in the UK 2050 climate target (black solid line = 80% target)



Only when embodied emissions generated in industry overseas (to produce technology components imported to the UK) are considered in the cost-optimal energy pathway, and hence mitigated in the UK's carbon budgets, are we able to influence the 98 Mt CO_2 (18% share) currently generated outside the UK. Results in the following sub-section therefore concentrate on the differences between S2 and S4. When mitigating for embodied emissions in the 80% reduction target (S4) by avoiding burden shifting abroad, UK combustion emissions need to reduce by almost 90% from 2010 to 2050 (in S2 they reduce 77%).

Cumulatively[2], in meeting the domestic 80% emissions reduction (S2), 14Gt and 6Gt cumulative CO_2 emissions are released in the UK and abroad respectively. 5 Gt are prevented from entering the atmosphere if imported emissions are mitigated in the UK's end-point target, emitting nearly 15Gt CO_2. To put this into perspective, the latest figures from the IPCC suggest less than 1,000 GtCO_2 can be emitted globally up to 2100 to have a 66% probability of limiting global warming to 2 degrees (Stocker et al., 2013). If national carbon budgets were apportioned based on current population the UK would have a 9Gt allowance, 40% under our best case scenario (S4). This is within the range suggested by Raupach et al. (2014), calculated to be between 7 and 12Gt CO_2.[3]

3.3.2 Energy system changes

This sub-section describes changes to the energy sources, demand technologies and cost to the energy system when mitigating for embodied emissions. This is done by comparing two scenarios: imported emissions are included in the target (S4) compared to the territorial target (S2). The underlying dynamics of UKTM, such as technology and cost characteristics, remain a strong determining factor with the addition of embodied emissions.

Figure 9 shows the change in composition of UK primary energy consumption (PEC) in 2030 and 2050 between the two scenarios. Fossil fuel sources contribute 88% (8,565PJ) to PEC in 2010 reducing to 53% (5,137PJ) and 36% (3,315PJ) in 2050 in S2 and S4 respectively. To meet the territorial target (S2) natural gas retains over a third of the share (3,543PJ), yet when embodied emissions are included (S4) the share drops to a quarter (2,201PJ). The share of renewables increases to 6% in both scenarios (475-478PJ) in the medium term (2030) and then reduces to 1% in the longer-term (2050) (122-133PJ). The share of biofuels steadily rises in both scenarios to make up over a fifth of energy consumption. The most notable difference is the increase of

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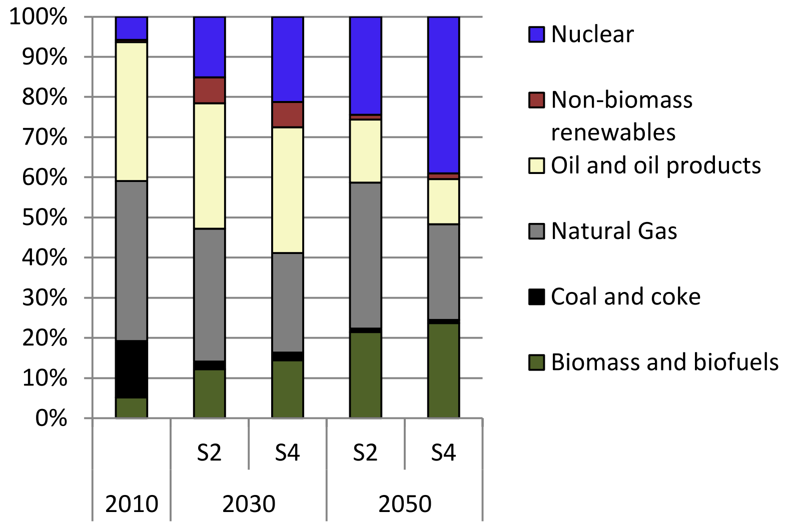
[2] The model is run at five year intervals and the results are interpolated between years and summed to calculate cumulative emissions.

[3] Raupach et al. estimate Europe has a carbon budget of 90 to 159GT CO_2 under three burden sharing principles. We estimate this to be in the region of 7 and 12 Gt for the UK given the UK's 2015 share of Europe's population to be 7.6%.

nuclear energy from 6% (562PJ) in 2010 to 24% (2,377PJ) and 39% (3,610PJ) by 2050 in S2 and S4 respectively.

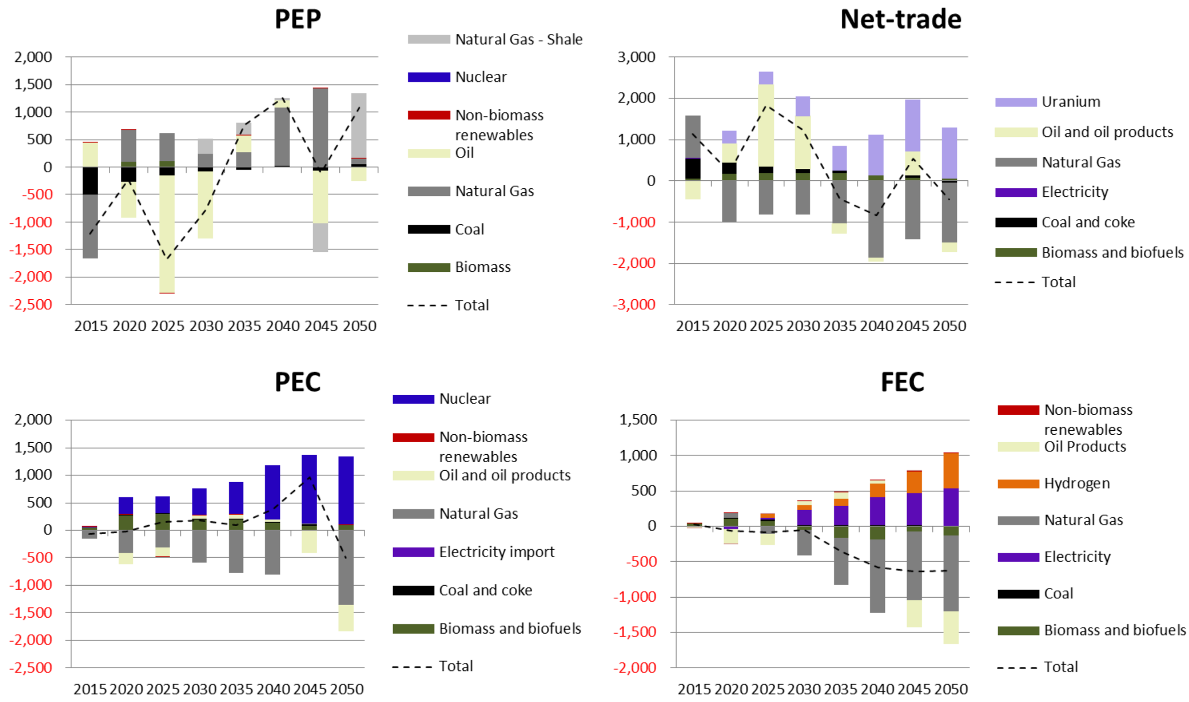
Figure 9: Composition of UK primary energy consumption in 2030 and 2050 compared to 2010 for S2 and S4



In order to compensate for the stricter carbon budgets, the trends in technologies selected tend to remain similar between S2 and S4, yet the deployment of lower carbon technologies is greater in S4 when mitigating embodied emissions alongside operational ones. Under the technology assumptions for this scenario set, UKTM generally projects the long-term (levelised) costs of nuclear lower than (intermittent) renewables plus back up, with and without embodied emissions. Sunk infrastructure costs are a relatively low share of the overall costs of electricity technology options and allows interim (in this case renewable) technologies to be invested in and then not replaced when first generation units reach the end of their working life.

Primary energy consumed (the composition of which is shown in Figure 9) is sourced from domestic energy production and imported fuels. The UK also exports fuels for consumption overseas. Figure 10 shows the decadal change from 2010 to 2050 in territorial primary energy production (PEP), the trade balance of fuels (i.e. imports minus exports), primary energy consumption (PEC) and final energy consumption (FEC) between S4 and S2 by energy source. This illustrates the change in energy production and trading in fuels that would cost effectively meet the emissions reduction required should the UK decide to mitigate the indirect energy system emissions.

Figure 10: Time series change in PEP, Net-trade, PEC and FEC from 2010 to 2050 when mitigating for embodied emissions in the UK's 2050 climate target (i.e. Scen 4 – Scen 2)

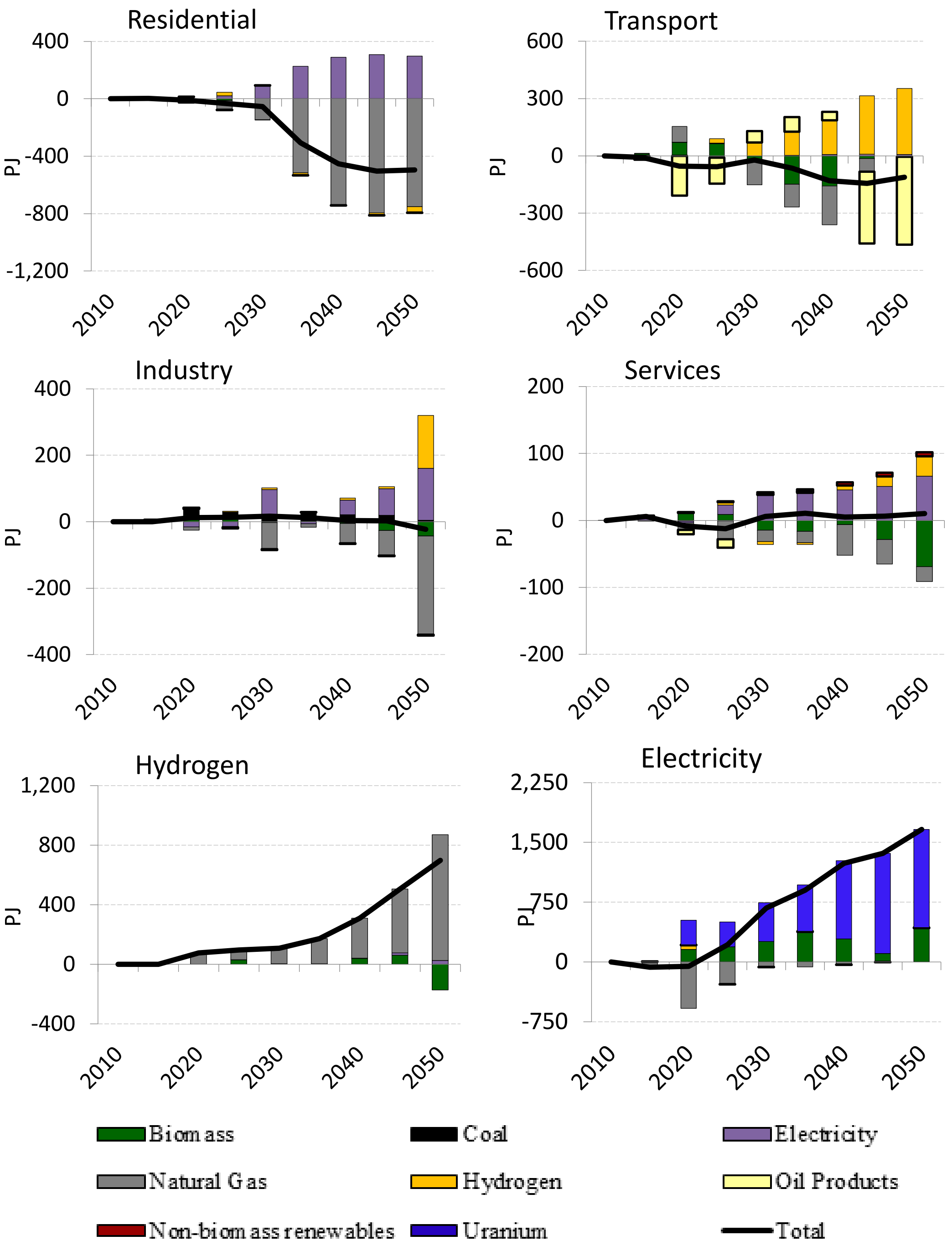


Pre-2025, the reduction in UK oil production outweighs the increase in gas produced. Despite achieving a cumulative reduction in PEP between 2010 and 2050, post-2025, PEP starts on an upward trajectory as natural gas production becomes greater than the reduction in oil being produced. By 2050, shale gas is responsible for the majority of increases in PEP. UK fuel trading shows the opposite trend. Cumulatively, the UK imports more fuels than it exports over the time period, but net imports are on a downward trend from 2025. Until 2030, the UK continues to import more oil than it exports, followed by an increase in net imports of uranium in the 2030s. However, post-2030 net exports of UK natural gas grow, and grow at a rate greater than the imports of uranium. Whilst production of gas in the UK increases (almost an additional 18,000 PJ is produced between 2010 and 2050), it proves cost-effective to export, and therefore primary consumption reduces. The reduction in natural gas is compensated mainly by an increase in imports of uranium (nearly 23,000 PJ) and biomass (nearly 5,000 PJ), which have lower life cycle emissions. Embodied emissions results in the overall emission budget under S4 being tighter, and hence, the intertemporal UKTM reduces domestic oil in the near term and overall oil use in the aggregate. The reduced demand for gas in the UK and the equivalent embodied emissions for domestic and international gas combine to allow the UK to export more. UK oil and gas resource is generally not co-productive whilst imports of these fuels occur via separate international markets.

Figure 10 also compares the impact of mitigating indirect emissions on final energy consumption (FEC). FEC by intermediate (electricity and hydrogen) and end-use (residential, transport, industry and services) sectors are presented in Figure 11. The reduction in FEC is marginal from 2010 to 2050, except between 2030 and 2040 where annual final energy consumption reduces to around 600 PJ. This reduction is achieved in the residential and transport sectors, with energy consumption of industry and services changing very little. With the exception of transport, electrification happens across all sectors, and hydrogen displaces fossil fuel consumption in transport. Electrification is supported by the increase in imported nuclear fuels, which displaces final demand for natural gas, yet hydrogen production in turn consumes natural gas.

As is clear from the results, UKTM favours particular technologies and fuel pathways. Nuclear becomes a dominant fuel source by 2050 in both scenarios, mainly displacing natural gas. The same climate outcome could be met by renewables or biofuels, but under the assumptions of UKTM in this study surrounding the cost and technical features of different technologies and fuel sources, nuclear is the lowest cost low-carbon option, with and without accounting for embodied emissions. Similarly, less importing of natural gas is favoured over less consumption and more domestic production (Figure 10). A feature of technology selection in least-cost ESOMs, like all linear optimisation models, is “penny switching behaviour”, where a small change in costs can lead to sudden changes in results. Given the uncertain nature of future costs and policy and social constraints, and given that investment behaviours do not conform to this penny-switching, these results should not be interpreted as a forecast of the future but rather a set of informed scenarios, sensitive to input assumptions.

Figure 11: Changes to FEC by end-use sector and intermediate energy consumption by electricity and hydrogen when mitigating for embodied emissions (i.e. Scen 4 – Scen 2)



Increasing the UK's reduction effort to mitigate its indirect energy system emissions comes at an additional cost. Table 8 describes the annual cost increase (at five year intervals) and cumulative change in energy system cost from 2010 to 2050 (undiscounted[4]) when mitigating

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[4] We are comparing the costs between two scenarios therefore the difference would be the same whether costs were discounted or not

for indirect emissions (S4), compared to S2 (achieving the territorial target). Overall this increases the cost of S2 by 3.7% - £682.5 billion from 2010 to 2050. Generally, higher costs will be faced in the future and by 2050 it is estimated that mitigating the additional emissions increases costs by around 5% of what they are estimated to be if they were not included in the target. However, these costs do not consider the reduced costs of adapting to climate change and therefore offer a comparability of mitigation costs between scenarios, but not the overall cost to the economy.

Table 8: Additional annual undiscounted energy system costs and percentage increase at 5 year intervals and cumulatively when mitigating for embodied emissions (i.e. increased cost of S4 compared to S2)

Year	2015	2020	2025	2030	2035	2040	2045	2050	2010-2050
Extra cost (£M)	2,630	10,492	16,953	17,474	17,581	21,980	30,422	30,910	682,547
%	0.8	2.7	4.0	3.7	3.5	4.1	5.4	5.2	3.7

3.4 Policy discussion

While low-carbon technologies and fuels can deliver a substantial reduction in emissions, even taking embodied emissions into account, there are adverse effects on global emissions. The UK increasingly imports goods and services from countries outside the EU (Committee on Climate Change, 2013). When comparing the embodied emissions of energy infrastructure from equivalent productive sectors in the UK and overseas, we found overseas technologies to have been produced on average more carbon intensively than in the UK (see section 5 of the supporting information in Daly et al. (2015)). This paper's analysis shows that emissions generated outside the UK to meet its energy infrastructure demands are set to increase through to 2050 and could be in the region of 60% higher than UK direct emissions. This poses a policy problem as only a few countries, representing 15% of global emissions, are currently being held to legally-binding emissions reduction targets (Grubb, 2013).

In modelling the UK's mitigation of emissions embodied in its energy supply in the 80% end-point target, the overall cost of the low carbon transition increases by 3.7%. The most substantial change in the model is an increase in nuclear capacity, largely to support electrification of final energy consumption. Uranium and biomass in the low carbon energy system pathway is increased from 24% and 21% to 39% and 24% respectively. This increase is met by imports, and the UK exports more gas to be consumed abroad, falling outside the UK's emission boundary. While under these modelling scenarios renewable energy does not play a major role, ESOMs are not forecasting tools and have a limited capability for incorporating uncertainties in long-term costs and constraints, and so should not be used as a single tool for planning future policies.

If the UK was to take responsibility for the additional emissions generated abroad, adjustments to budgets would need to be made to ensure the same intended carbon outcome (i.e. an 80% reduction in emissions) if the accounting system was to remain as is. However, recent reductions in the UK's territorial emissions, reaching 8% in 2014 despite strong economic growth, have not been the result of planned climate policy. Many of the reductions from building, industry and power emissions reflect one off changes and uncertain factors rather than replicable ongoing trends, e.g. a mild winter (CCC, 2015b). The CCC also perceives a gap between existing and foreseeable climate policies and future UK carbon budgets. Given this and the widespread barriers and risks associated with low carbon energy technology solutions (documented in Bruckner et al., 2014) there are alternatives that would ease the dependency on unprecedented rapid deployment rates; publicly debated technologies (particularly nuclear); and rising costs from greater reduction requirements; whilst increasing the scope to reduce imported emissions. Taking a supply-chain or embodied perspective of energy brings other policy opportunities into view. We identify the evidence for these under four broad categories: demand, business models, trading schemes and international effort-sharing:

- Demand response – Emissions could be avoided by achieving an absolute reduction in energy demand. Anderson et al. (2008) suggest that the neglect of energy demand reduction is eroding the UK's ability to play its part in maintaining a two degree future. Although demand reduction initiatives have not been modelled in this paper they have been shown to be cost effective and complementary to technology led decarbonisation (Strachan et al., 2008) and have the scope to reduce both domestic and imported emissions through reducing demand for materials, goods and services that embody energy (Barrett and Scott, 2012). Emerging evidence shows the potential for material and product consumption to contribute sizeable reductions in emissions (Barrett and Scott, 2012, Allwood et al., 2010b, Allwood et al., 2011).

- Business response – Alternative business models whereby product sales are replaced with a service or leasing contract can decouple resource needs from energy demand (Roelich et al., 2015a, Steinberger et al., 2009, Hannon et al., 2013). Energy Service Companies can shift away from selling metered quantities of energy towards selling energy services such as thermal comfort and illumination (Sorrell, 2007). Profits are incentivised by improvements in energy efficiency instead of selling more units. In addition energy using appliances can be leased whereby the provider retains ownership and is responsible for its general maintenance and the consumer has possession and use of the asset for a prefixed payment period. In this situation energy efficiency is shown to play a bigger role in replacement decisions, and remanufacturing is increased (Roelich et al., 2015a).

- Trade response – Currently the EU Emissions Trading Scheme compensates or exempts carbon-intensive industries perceived as being at risk of competition from cheaper energy costs elsewhere (Martin et al., 2014). Extending the EU Emissions Trading Scheme (ETS) to account for the emissions embodied in trade could increase the scope for reductions whilst reducing competitive worries (Carbon Trust, 2006, Carbon Trust, 2008). For example international agreements could be set up which incorporate the major competitors in a particular sector whereby the carbon costs are reflected across all producers' sales products. Alternatively border tax adjustments can be implemented on energy-intensive imports to close the cost differentiation (Vivid Economics with Ecofys, 2013).

- International response – Effort-sharing frameworks could help address distributional issues between industrialised and developing countries (Edenhofer et al., 2014). Interregional instruments such as the Clean Development Mechanism and Joint Implementation involve the transfer of technologies, renewable energy implementation projects or the financing of abatement projects overseas, for which the UK can receive carbon credits. These can currently be used to offset excessive emissions generation in the EU ETS, and have been shown to offer cheaper mitigation opportunities as they have less installed abatement measures (Harris and Symons, 2012).

These four policy options would require additional modelling work to assess their overall impacts on the role of embodied emissions, but they do address the problem and present an alternative from a purely technological driven solution.

3.5 Conclusions

This research has focused on novel linked modelling, using the UK as a case study, for integrating embodied emissions (both domestic and international) within energy supply, given its prominence in energy and climate policy. Even when the embodied emissions of a new low carbon energy infrastructure are left unabated, low carbon technologies can deliver a substantial reduction in emissions. However, changes in the UK energy system generate additional emissions outside the UK and in many cases the EU and their emissions reductions targets. This is problematic because globally legally-binding emissions reductions targets only capture 15% of emissions. If imported emissions remain excluded from climate targets, this figure is less likely to change. The UK could extend the scope of its own carbon budgets to ensure it achieves the same intended outcome, a reduction in its emissions by 80%, by increasing the speed of low carbon technology roll-out or further exploration of other consumption-side/ energy demand factors.

In this paper, embodied emissions have been considered up to the point of supply and future research could consider embodied emissions within the same framework for end-use services such as boilers, electrical appliances and vehicles, all of which consume and embody energy. These will both increase emissions allocated to the energy system modelled, currently sitting in the industry sector and country in which they are produced, and provide opportunities for emissions reductions through behavioural changes. Exploiting more demand reduction, service delivery and international opportunities could deliver energy and emissions reductions at a reduced cost, and need to be assessed in a holistic framework.

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4 Addressing globally traded emissions through domestic consumption policies

This chapter is the author submitted manuscript under review: Scott K., Roelich K., Owen A., Barrett J. (2015) Addressing globally traded emissions through domestic consumption policies, submitted to Environmental Research Letters

Abstract

Existing international emissions reduction policies are not sufficient to meet the internationally agreed objective of limiting temperature rise to two degrees. Studies have shown there has been an increase in emissions transfers via international trade, which is left largely unaddressed by climate mitigation policies. Materials act as a carrier of industrial energy that allows, through trade, the transfer of embodied emissions between sectors and countries. Industrialised countries have managed to stabilise their production emissions, partially from growing imports from developing countries. However, the use of materials has been completely overshadowed by policies focusing on deploying a low carbon energy supply. Policies based on resource consumption can support climate change mitigation and presents an opportunity to address emissions resulting from trade. We investigate the increase in emissions coverage by extending EU Directives that currently target the energy use of products in operation (cars, buildings and appliances), to include the emissions required to produce the goods (i.e. embodied emissions). We demonstrate how a greater integration of resource efficiency strategies within climate change mitigation policy can contribute substantially to abating emissions.

4.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) presented a stark warning of temperature rises to come if trends in global greenhouse gas emissions cannot be reversed (Collins et al., 2013). Around a fifth of global carbon emissions can be attributed to five key materials: steel, cement, plastic, paper, and aluminium (Allwood et al., 2010a), which form the backbone of modern economies (Müller et al., 2011, Müller et al., 2013, Pauliuk and Müller, 2014, Steinberger et al., 2010). Reducing the total consumption of these materials could make a significant contribution to emissions reductions, yet their production and consumption has surged in the last few decades (Pothen and Schymura, 2015, Schaffartzik et al., 2014). This paper analyses how a greater integration of resource efficiency within climate change mitigation policy can contribute substantially to abating emissions by extending existing energy efficiency standards to include embodied emissions. We focus on the EU, and its trade with the rest of the world, because it has the most advanced climate policy and a strong resource efficiency agenda; however the two issues are rarely considered together. There are additional layers of policy within EU Member States as they translate EU policy objectives into their national policies, but we concentrate on the original policies defined at the level of the EU.

A growing body of literature analyses the material use (Schaffartzik et al., 2014, Pothen and Schymura, 2015, Giljum et al., 2014a, Wiedmann et al., 2015) and emissions (Kanemoto et al., 2014, Davis and Caldeira, 2010, Hertwich and Peters, 2009, Peters et al., 2011, Xu and Dietzenbacher, 2014) embodied in international trade. These apply methods which attribute material extraction and production emissions to the consumption of goods and services. As carriers of industrial energy, the trade of materials and products results in the transfer of embodied emissions between countries and consumers. For example, China's production emissions have rapidly risen, with net exports accounting for around a fifth of its emissions (Qi et al., 2014), destined mainly for consumption in developed countries (Kanemoto et al., 2014). Resource efficiency measures influencing the supply and use of materials and products could reduce emissions both within and imported to a country. This becomes increasingly important due to the limited opportunities for energy efficiency in material production (Pauliuk and Müller, 2014, Liu et al., 2013, Milford et al., 2013), which tends to be very energy efficient already due to energy being a major cost factor (Müller et al., 2013).

In 2009 the EU produced 14% of global emissions from institutional units resident in its economy, yet 17% of global emissions were associated with the goods and services consumed in the EU[1] (Boitier, 2012) (see Appendix 6.8 for a description of different emissions accounting approaches). Similar trends are observed for most other developed countries. Climate policy largely addresses the direct emissions from production and not emissions embodied in the use of materials. The EU Emissions Trading Scheme (EU ETS) is the primary vehicle for addressing EU industrial emissions. It places a cap on emissions generated by selected energy-intensive industries above a certain size, creating a market for carbon allowances that these industries can buy or sell when they have a carbon shortage or surplus. However, around 60% of the carbon allowances are allocated for free due to competitiveness concerns that have yet to materialise (Bassi and Zenghelis, 2014) and many producers in the scheme have enough allowances to satisfy their production for several years (Sandbag, 2014). Therefore, the EU ETS is failing to incentivise low carbon production, including the reduction of material use (Spash, 2010), to levels required for a two degree future. Commercial, residential and the remaining industrial emissions outside the EU ETS rely on regulations and standards to improve their energy efficiency, yet an efficiency measure does not guarantee a reduction in absolute energy use.

To deliver resource efficiency the EU is proposing a circular economy agenda (by the end of 2015) which is intended to address all aspects of product supply chains (i.e. resource consumption) and not rely on end of life waste management solutions. As stated in the EU's

[1] Consumption = production emissions + emissions embodied in imports – emissions embodied in exports

recent Roadmap to a Resource Efficient Europe, progress is to be measured by resource productivity (GDP/ DMC[2]), despite the measure both reflecting differences in economic growth rather than a reduction in absolute material use (Schaffartzik et al., 2014, Steinberger and Krausmann, 2011), and not considering up-stream resource requirements of traded goods beyond the weight of the imported product (Giljum et al., 2014a). Therefore, the indicator cannot guarantee a reduction in absolute material use, which is the main vehicle for emissions, nor does it extend to the total material used along increasingly global supply chains. The impact per tonne of different materials will be significantly different meaning that resource efficiency is not a goal in its own right but a vehicle to reduce environmental pressures, such as GHG emissions.

Resource efficiency remains somewhat detached from EU climate policy. Evidence shows there is significant potential in emissions reduction through resource efficiency measures. In analysing the 'reach' of EU-wide collective corporate action, Skelton (2013) identifies the EU has influence over additional (non-traded) emissions in the region of 1 Gt CO_2, amounting to nearly a third of EU industry production emissions, by addressing company supply chains. Barrett and Scott (2012), Girod et al. (2014), Pauliuk and Müller (2014) and Allwood et al. (2011) show the potential for resource efficiency and consumption measures to contribute to reducing emissions. Strategies include material substitution (Giesekam et al., 2014a), product longevity (Bakker et al., 2014), lightweight design (Müller et al., 2013), urban planning (Müller et al., 2013) and product-service systems (Reim et al., 2015, Roelich et al., 2015b).

We suggest that current climate policy fails to identify the mitigation benefits of resource efficiency. Rarely addressing the link between resource consumption and embodied emissions neglects the leverage resource efficiency strategies have to mitigate climate change, including emissions embodied in trade. Recognising the synergies between material consumption and emissions, and the importance of international trade, we analyse the potential greenhouse gas emissions reductions associated with material consumption in the EU. We aim to answer three research questions: what are the emissions associated with resource flows (which include both materials and manufactured products made up of materials) in and out of the EU? What proportion of EU consumption-driven emissions are excluded from its domestic climate policies? How many more emissions could the extension of EU product-specific energy efficiency policies to include resource use reach? The discussion centres on the design of such policies.

[2] Domestic material consumption (DMC) is domestically extracted plus imported, measured as weight of imported product, minus exported materials. It comprises the use of biomass, fossil fuels, and minerals including metals.

4.2 Method

At the macro level environmentally-extended multi-region input-output analysis (EE-MRIO) is a well-established method which reallocates production emissions through trade flows to consumption (Wiedmann, 2009, Steen-Olsen et al., 2014, Kander et al., 2015, Davis and Caldeira, 2010, Peters et al., 2011, Peters, 2008, Hertwich and Peters, 2009). In the 1930s Wassily Leontief developed a series of linear equations that describe how producing a single unit of final demand requires inputs from all sectors of the (global) economy. The economic framework was later extended to include a vector of 'externalities' which measured tonnes of pollution per unit of output for each industrial sector (e.g. CO_2/ £). The different sectors of an economy not only require materials and resources to produce different goods and services, but they also generate several by-products (e.g. pollution and waste) during their production processes. Calculations could then determine how pollution originating from producing sectors could be reallocated to the final users of goods and services (Appendix 6.9).

In our analysis greenhouse gas emissions flows associated with global trade in materials and products are calculated using an emissions-extended multi-region input-output model (EE-MRIO). EE-MRIO traces the source of emissions for products consumed by EU final consumers, through intermediate trade transactions. We use a spatially aggregated version of the Exiobase MRIO table (Tukker et al., 2013, Wood et al., 2014) which represents 163 production sectors and product groups for three regions: the EU, non-EU Annex I countries, and non-Annex I countries (see Appendix 6.9.2.). Compared to other MRIO models, Exiobase has the greatest disaggregation of material and manufacturing sectors (Appendix 6.9.3.), the focus of our study. For the purpose of display, sectors are aggregated into 7 high-level groupings (Table 1 in Appendix 6.9.2). Emissions embodied in products aligned with existing EU climate policies are calculated (Appendix 6.9.4), and those emissions originating in EU ETS sectors excluded (Appendix 6.9.5), to estimate the volume of emissions that could be addressed by an extension of the policy that targets embodied emissions. Emissions associated with all material-intensive manufactured products are calculated to estimate the total emissions scope of standards on the carbon content of goods (Appendix 6.9.4).

4.3 Results

Figure 12 shows the supply chain emissions from production to the final consumption of products embedded in EU consumption, including imports in and exports out of the EU. Production emissions in the EU in 2007[3] were 5,213 Mt CO_2e, with the width of each bar on the left-hand side of Figure 12 representing production emissions by sector, the conventional

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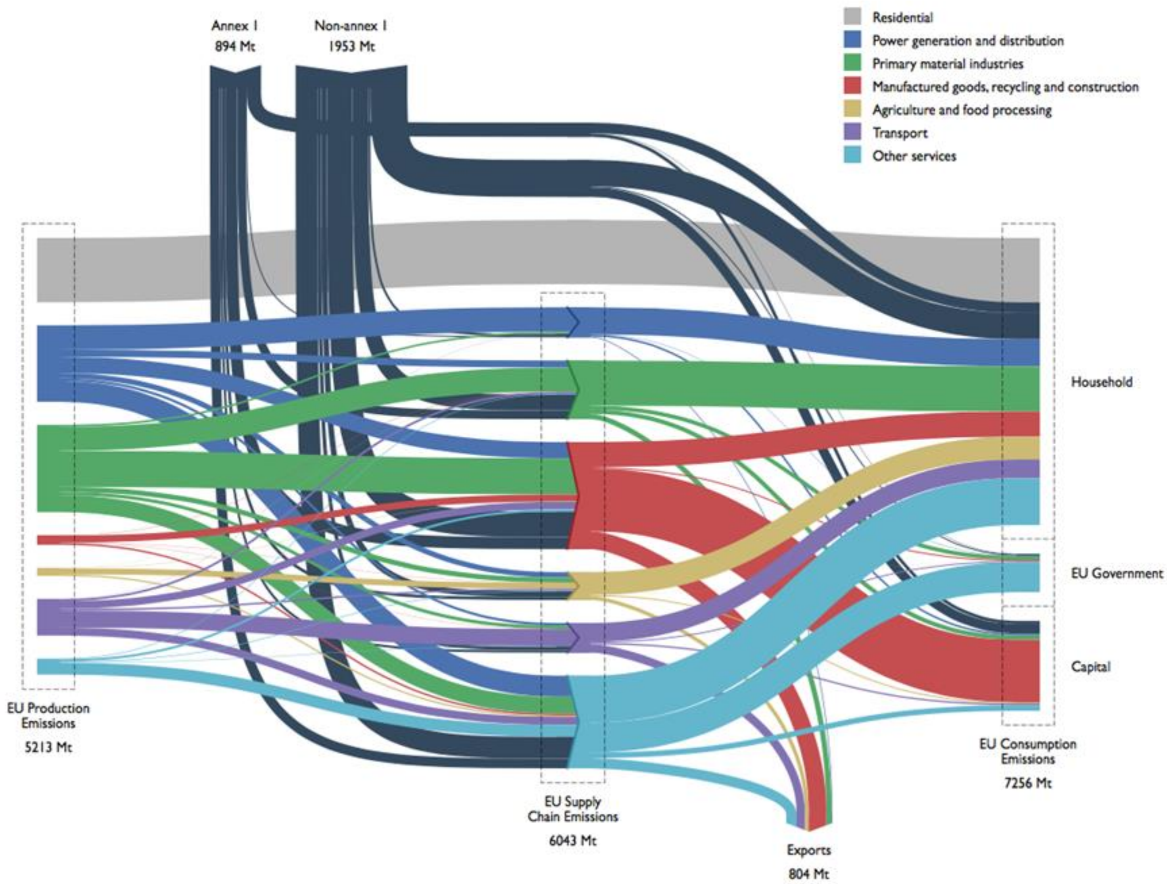
[3] 2007 is the latest year available for Exiobase, which has the necessary sector disaggregation for materials and products we are analysing.

accounting approach. When adding emissions embodied in imports (2,847 Mt CO_2e) and subtracting emissions embodied in exports (804 Mt CO_2e), the EU's net traded emissions add 2,043 Mt CO_2e to EU production emissions. Around two thirds of imported emissions are from non-Annex I countries, whose emissions are not currently covered by binding international emissions reduction targets, but on average continue to rise.

When accounting for the emissions embodied in products, the middle column in Figure 12, the emissions profile of sectors change. Services and manufacturing sectors combined directly produce 447 Mt (9%) of EU production emissions. However, the emissions embodied in these sectors across their respective supply chains account for 1,619 Mt (22%) and 1,869 Mt (26%) of EU consumption emissions. Around a third of emissions embodied in both product groups are generated outside EU territory. The EU is heavily reliant on materials extracted and processed abroad. 38% (622 Mt) of the emissions embodied in services is attributable to the primary material sectors and 32% (517 Mt) to electricity. The use and material intensity of resources along the supply chain is therefore a key leverage point where emissions can be reduced.

Figure 12: The supply chain emissions associated with global product flows of the EU



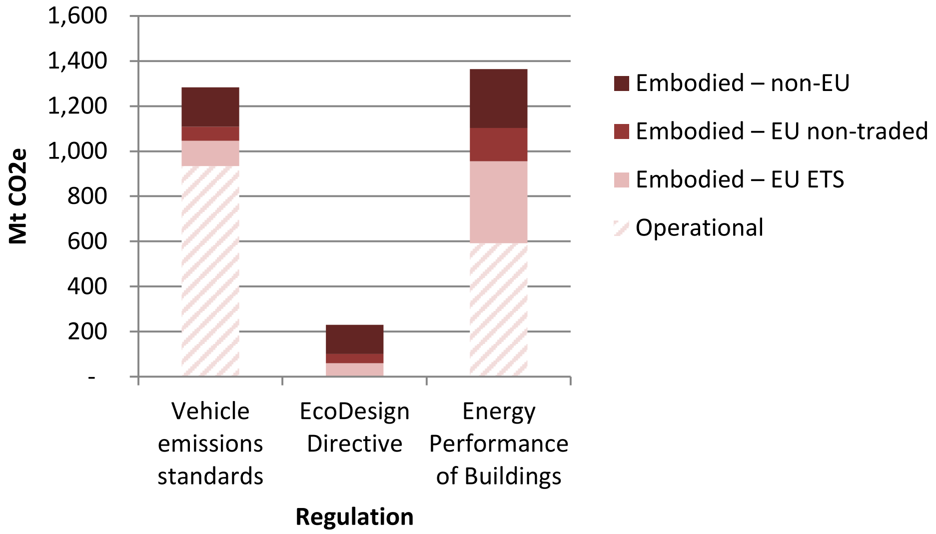
Around 45% of EU production emissions are generated in industries capped in the EU ETS, reducing at an annual rate of 1.74%, increasing to 2.2% post 2020. This includes emissions from the power sector (72% of ETS emissions), energy-intensive industries such as oil refineries and steel works (22% of ETS emissions), and commercial aviation (separated into its own cap). To address the remaining 55% of emissions outside the EU ETS, there a number of EU directives focusing on energy efficiency. Many studies have explored the options for reducing operational energy use and emissions of products, such as buildings and cars, but most neglect the materials necessary to manufacture and construct these (Müller et al., 2013). Embodied emissions however are becoming an increasing share of the impact of energy-using products (Ibn-Mohammed et al., 2013). We have identified three main directives that apply energy efficiency performance standards to appliances, buildings and vehicles, and therefore have the framework in place to extend these standards to cover embodied carbon:

- EcoDesign Directive: sets minimum mandatory requirements for the energy efficiency of products, such as household appliances and information and communication technologies (Directive 2009/125/EC).
- Energy Performance of Buildings Directive: sets minimum energy performance requirements for new buildings, for the major renovation of buildings and for the replacement or retrofit of building elements (e.g. heating and cooling systems, roofs, walls, etc.) (Directive 2002/91/EC).
- Vehicle Emissions Performance Standards: sets emissions standards for fuel combustion in passenger cars and light commercial vehicles (Directive 98/69/EC).

Figure 13 compares the operational (the conventional accounting approach) and embodied emissions related to the products addressed by the EU directives that we have identified as having the potential to be extended (Appendix 6.9.4). The values include emissions embodied in products sold to both intermediate (industries) and final (households, government and large capital investments) consumers. Some of the embodied emissions will originate in sectors already capped under the EU ETS (536 Mt CO_2e) (Appendix 6.9.5).

For modelling purposes, the Building Directive has been applied to the construction sector in the input-output model; vehicle standards have been applied to the manufacture of motor vehicles; and the EcoDesign Directive to the manufacture of office machinery and computers, electrical machinery and apparatus and radio, television and communication equipment and apparatus. To calculate the emissions potential of extending all three directives you cannot sum the emissions embodied across each product group in Figure 13 (Appendix 6.9.4). This would give an overestimate as each product can be a supply chain input to the others, and therefore some emissions related to vehicles will be included in construction activities. All three product groups need to be included in one calculation to exclude any overlap.

Figure 13: Operational and embodied emissions of selected products in 2007, Mt CO_2e [4]



230 Mt was emitted in the manufacture of electronics and electrical appliances in 2007, a sector which has been growing in physical terms. Operational emissions are allocated to the power sector and not directly to electrical appliances, as they are emitted where the fuel sources are combusted. From 1996 to 2012, EU consumption of telephone equipment rose tenfold; demand for other electronics such as computers, tablets and televisions rose fivefold; and purchases of household appliances such as fridges and freezers remained stable (European Environment Agency, 2014c). 60 Mt of the 230 Mt CO_2e (26%) embodied in appliances used in the EU sit within EU ETS sectors, leaving 170 Mt unaddressed potential (2.4% of EU consumption emissions).

The building performance directive tackles the energy use of buildings, which continues to increase at approximately 1% a year, despite implementation of the directive in 2002. In addition to the 594 Mt CO_2e released directly from commercial, institutional and residential buildings (European Environment Agency, 2014b), 773 Mt were embodied in construction materials themselves. An equivalent of 5.7% (406 Mt) of EU consumption emissions were outside the reach of the building directive and ETS.

934 Mt CO_2e were emitted by road transport in 2007 (European Environment Agency, 2014b), representing 18% of EU production emissions. An additional 346 Mt were embodied in the manufacturing of the vehicles purchased in the EU. A third of these are captured in industries capped by the EU ETS, leaving two thirds of the embodied emissions outside the scope of EU climate policy (3.3% of EU consumption emissions). Using the same logic, regulations on embodied emissions can be applied to all non-energy using products, currently not addressed specifically by EU climate policies.

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[4] Operational emissions of electrical appliances are allocated to the power sector where the fuel sources are combusted

We calculated the total emissions reach across all manufactured goods, not just energy using ones. We estimate that 2,061 Mt CO_2e, equivalent to 40% of EU production emissions, are related to material-intensive manufactured products' supply chains, both for use by intermediate and final consumers. 789 Mt (38%) of these greenhouse gases are emitted within EU ETS sectors, however the suggested policy extension would increase the coverage of emissions beyond the EU ETS to include both domestic non-traded and imported emissions. These figures represent the potential reach of policies, but not the emissions reduction potential as we don't know how politically feasible they are, or the reaction of consumers to such policy changes.

4.4 Discussion

We have analysed the potential reach of extending product standards and regulations to address the emissions embodied in manufactured goods to fully exploit the mitigation potential of resource efficiency. Extending energy-efficiency regulations to include the carbon or material content of all manufactured goods would set minimum carbon or resource efficiency standards. However, evidence on emissions drivers suggests there needs to be a greater focus on final demand reduction (Rosa and Dietz, 2012, De Koning et al., 2015), questioning whether resource efficiency can bring about a reduction in emissions without affecting the final demand for products (Barrett and Scott, 2012). This could be achieved using an enhancement mechanism which measures the carbon content of a product over its lifetime (e.g. emissions / year) thereby addressing product longevity, leading to a number of changes in business models (e.g. a shift from goods to services or longer product guarantees) and product design.

Thought needs to be given to how the policies are designed, and to ensure they do not undermine the effectiveness of others. For example, energy efficiency lowers production costs and creates financial savings which are freed up to spend on additional consumption and its associated impacts, known as rebound effects (Sorrell, 2009). Reduced demand for energy and materials within EU ETS sectors can also free up allowances enabling trading participants to emit at a lower cost if the equivalent volume of allowances are not retired from the scheme (de Perthuis and Trotignon, 2014, Koch et al., 2014). Therefore there needs to be some way of dynamically managing caps either through auction release or changing cap (de Perthuis and Trotignon, 2014). This would avoid rebound effects as it maintains the carbon price and carbon is actually removed from the system.

The nature of instruments has implications for how easy they are to extend and how they interact to deliver emissions reductions. The EU ETS could be extended to include additional sectors but, in its current form, would still only capture a proportion of production emissions. Regulations and standards can more readily be extended to include embodied emissions, either within their current scope or with the addition of new requirements (Table 9).

Table 9: Potential to extend selected policies to include embodied emissions

Current regulation	Possible addition	Additional requirements /next steps
EcoDesign Directive	Within current scope to set requirements to address some aspects of embodied emissions, including minimum guaranteed product lifetimes and promoting modularity, upgrading and repair (European Union, 2009a).	More appropriate methods to be used for preparatory studies in the EcoDesign Directive, which used more recent data, accounted for technology development and took into account product lifetimes.
Energy Performance of Buildings Directive	Extend current requirements to include embodied energy in the integrated energy performance of buildings (Szalay, 2007).	Standardisation of the calculation of embodied energy for building elements and processes.
Vehicle Emissions Performance Standard	Extend standards to include whole-lifetime emissions (Correia et al., 2014).	Standardisation for the calculation of embodied emissions for vehicle elements and processes.

The Energy Performance of Buildings Directive and the emissions performance standards for light-duty vehicles do not include embodied emissions (European Union, 2009b, Szalay, 2007); however the EcoDesign Directive was designed to take a more holistic approach. The EcoDesign Directive requires that a preparatory study is carried out to determine whether a product group necessitates requirements to be set, and for which stages of the product lifecycle these should be implemented (European Union, 2009a). However, many product groups were assessed before recent advances in energy efficiency and when embodied emissions data was sparse and of poor quality (Huulgaard et al., 2013). Furthermore, the approach to lifecycle analysis underpinning preparatory studies uses boundaries that exclude considerations such as product durability (Cullen and Allwood, 2009). We suggest using a measure that counts for embodied emissions measured over the lifetime of a product. Therefore, all EcoDesign Directive requirements have been related to operational energy and no products have had requirements set for embodied emissions to date (Maxwell et al., 2011). Our research indicates that these measures can however enhance the policy package for climate mitigation.

4.5 Conclusions

Through its consumption of material goods and services, EU consumption embodies nearly 40% more emissions that it produces, a trend found across nearly all industrialised countries. We calculate that just under a quarter of EU consumption emissions are capped under the EU ETS and that emissions from material intensive sectors are not easy to reduce from energy efficiency policy alone. The emissions flow chart in Figure 12 presents a framework which identifies different leverage points in the economy at which policy can intervene to reduce resource use and greenhouse gas emissions. Through resource reduction measures, industrialised countries can target emissions sitting outside their current climate policies, including imported emissions.

Opportunities to increase the scope of climate policy are not restricted to those in this paper, but we have attempted to show the additionality of integrating resource efficiency into existing climate mitigation policy. Resource efficiency policy which considers product supply chains has the potential to influence additional emissions than those from production. When analysing material-intensive manufactured products, we calculated their embodied emissions to be the equivalent of over 40% of EU production emissions, offering significant scope for emissions reductions.

There is work to be done with intermediate and final consumers on designing the right policies to exploit these opportunities. Further consideration needs to be given to the practical implementation of polices addressing embodied emissions, including the accounting procedures and administrative requirements for measuring and monitoring supply chain emissions crossing international borders. The exact mechanisms to ensure any overlap between policies are complementary in bringing about an absolute reduction in emissions, and do not undermine existing policies, need to be identified. This forms the basis of our next analysis.

A limiting factor of this study is that we calculated emissions associated with resource flows by the magnitude of economic transactions between sectors, and not the physical quantity of traded materials and products, which is not available in such detail at a global scale. For example, emissions from steel production are attributed to procurers of steel based on the price each consumer pays for it. Therefore, it doesn't reflect that different consumers pay different prices for the same commodities. Global commodities are aggregated into 163 product groups, and reflect an average emissions flow for the combined group, when the emission intensity within groups can vary considerably. Publications on the integration of physical data with global economic trade flows are increasing, with such developments hopefully able to contribute to similar policy assessments in the very near future.

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5 Discussion and conclusions

This thesis has the overall objective of determining how the implementation of embodied emissions, achieved using consumption-based accounting measures, would redefine existing climate policies and targets, and to explore further opportunities for consumption orientated policies in climate mitigation. It analyses this through an investigation of the UK's 2050 territorial emissions reduction target, the UK's energy pathway, and EU energy efficiency policies. In the first two analyses policy decisions on these topics are largely decided at the UK-level, however the third analysis investigated extending energy efficiency policies to include resource use of which the main policy driver is EU resource efficiency strategies. Accounting for embodied emissions makes a valuable link between industrial energy use to material production and then consumption. One of the main conclusions to emerge is the additionality that material efficiency strategies offer to the portfolio of energy-dominant mitigation policies in place.

To limit global temperature rises to less than two degrees there is increasing recognition that there needs to be a reduction in aggregate energy demand, at least in the near term (Edenhofer et al., 2014, Anderson et al., 2014). Edenhofer et al. (2014) however only refer to direct energy demand reduction. Energy demand goes beyond purely direct energy use and includes the energy embodied in all goods and services (i.e. indirect energy demand). Therefore I define demand reduction as a reduction in the consumption of all goods and services. Mainstream policy relies on reducing direct industry and household energy use through decarbonisation and efficiency improvements such as more efficient or low carbon technology installations and insulation measures, despite current policies continuing to maintain an emissions gap between cumulative emissions levels and the carbon budget for a two degree future.

This thesis applies methods for consumption-based accounting to demonstrate practical policy solutions. It advances existing research which has refined consumption accounting methods (Wood et al., 2014), reported results (Kanemoto et al., 2014), focused on revising national targets (Springmann, 2014) and investigated border tax adjustments that directly target traded emissions (Steininger et al., 2014). Only a limited number of papers measure the emissions impacts of broader consumption policies (Barrett and Scott, 2012, Girod et al., 2014, Müller et al., 2013, Allwood et al., 2011, Roelich et al., 2015b) and this thesis starts to bring together these opportunities into a comprehensive analysis of consumption in UK climate policy within a European context. Each chapter builds on the implementation of consumption accounting from measuring and monitoring consumption-based emissions (Chapter 2), to its integration into climate models (Chapter 3) and finally its integration into policies (Chapter 4). Such research is vital for advancing the application of consumption-based emissions accounting and extending the emissions reduction potential of prevalent energy supply policies to include resource use. This is increasingly important given that we are heading for temperature rises that will have a severe impact on people and the planet, unless we can rapidly reverse trends in rising global emissions.

The findings of each research question are summarised next, covering their contribution to the current literature, the empirical evidence base and policy recommendations. This is followed by the research limitations. The environmental potential and policy implications of integrating embodied emissions into climate mitigation policy are then discussed more broadly. Based on the evidence base and thesis results, a pragmatic proposal for the implementation of consumption-based accounting and policies is finally presented. This includes steps for future research.

5.1 Revisiting the research objectives

Research question 1: How would the integration of embodied greenhouse gas emissions alter UK climate change mitigation policies?

To my knowledge, this is the first paper to indicate the scale and source of a country's consumption emissions pathway, given pledged and agreed international climate mitigation policies to 2050. Its value lies in being able to explore plausible speeds, scales and sources of changing emissions, and how different consumption emissions would be from existing national carbon budgets and targets. The UK's consumption-driven impact is likely to exceed its production-based target, even if ambitious global mitigation efforts for a two degree future are implemented. By 2050, I estimate UK consumption emissions to be in the region of 50% to more than double (257%) UK production emissions, dependent on the implementation of existing, expected and desirable climate policies and trends in UK consumption and trade. The emissions profile of production sectors will shift given planned abatement measures, from energy currently being the dominant source of emissions to manufactured goods and transport services dominating in the future.

From a cumulative perspective, I estimate that to satisfy UK consumer demands, net imports will result in an additional 5.5 to 11.5 Mt CO_2e being emitted outside the UK, based on assumptions of the UK meeting its carbon targets and on the ambition of global mitigation efforts. These emissions would need to be mitigated in addition to the existing production target for the UK to have the same intended climate outcome. There is no evidence to suggest that it was the intention of the UK's Carbon Plan to meet its targets by outsourcing manufacturing. The intention was to deliver a specific carbon outcome and therefore this would suggest that responsibility for these additional emissions should be taken by the UK.

However, evidence suggests that only a small proportion of recent reductions in UK production emissions are directly the result of its climate policies, implying the need to consider alternative and additional policy options. For example, the recession in 2009 and warm winters has had a greater effect on reducing emissions than climate policy. This leaves the UK vulnerable to external factors and does not create the underlying conditions for a low carbon pathway. The paper provides a framework for reducing net imported emissions, involving stronger domestic efforts, more effort-sharing agreements and the transfer of finance and/or technology to less developed economies, which also addresses differences in the mitigation capacity of countries. This is already happening under the Clean Development Mechanism, of which the UK is Europe's key trader in Certified Emission Reductions (Gorecki et al., 2010). Evidence around governance suggests this will encourage non Annex-I countries to reciprocate emissions reductions without risking their economic development as they would have the technologies to retain a certain degree of competitive edge. As referenced in Chapter 2, published studies show that policies aimed at reducing consumer demand can be greater than the net imported emissions gap, enabling the UK to fully mitigate its consumption-driven impacts.

Research question 2: How would the UK's low carbon energy transition adapt when mitigating embodied emissions, not just operational emissions, from energy supply?

I collaborated with University College London to integrate embodied emissions into a cost optimisation model of UK energy supply and demand (UKTM), constrained to territorial greenhouse gas emissions targets. We developed a novel modelling approach (Daly et al., 2015) to analyse the policy implications of including energy technology supply chain emissions in developing UK energy pathways to 2050. I calculated embodied emissions using MRIO analysis and assigned these to the fuels and technologies represented in UKTM. I used the results from UKTM model runs to analyse the implications of accounting for embodied emissions in the UK energy system, both in terms of potential changes to the energy supply pathways and the UK's national energy and climate policy. By using UKTM, which provided evidence on energy pathways for the UK's Carbon Plan, I can see how evidence that directly guides UK policy would change. I show how energy supply pathways based on combustion alone would need to adapt so as not to shift the production burden abroad.

I found that the emissions generated outside the UK to meet its energy demands and associated technology infrastructure are set to increase through to 2050 and could be in the region of 60% higher than UK combustion emissions. When measuring embodied and combusted emissions associated with UK energy supply, the deployment of low carbon energy technologies achieves a 50% reduction from 2010 to 2050, compared to 77% when measuring combustion (operational) emissions only. UK combustion emissions need to reduce by almost 90% from 2010 to 2050 if the full supply chain emissions are to be reduced to 80%. Given the cost-optimal and technology features characterised in UKTM, energy pathways, both with and without embodied emissions, favour nuclear as a low carbon electricity source replacing fossil-based energy sources to mitigate the additional emissions. The underlying model characteristics remain a strong determining factor of the model outcomes even when embodied emissions are considered. Electrification and an increase in hydrogen production lead to further emissions reductions in the residential and transport end-use services. The mitigation costs of meeting the

80% target are estimated to increase 5%; however this does not consider cost savings from reducing adaptation requirements. Further analysis is needed to validate the model results, which I discuss shortly in section 5.2.1.2.

Given the widespread public opposition and perceived safety risks associated with particularly nuclear, there is evidence of alternative policy opportunities that would ease the dependency on unprecedented rapid deployment rates, publicly debated technologies and rising costs from greater reduction requirements; whilst reducing imported emissions. These address reducing the consumption of energy-intensive materials, incentivising end-use energy performance and not profit driven sales, regulating traded emissions, and the transfer of finance and technologies to less developed countries in return for carbon credits.

Research question 3: What is the additional emissions scope of energy efficiency policy when embodied emissions are included?

To my knowledge, this is the most comprehensive study quantifying and appraising the potential for extending EU energy efficiency product policies to include emissions embodied in all resource use, which includes internationally traded emissions outside the scope of existing EU climate policy. As resource efficiency is essentially a vehicle to reducing impacts (e.g. emissions, water consumption, deforestation etc.) from resource consumption it offers policy additionality when integrated within other policy domains, in this case climate mitigation. Climate and resource policies are currently developed almost entirely separately from each other.

Emissions embodied in EU consumption are almost 40% greater than those emitted from its production. Through international trade the EU imported the equivalent of 2,847 Mt CO_2e in 2007, which minus its exports resulted in net imports of 2,043 Mt CO_2e. I estimate the emissions embodied in material-intensive manufactured goods (includes energy and non-energy using products e.g. furniture and packaging) to be in the order of 40% of EU production emissions, indicating the potential for resource efficiency measures to contribute to mitigating these emissions.

A mitigation plan comprises many actions, for example decarbonisation, industry efficiency, carbon capture and storage, a shift in business practices, and changes in consumption levels, whose combined effect can only be estimated within a consistent framework. An advantage of using input-output analysis is that overlap across policies can be captured as it measures the supply chain interactions between sectors. For example 38% of the emissions embodied in manufactured goods originate in EU ETS sectors, and can act to undermine the carbon price, unless mechanisms are in place to prevent this. In this case, simply stacking these policies could deem them less effective.

5.2 Research limitations

In this section I first outline the modelling limitations and then the limitations in terms of the research context.

5.2.1 Modelling

5.2.1.1 Input-output analysis

From a modelling perspective input-output analysis has its limitations, which are quite widely documented (e.g. see Peters et al. (2012a) and Owen et al. (2014)), but difficult to overcome. Environmentally-extended multi-region input-output (MRIO) analysis relies on the compilation of secondary economic, environmental and trade data into a MRIO framework, which is subject to a number of adjustments and balancing procedures. Different consumption-based emissions results across different models and studies can be attributed to the use of different production emissions data sources, different definitions of consumption and different economic and trade structures. Here, I elaborate on some of the limitations that have specific relevance to the thesis.

Sectors are aggregated into between 26 and 163 representative economic profiles across available MRIO databases. When analysing emissions, it is better to have sectors with similar emissions profiles grouped together, however the raw data are collected primarily for economic analysis. De Koning et al. (2015) suggest a higher sector resolution is the preferred approach when calculating emissions embodied in trade at the level of technical detail required to investigate meeting tight carbon targets. As the papers that make up this thesis have been written, I have tried to apply the model most fit for purpose. For example, when integrating input-output analysis with the UKTM energy model, I selected a UK centric model with the highest disaggregation of the energy sector at the time. When investigating the potential reach of resource efficiency policies I selected the input-output model with the highest disaggregation of energy-intensive, material, and manufacturing sectors. The disaggregation of input-output models is subject to ongoing research.

Another limitation of input-output analysis is that emissions associated with resource flows are calculated according to the magnitude of economic transactions between sectors and not the physical quantity of traded materials and products, which is not available in such detail at a global scale. For example emissions from steel production are attributed to procurers of steel based on the price each consumer pays for it (refer to section 1.1.3.4. for more detail). Therefore, the analysis doesn't reflect that different consumers pay different prices for the same commodities. As materials are the vehicles for transferring emissions via trade, physical flows are a more accurate representation of embodied emissions. However, input-output analysis can trace the sales and purchases of materials through complex global supply chains, for example to service sectors that use thousands of products to deliver their services. Material flow models do not trace this level of detail in producer-consumer linkages.

5.2.1.2 Scenario analysis, sensitivities and data validation

Our ability to project the future is highly constrained, and scenario analysis has developed as a means of exploring aspects of uncertainty and alternative futures (Mander et al., 2008, Mander et al., 2007). Every approach has its limitations. Input-output analysis is a static model and therefore does not capture the dynamic effects of climate policies e.g. technology deployment and changing prices, which in turn impact on emissions. In Chapter 2 I used a static MRIO model where the model variables are exogenous to the model and I used past trends, secondary and expert information to make changes to the model variables (e.g. economic growth, production emissions and trade). However, there were over 85,000 data points in the trade matrix alone, and projecting the development of all these interactions to 2050 is impossible. Therefore broad assumptions were made and in most cases trade relationships were assumed to remain at 2010 patterns, yet the level of demand between domestic and imported products changed. In Chapter 3, the static embodied emissions coefficients were made endogenous within a cost optimisation model. In other words, they became a criterion for technology selection. Each approach has its own set of limitations. The former doesn't consider feedback, such as the effect of price changes, whereas the latter gives little consideration to political, behavioural and institutional realities (Barker, 2004, Scrieciu, 2007, Barker, 2010) and therefore they simulate quite artificial macro-economic responses.

Sensitivity analysis offers insights into the influence of variations in IO model input parameters on the consumption-based emissions results. When isolating the effect of a change in one coefficient, results to the overall footprint are shown to be marginal. However, when making changes simultaneously, the change to emissions results can be greater than the initial change to the variables. Understanding which variables have a greater influence on the results could have helped understand how sensitive the models used were to changes and assumptions in the model parameters. Mattila et al. (2013) investigated the use of IOA for building scenarios of sustainable development. They first did a perturbation analysis of Finnish input-output tables to identify which input data are most decisive for the results in terms of their relative sensitivity. Changes were made to direct intensities, technology coefficients and final demand. This however does not model rebounds or substitution changes relating to the initial change. Such changes in behaviour need to be modelled as a scenario. Individually, most parameters had little impact on the model outcomes, and energy-intensive sectors had the highest impact. Emissions intensities and final demand had a bigger impact than changing technical coefficients, a result shared for the UK between 1992 and 2004 in Baiocchi and Minx (2010a).

When investigating the effect of isolating a change in one technical coefficient by 10% at any one time, Wilting (2012) calculated the results on the Dutch carbon footprint were at most 1% of the total footprint. When all technical coefficients were increased/ decreased 10% simultaneously, the combined effect on the footprint was a 34% increase/ 20% reduction respectively. Hence, the resulting changes on the Leontief matrix (the inverted technology matrix) were much larger than the original change in the technology coefficients. The coefficients that had the largest individual impact on the Dutch carbon footprint were from foreign production and predominantly covered energy and basic industries. This does not seem surprising as these are likely to be present across many supply chains. Wilting concludes that the import linkages have less influence on the footprint results than representation of domestic production

Steen-Olsen et al. (2014) find emissions multipliers are sensitive to the aggregation level of the input-output table, although not in any specific sectoral pattern (i.e. energy-intensive sectors were no different to financial and public services). The level of aggregation selected can have a significant impact on the carbon footprint generated.

The intention of chapter 3 was to determine how the UKTM's model outputs would change when indirect emissions are included in the energy system modelling. Whilst I indicated that there are behavioural, economic and technical barriers and uncertainties to realising the energy supply changes, it is important to take a more contextual and critical perspective to the outcomes of the model. Taking the example of nuclear, which has the highest shift when mitigating indirect emissions in the UK climate target, the model outputs suggested up to 40% of primary energy would be sourced from nuclear, primarily to increase final consumption met by low carbon electricity. However, I now show such ambition is far from the current situation, questioning its feasibility to producing outputs for devising realistic energy pathways and policies.

In 2014, 335 TWh of electricity was generated, with nuclear providing 17% (DECC, 2015), equating to around 57 TWh. Currently, there are 15 operating reactors in the UK totalling 9.5 GW capacity. Around half existing capacity is due to be retired by 2025, but the UK has plans to deliver around 16 GW of new nuclear by 2030 from 12 new reactors, which still requires significant capital investment (HM Government, 2013). If these plans were successful, installed nuclear capacity would be around 20 GW. The newest and largest nuclear power plant with an electrical output of 1191 MW, Sizewell B, generated a record-breaking 10.51 TWh in 2015. If each GW of installed capacity could generate an equivalent power output, this would equate to 176 TWh. However, UKTMs estimates final energy consumption of nuclear sourced electricity is set to increase year on year to around 1,250 PJ, around 350 TWh, by 2050. Therefore, assuming a start date of 2025, this requires in the region of an additional 1.3[1] Sizewell B each year which is far from the UK's nuclear strategy. Using the example of nuclear alone raises questions on the robustness of the model assumptions.

Understanding uncertainties in consumption-based emissions data provides an indication of the robustness of the methods for use in policy making. Data validation is important for determining

[1] 350 TWh/ 10.51 TWh/ 25 years = 1.33

how much influence the methodologies employed, models selected, and scenario assumptions chosen (e.g. consumption rates, trade patterns and carbon intensities of production) could have on the model outcomes to give confidence in the data. Whilst national-level trends in consumption emissions reported across different MRIO models are consistent within 10%, results by country and sector are more varied (Moran and Wood, 2014). Scenarios are very sensitive to the data and assumptions used and as such should be viewed as an exploratory analysis. Whilst we cannot rely on modelling exercises alone, the evidence presented provides a robust foundation estimating the additionality consumption accounting offers mitigation policies. In reality we do not have the modelling capability to understand what will happen in the future, and how the global economy will respond to a low carbon transition. However, we need to implement policies now that we think can make a difference, whilst continuing with decarbonisation and global cooperation efforts.

5.2.2 Research context

Besides the method, there are some contextual limitations related to the scope of the research. As critiqued in section 1.2.2., the quantitative climate targets set in the UK are weaker than the qualitative description of UK's responsibility for mitigating climate change. I estimated that UK targets are 60% greater than an equal per capita-based distribution of global carbon budgets to prevent 'dangerous' climate change. From this evidence base, I would argue the need for existing UK climate targets to be reframed on this basis. In addition, based on COP21 in 2015, there was considerable support for lowering the level of warming from 2 to 1.5 degrees. This would require additional movements on the targets, which would have implications for timeframes and costs associated with a low carbon transition.

This PhD was conducted before the latest UNFCCC negotiations at the 21st Conference of Parties (COP21) in Paris in December 2015. Since then countries and representative regions have submitted new pledges in the form of intended nationally determined contributions (INDCs) to replace the existing pledges analysed in Chapter 2. More countries now have targets in place that will not have been fully captured. Despite greater global ambitions agreed in Paris, many experts believe the INDCs still fall short of preventing 'dangerous' climate change (UNFCCC, 2015b), and sought to limit temperature rise to 1.5 degrees. The next IPCC assessment report in 2018 will look at the feasibility of achieving greenhouse gas emissions reductions aligned with this temperature target (UNFCCC, 2015a). This greater ambition further strengthens the need for additional demand-side measures to meet tightening carbon budgets.

Demand-side measures are not considered mainstream and without price adjustments to compensate for the reduction in consumption would reduce economic growth[2] which is seen as

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[2] GDP can be calculated as the value of total expenditure of domestic consumers (households and government) on final goods and services

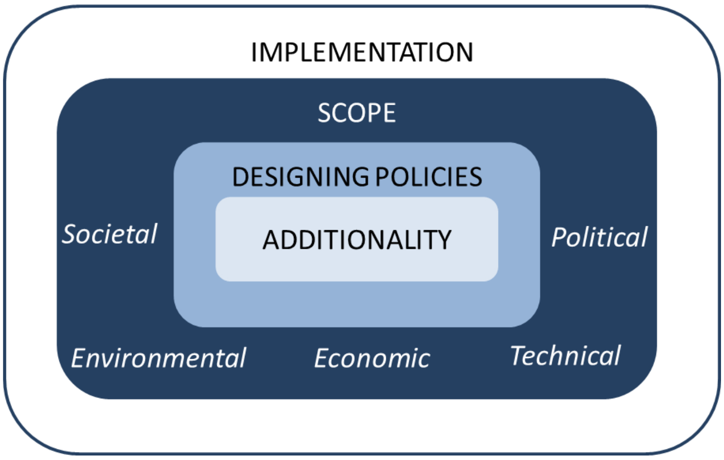
maintaining current lifestyles and as a vehicle for countries to develop. I have not explicitly addressed this tension. However, ecological economists have long been arguing that economic growth generates social and environmental costs, and once a certain level of wealth is achieved its increase fails to improve quality of life (Howarth and Kennedy, 2016). A number of ongoing initiatives, both national and international, are establishing, improving and monitoring indicators beyond GDP (Costanza et al., 2014), e.g. the creation in 2008 of the Commission on the Measurement of Economic Performance and Social Progress; the EU's 'Beyond GDP' initiative; The UN's Human Development Index; The New Economics Foundations Happy Planet Index are a few of the most influential ones. These centre more on social and environmental well-being than generating economic growth, and could shed more light on the benefits of consumption policies. Working less for example has shown to improve health and happiness amongst those working too long or too short hours (Zwickl et al., 2016). In the UK, since 2001 Defra have been publishing Sustainable Development Indicators which were revised in 2012 in partnership with the Office for National Statistics (ONS) new measures of national well-being. As consumption is integral to people's quality of life (and not based on the assumption that increasing consumption increases wellbeing) consumption measures can be assessed within these types of monitoring frameworks to understand the wider economic, social and institutional impacts and co-benefits.

I have focused on the role of government policies to encourage changes in consumer behaviours and not on other influences such as civil society and NGOs. However, change can stem from outside government policies. Research on public perceptions suggests public values are critical for the success of policies (Demski et al., 2015). There are also different scales in which policies are implemented, of which I have concentrated on UK and EU policies, but not how they are translated into local governments for example. Changing behaviours is certainly not restricted to national government actions, and happens at many scales across many stakeholders. This is just one route for encouraging change.

5.3 Integrating embodied emissions into climate mitigation policy

In this section I explore the motivations, potential barriers and approaches to integrate embodied emissions into climate policy. The structure of the discussion is framed in Figure 14, which indicates the steps (included in the box) needed to implement policies. Firstly, the evidence in this thesis suggests that consumption accounting can offer **additionality** in terms of increasing opportunities for reducing greenhouse gas emissions. I present an alternative framework to **designing policies** that are complementary to production-based technology measures to include consumption. There are different policy mechanisms available to reduce consumption, each with its own strengths and limitations. I have measured the **environmental effectiveness** of policies in this thesis, however, they must also be **technically and economically viable and politically and socially acceptable** to be implemented, which I discuss. For example if a policy has a strong environmental potential but no political and public will it is less likely to be effective. From a practical perspective, there is a robust empirical basis on which to monitor and measure progress and policies using consumption emissions accounting, with ongoing developments refining these methods. Given this I conclude that there is a middle ground role for the **implementation** of consumption accounting that will bring consumption strategies into designing polices for achieving emissions reductions. This is outlined in my pragmatic proposal for integrating embodied emissions into climate mitigation policy.

Figure 14: Discussion framework for realising consumption-based policies



5.3.1 Additionality

The International Energy Agency (2012) demonstrated the gap between international climate mitigation policies and emissions reductions required to limit future temperature rise to two degrees. I have summarised several reasons given in the literature for the disconnect of climate mitigation policy from climate science which determines a carbon budget for probabilities of achieving different levels of global warming. These bring to the forefront the need for more policy options and the need to think about additional demand-side measures beyond a direct reduction in energy demand resulting from energy efficiency and technology improvements:

1. Policies have focused on the producing industries, leading to a plethora of industry technology solutions, which has been competing with increasing population, economic growth and consumption. Globally, efficiency improvements have not been enough to offset rising consumption and according to the rebound effect could contribute to further increases in consumption (Sorrell, 2009).
2. A territorial boundary definition has been criticised for enabling carbon leakage where a reduction in emissions (relative to a benchmark) is offset by an increase outside the country's jurisdiction (Peters, 2010a). These traded emissions are not directly targeted by policy, and a large proportion is excluded from existing climate pledges (Peters and Hertwich, 2008b).

3. The text of the UNFCCC agrees on the principle of common but differentiated responsibilities and respective capacities to deal with climate change. However, formal definitions on a fair emissions burden-sharing scheme, beyond inclusion in Annex I or not, is lacking.
4. There is still a tendency to discuss end point targets instead of cumulative budgets (Anderson and Bows, 2011) even though the science of climate change is clear on the cumulative impact of emissions (Meinshausen et al., 2009). This is not dependent on the accounting principle employed; however a move to a carbon budget approach would require the remaining carbon space to be divided between countries following attributional principles agreeable by all.

Early signs pre-COP21 indicated the new pledges (INDCs), which are intended to add up to emissions reductions for two degrees, are still not enough to realise necessary emissions reductions to prevent serious climate impacts (UNFCCC, 2015b). Furthermore, many nation states argued for a 1.5 degree target which strengthens the argument for the need for greater policy options (UNFCCC, 2015a). The results of this thesis demonstrate the integration of embodied emissions into climate policy can address some of the barriers to achieving a two degree or lower future.

Using the IEA scenarios which were based on trajectories of national-level production emissions I did a similar analysis from a consumption perspective in the first analysis chapter (Chapter 2) to investigate the divergence between UK production and consumption emissions. Measured against a territorial baseline, a change to UK consumption is likely to underestimate the emissions reduction potential, as on average 50% of UK consumption emissions are generated abroad (this varies by product) (Barrett et al., 2013) and therefore would not count towards the UK's saving. However, in effect, the emissions saving potential would be on average double the territorial emission reduction. In Chapter 2 I estimate that in 2050 as much as 60% of emissions embodied in UK consumption could be from imports and would therefore be influenced by changes to UK consumption.

As shown in the third analysis chapter (Chapter 4) emissions from EU final consumption are currently 40% higher than those produced by EU sectors. If the EU and its Member States included net-imported emissions in their mitigation targets, collectively they would have influenced an additional 2,043 Mt in one year. This becomes a higher priority as international governance remains weak. It can also provide a lever to negotiate between Annex I and non-Annex countries in terms of attributing responsibility for emissions reductions. Edenhofer et al. (2015b) suggest that Annex I countries taking on greater mitigation efforts would go some way to bringing non-Annex I countries on board.

This thesis identifies, from a supply chain perspective, that the current focus of policy on energy decarbonisation compartmentalises the problem too much. When calculating the emissions embodied in a country's consumption, different sectors become more emissions dominant. Figure 12 in Chapter 4 showed that manufactured goods and services have the highest embodied emissions compared to the power sector which dominates production emissions. This is a result of the carbon intensity of resource inputs further up the supply chain in the provision of these products. Decarbonisation reduces the impact of direct energy consumption of these sectors, however as alluded to by Ayres and Warr (2005) this does not address the use of carbon intensive inputs such as primary materials.

The UK energy system cannot be viewed in isolation of its links to other productive sectors and regions. Changes in demand, by both intermediate (industry and services) and final consumers (households, governments and large infrastructure items) have the ability to substantially reduce emissions. Some suggest this can be achieved by material efficiency measures (Allwood et al., 2011), whilst others suggest an absolute reduction in consumption is needed (Anderson et al., 2014). Even if climate policy remains based on production however, measuring embodied alongside territorial emissions can reveal underexploited policy options (presented in the following sections) that can be less costly and technically easier to implement. Given the slow pace of planned decarbonisation, the uncertainty of negative emissions technologies and the increasing impact of consumption on trade, it increases the levers available to climate policy makers.

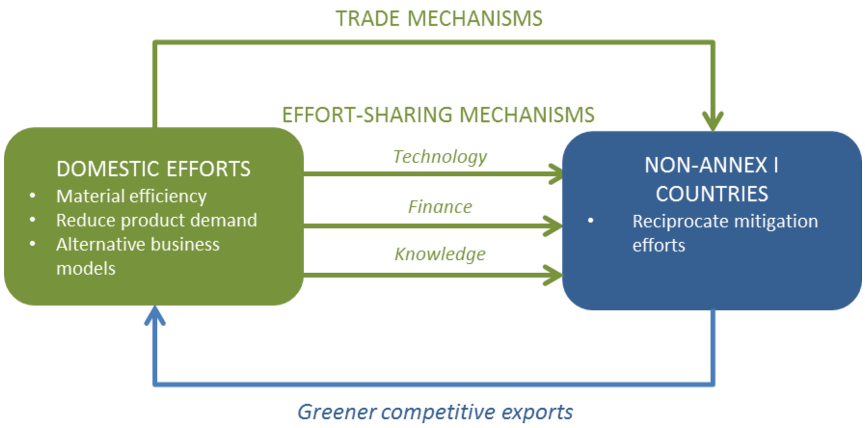
5.3.2 Designing policies

In its original form (i.e. excluding embodied emissions) the energy system optimisation model UKTM, which we extended in Daly et al. (2015) to include embodied emissions, is used as evidence to inform the UK's Carbon Plan and energy policy. The intention of Chapter 3 of this thesis was to show how the energy supply pathways from the model results would change when including emissions embodied in energy infrastructure in the UK's territorial target. The model outcomes suggest that, based on technical, investment, innovation and deployment limitations, the UK can increase the share of low carbon technologies, particularly nuclear, to meet an 80% reduction at an additional 5% of the cost[3]. However, when validating the model outcomes (section 5.2.1.2.) the robustness of the results were brought into question, raising concerns around the feasibility of the capacity of nuclear deployment suggested from now until 2050. In addition, when considering uncertainty in low carbon technology deployment rates, policy uncertainty, and a strong public opposition to nuclear, often first-best outcomes are deemed infeasible and second-best measures need to be considered.

[3] Undiscounted, see section 3.3.2

Whilst not mainstream in climate policy, governments have tools and policies available to address emissions embodied in consumption that do not always rely on technology solutions (illustrated in Figure 15). However, they often require user behaviours to adapt which is not necessarily easier to achieve. These tools address industry and business practices, consumer lifestyles and trade partnerships and can target traded emissions directly through trade mechanisms or indirectly through international transfers and changing domestic consumption, as initially presented in the discussion in Chapter 2 and expanded in Chapter 3 and 4's discussion.

Figure 15: Framework for designing policies addressing emissions embodied in consumption (green = actions by Annex I countries)



Market-based mechanisms targeting internationally traded products directly through a regulation or tax such as carbon border adjustments could threaten the welfare of net exporting economies by increasing their costs and providing an additional administrative burden to collect, comply and monitor all traded commodities. Evidence has suggested that to reduce an equivalent volume of emissions, strengthening and extending the coverage of domestic efforts in net importing countries could yield greater global welfare improvements than applying border taxes by equalising the marginal abatement cost and associated benefits of carbon trading compared to encouraging production in regulated regions (Springmann, 2012).

Effort-sharing agreements, like the Clean Development Mechanism, could become more important if traded emissions are to be addressed and international climate policy remains fragmented. Their effectiveness will change depending on the level of global ambition and the allocation of mitigation responsibilities. Mitigating for 1.5 degrees will require reductions in all areas and therefore countries cannot offset their emissions through mitigation efforts in another country, however there will need to be a flow of capital from developed to developing countries to finance the low carbon transition. Whilst mechanisms such as the CDM are intended to provide less developed and industrialising countries with the means to both reduce the carbon intensity of production and remain competitive as emissions controls tighten, such actions could increase the future mitigation costs of developing countries if developed countries take out the least cost measures and claim the credits for them. Additionally an increase in one unit of renewable energy deployed has shown to only offset a quarter of a unit of fossil fuels even when controlled for demand (York, 2012), questioning the effectiveness of technology transfers in practice.

Governments have been reluctant to implement policies addressing domestic consumption, however, in a previous paper, Barrett and Scott (2012), identified case study evidence for changing consumer behaviours of producers and final consumers. We estimated that, excluding energy and transport measures, altering consumption patterns of goods and services could contribute up to 10% of UK 2050 targets (equating to 30% of emissions in non-energy and transport sectors). Other studies have also demonstrated emissions savings from a range of consumption strategies applied to industries (e.g. Allwood et al. (2010a)), infrastructures (e.g. Müller et al. (2013), Roelich et al. (2014) and Knoeri et al. (2015)), the circular economy (Stahel, 2016) and consumer lifestyles (e.g. Barrett and Scott (2012), (Girod et al., 2014) (Table 10).

Table 10: Examples of consumption strategies for industry, infrastructure and final consumer purchasing

Business to business	Infrastructure	Lifestyles
• Reducing material yield losses in the energy-intensive primary processing stages • Increasing the use of recycled materials which are less energy intensive than primary production • Using products for longer and more intensely through repair and maintenance and modular design allowing component upgrading • Product re-use e.g. through second-hand markets • Lightweight product design	• Apply the material efficiency principles in the first column • Integrating infrastructure into urban planning to reduce infrastructure needs e.g. shared infrastructure and coordinated public transport systems	• Shift in consumption pattern without changes in consumption level e.g. changing diets and travel modes • Purchasing the same but lower impact products e.g. solar panels and electric cars • Changing the way existing products are used e.g. driving practices and lowering household heating • Buying less

A crucial step of realising these strategies will be the ability of governments to set the right policy framework to incentivise shifts in practice. Governments could lead by example and specify low material, remanufactured and or locally sourced (if lower carbon) requirements in tenders, which involves millions of pounds spent annually on infrastructure (ERP, 2014). Reducing material and product consumption could be more effective if business models shifted from profit-driven to performance-driven sales (Steinberger et al., 2009). Using the example of a car club, under this model business would provide a fleet of cars to customers for a (monthly) fee instead of selling each a car. The incentive would transfer from increasing sales to maintaining a stock of cars as efficiently as possible to keep costs down. Hence it would reduce material throughput. This is not a new but a niche business model, for example it is practiced across a range of intermediate and end-user products including sports equipment, electronics, IT equipment, cars and aircraft, and Li and Xu (2015) suggest it can present an economically viable business model. Moving forward, the main challenge will be in understanding how to move niche consumption strategies into the mainstream for a range of products and stakeholders.

5.3.3 Policy scope

The rationale behind most climate policy instruments is rooted in conventional economic theory, which presumes that the optimal quantity of a pollutant is equivalent to the associated pollution control costs and the benefits of the control (Spash, 2010). Mayrhofer and Gupta (2016) found the scope for co-benefits is 'enormous', covering economic, environmental, social and institutional co-benefits including enhanced energy security, reduced air pollution, health improvements and the promotion of political stability. Practitioners try to quantify these in monetary terms, and compare them to the cost of the mitigation control. Pollution control optimisation happens when the costs of mitigation outweighs the reduced costs of the benefits to society. However, many of the benefits are impossible to quantify economically (Mayrhofer and Gupta, 2016) and therefore estimates rarely reflect the true cost to society. In addition, if the immediate (carbon) costs become too high for the implementing industry/ sector, sectors are anticipated to have the knowledge and ability to innovate to reduce them. Such simplified assumptions ignore complex realities, and the drivers and motivations besides cost-based decisions. Exclusion of the realities in designing policies will have implications for their effectiveness. I now consider whether there is the political, technical, economic and social scope to implement consumption strategies referred to in the previous section (Table 10), and the interactions and overlap between policies:

1. Political scope - deployment of low carbon technologies has been weak and there is a lack of integration of consumer behaviour in climate policies.
2. Technical scope - future technologies are assumed in low carbon pathways to achieve a two degree future, yet their technical potential is uncertain.
3. Economic scope – while offering some low cost opportunities, reducing consumption is at odds with government objectives on economic growth.
4. Societal scope - strategies are susceptible to behavioural responses, for example public and political lobbying.
5. Interactions – sectors are interlinked through global supply chains and cannot be considered in isolation.

5.3.3.1 Political

Despite the UK being one of the first countries to set 2050 climate targets, policy implementation has been weak. Although the EU met the first round of Kyoto targets, the evidence suggests this has been possible due to the exclusion of international aviation and shipping (Gilbert and Bows, 2012), the economic recession (Peters et al., 2012b), generous carbon allowances under the EU ETS (Spash, 2010), and outsourcing (Kanemoto et al., 2014).

Recent reductions in the UK's territorial emissions, which reached 8% in 2014 despite strong economic growth, have not necessarily been the result of planned climate policy. Many of the reductions from building, industry and power emissions reflect one off changes and uncertain factors rather than replicable ongoing trends (CCC, 2015b). Had it not been for a mild winter in 2014, the 15% reduction in building emissions would have been 2%. While coal combustion in power generation has reduced, leading to an 18% reduction in emissions, it has been replaced with imports, and low carbon sources accounted for only 4% of the reduction in 2014 emissions from power generation. Despite good progress in for example the deployment of renewable electricity generating capacity, installation of efficient boilers and increased insulation rates, there has been limited progress in low carbon heating, uptake of efficient appliances, and reduced travel demand. The UK Committee on Climate Change (2015b), tasked with monitoring UK climate policy and progress independently of the UK government[4], have also perceived a gap between existing and foreseeable climate policies and meeting future UK carbon budgets. Therefore, there is a need to focus on how climate policy will deliver targets, and the additional measures needed to bridge the emissions gap.

Whilst the UK is one of a few countries to publish national consumption emissions accounts, responsibility for them was assigned to the Department for Environment, Food and Rural Affairs (Defra) and not the Department for Energy and Climate Change (DECC). Defra is largely responsible for sustainable consumption and production, which was separated from climate mitigation. Also, since the economic recession, Defra's budget has diminished and work on consumption has been cut. Whilst there was an enquiry in 2012 by the UK government to investigate the implications that consumption-based accounting could have for UK carbon targets and devising climate change mitigation policies, which concluded that DECC measure and monitor UK consumption emissions, this has yet to be implemented. Due to the environmental potential of consumption-related policies, consumption policies should be an integral part of climate mitigation portfolios.

5.3.3.2 Technical

Currently cumulative emissions largely depend on how effectively policy can enable the deployment of low carbon technologies. There is technical uncertainty in the development and deployment of low carbon technologies, particularly negative emissions technologies such as carbon capture and storage (Smith et al., 2016), which is a risk given many two degree scenario pathways rely on their deployment (e.g. included in the IPCC's Representative Concentration Pathways for two degrees). Delaying action to be able to maintain current lifestyles at the 'least cost' with the expectation that such technologies will work in the future is a high risk strategy that could be disastrous as the temperature-rising emissions will already be in the atmosphere,

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[4] Although some would argue they are not independent

and will be much more costly (if not impossible) to abate (Edenhofer et al., 2015a). Given that technical scope can be limiting and many demand-side measures do not rely on technologies, consumption strategies present an attractive policy option to those serious about mitigation.

Barriers to reducing resource consumption are not often technological ones. Skelton and Allwood (2013) suggest the cheap costs of materials (they focus on steel) compared to other inputs, particularly labour, mean that there is little incentive for companies to implement material efficiency measures such as lightweight design. The low cost of new products in comparison to repair and maintenance disincentivises product longevity and the economics for second-hand markets are poor (Allwood et al., 2011). People replace products early as their tastes change and technologies develop with new and improved functions (van Nes and Cramer, 2006). Information on product lifetimes are not well understood; people often place little value or attachment to products; and labour costs to repair are higher than the cheap cost of outsourcing manufacturing to low cost countries (Cooper, 2005). Therefore areas like product design, marketing and fashion can make a difference to people's perception of products and how they value them; and market conditions can incentivise good quality durable product design and product longevity for example through performance-driven sales and extended product warrantees.

5.3.3.3 Economic

Consumption spending is a component part of generating economic growth. Reducing consumption is therefore at odds with government objectives around economic growth. However, to recognise the limits of economic growth to continually improve people's quality of life there have been movements on redefining progress from an overwhelming emphasis on economic growth to more social and environmental factors that determine, for example, levels of happiness, with the intended outcome that prosperity can be achieved without necessarily the need for economic growth. van den Bergh (2011) for example suggests that we should not worry whether economic growth goes up or down, but instead just measure what ultimately matters for improving welfare.

Indicators are a useful tool for designing and assessing policies, and generally what gets measured gets managed. Despite rising criticism, for example failing to account for unequal distribution of wealth across a population, GDP remains the key indicator for assessing a country's material standard of living (O'Neill, 2012). If measurements are flawed, decisions can be distorted. A traffic jam for example would increase GDP generated from petrol yet would increase pollution and reduce people's well-being (both health and enjoyment) (Stiglitz. et al., 2009). Some research suggests that reducing consumption could have other co-benefits relating to quality of life (Pullinger, 2014, van den Bergh, 2011). Understanding these opportunities is important however this was outside the scope of this thesis. Policies should be evaluated against a range of sustainable development indicators and not a cost-benefit analysis in the conventional sense.

5.3.3.4 Societal

Whilst this thesis has demonstrated the environmental potential of consumption-side strategies, even if a policy is deemed to be environmentally effective, strategies 'are not devoid of behavioural requirements, self-control and social norms, in order to be effective, and the appropriate response must be embedded within an institutional and social frame' (Spash, 2010). Demski et al. (2015) suggest that public acceptability is of critical importance to the success of energy policy, as they can have strong preferences for some technologies (e.g. renewables) over others (e.g. CCS) and specific preferences or responses might play out depending on public attitudes and values. This is a large source of uncertainty of resource policies (Butler et al., 2015) and can be a help or a hindrance.

The public and industry both actively lobby government proposals for example, with the balance swayed in favour of large corporations. Publicised examples include public opposition for nuclear power and fracking, largely over safety and some environmental concerns. From an industry perspective many energy intensive industries have arguably been cushioned from climate policies e.g. EU ETS, by exercising their substantial lobbying power on governments, concerned first and foremost about their own market share and economic growth. Besides having shown to have had little effect on the competitiveness of EU industries, the EU is likely to remain locked into carbon-intensive energy forms if governments continue to protect the vested interests of energy suppliers (Moe, 2010). The success of consumption policies will depend on the ability of the government to shift incentives from profit-driven sales to performance-based operations, and encourage firms who see themselves as losers of the process to adapt and/ or diversify their activities. Policies must encourage climate friendly behaviours and enable those negatively affected to adapt to low carbon activities.

Policies addressing consumption need to be socially acceptable to be effective. Consumers need to be both able and willing to adapt to desirable patterns of consumption. For example, car ownership has become the norm, with 75% of UK households owning one or more cars, up 5% in 15 years (Department for Transport, 2013). Some people prefer the convenience of owning a car, whilst others perceive owning the latest model as a status symbol, and the 'value' of the product often varies across different socio-demographic segments of the population. Deciphering the factors that have led to this social norm will help government shift the incentive system towards public transport or low carbon business options such as car clubs that are more likely to be adopted. Models are available to describe consumer behaviour, see Jackson (2005) for an overview. They vary in their importance given to characteristics that are internal to the individual such as attitudes, values, habits and personal norms compared to behaviour as a function of processes and characteristics that are external to the individual such as physical and regulatory incentives, institutional constrains, and social norms.

However, putting an emphasis on the role of consumers as agents in mitigating climate change, framed as 'citizen-consumers' that are both agents of change and consumers with buying power in the capitalist system (Barr et al., 2011), is not so straightforward. Despite the majority of people in developed countries being aware of climate change, this does not necessarily translate into climate action (Tobler et al., 2012). Tobler et al. (2012) make reference to studies that indicate consumers with pro-environmental attitudes are more willing to support political changes that encourage sustainable behaviors, but are less willing to make lifestyle changes independently. The former is influenced predominantly by environmental concerns, the latter more by personal norms, yet this can differ when looking at specific policies. For example, people seem more likely to recycle and insulate their homes than replace car ownership for public transport. Consumers have also shown to be more willing to accept technical changes than shifts in consumption. In essence Tobler et al. (2012) found that consumers are more willing to adopt behaviours with a lower cost or effort involved (i.e. more convenient) and pro-environmental concerns are not enough to overcome higher costs and less convenient behaviours.

Social practice theory has been used to understand how everyday activities (i.e. social practices) shape people's consumption and use of energy, products and carbon. People do not necessarily question recycling of household waste as these are now somewhat ingrained in everyday practices, yet this does not lead to harder, bigger scale changes. Barr et al. (2011) found a general unwillingness to assume responsibility for climate change among interviewed participants, and a tendency to shift the blame to others. This was rationalized due to the global scale of climate change and feelings of powerlessness as an individual to make a difference. People often highlighted the unsustainable behaviours of others, or those setting the consumption environment (i.e. government and businesses), compared to themselves to defend their own behaviour. The scale of climate change seems to be very removed from everyday practice, and there is still a tension between consumption aspirations, like going on holiday, and knowing it can have a detrimental environmental impact.

Governments and industries often refer to consumer sovereignty, and the individual right of consumers, against sufficient consumption (Sanne, 2002). However, Sanne (2002) argues that consumers have become locked into structures and habits (understood for example through social practice theory), created mainly through producer and business interests, that are conducive to high consuming lifestyles, instead of them being necessarily unwilling actors of change. For example, persuasive marketing attracts people towards certain products and this has grown as communication technologies have developed, becoming sometimes intrusive. Marketing has become a considerable force worth billions of pounds on the basis of selling consumption, and hence will be influential in resisting change. Another example are employment laws regarding full time work which has tied people into certain working patterns despite surveys suggesting that people would prefer shorter working hours at less pay. More money, both individually and in aggregate, increases consumption. Sanne (2002) suggests the relationship between buyers (consumers) and sellers (producers) is uneven, with consumers being subject to persuasive marketing by producers, but with limited power themselves against certain products or processes. The balance comes down to the construction and achievement of political influence and power. Businesses tends to have a certain amount of power in government due to its economic capacity. Whilst media is intended to represent the interests of the public, it itself is funded, and therefore dependent on, advertising. Changing consumption, as suggested to by Sanne (2002), is rarely discussed due to its central role in maintaining economic growth, which is at odds with government and industry principles.

The above findings are supported by Gössling and Cohen (2014) discussion of transport 'taboos' in devising EU low carbon transport policies for cars and aviation. These sectors have no defined climate targets; people seem unwilling to drive or fly less, however environmentally motivated they are; the industries have, and have exercised, their power to lobby government policies framed as the human right to travel; aviation is still largely subsidized (probably as a result of substantial lobbying); and mobility is ingrained in social practices. They conclude that these inter-related transport taboos constitute a risk to decision makers who 'would be viewed as violators of norms and values'. Governments are reluctant to talk about the level of transport demand and are under pressure from the aviation and car industries lobbying for and pursuing technological innovations without subduing demand.

5.3.3.5 Economy-wide interactions

Finally, consumption-accounting reveals the interdependencies between economic sectors across countries. The impact of globalisation has resulted in increasingly complex and global supply chains, with different countries specialising in different products. Increasing consumption of a product in one country increases production in all sectors and countries which inputs to its supply chain. Chapter four identified two areas where policy effectiveness is weakened due to these interactions. Firstly, policies aimed at energy/ resource efficiency can lead to cost savings, which are spent on more of the same, or another consumption activity which embodies emissions, known as rebound effects. Secondly, a reduction in energy/ material demand from sectors in the EU ETS through efficiency measures reduces the carbon allowances those sectors require, which increases the number available for other activities. Having an allowance surplus lowers the carbon price, making it cheaper to pollute. Therefore, policies cannot be considered in isolation, and need to be designed as part of a policy package so as to offset any potential adverse consequences. However, the number and diffuse nature of actors involved in production-consumption linkages from a supply chain perspective makes supply chains complex to govern. Whilst polycentric systems of governance have shown to solve collective-action problems, this tends to be at a more localised level.

5.3.3.6 Summary

To summarise, whilst consumption policies in addition to technology installations and efficiency improvements are less technically limited, they require businesses and final consumers to adjust their seller and user practices. Reducing aggregate consumption is also at odds with economic growth objectives and will affect the income generation of some intermediate consumers more than others. However, there will always be 'losers' from any proposed policies which has shown in the case of the EU ETS to be prevented by strong lobbying and weak governance. Evidence on the costs and co-benefits of consumption policies need to be improved, and can be aided with the inclusion of broader sustainable development indicators in policy appraisals, to be attractive to energy and climate policy makers.

5.4 A pragmatic proposal

Currently international emissions accounting and mitigation policies are regulated and evaluated on a fully production-based approach, with a minority of voluntary reporting performed using consumption-based accounting. It is well understood that the current policies in place are not enough to reach the globally agreed two degree target, and some literature advocates the need to reduce consumption to meet the remaining emissions gap and reduce the risk of pathways dependant on technology-related uncertainties. Much of the more recent literature on global responsibility for emissions reductions suggests countries, particularly those with legally binding carbon targets, should not be allowed to meet those targets by shifting the emissions burden abroad. These two points are strong indications of the need to put policies in place to address emissions embodied in consumption, using consumption-based accounting to prioritise high emissions flows and assess the environmental potential of alternative trade and demand-related policies. Consumption accounting would provide a more comprehensive understanding of emissions progress and provide an evidence base to ensure the impact of consumption is not just transferred from one country to another. However, there is likely to be more political traction when referring to policies and practices that do not radically reframe the existing emissions monitoring, reporting and evaluation framework. Therefore, moving forward, I propose a middle ground option where national consumption accounting is mandatory yet does not replace the existing production inventory approach. National departments tasked with climate change should use these when devising and appraising policies to ensure consumption-related policies are considered alongside technology ones and that policies cannot reduce territorial emissions whilst transferring emissions abroad.

Consumption-related polices are not dependant on consumption accounting, and likewise the implementation of consumption accounting does not necessarily mean consumption policies will follow. However, making consumption-based emissions accounting mandatory would increase the incentive to reduce them and to implement consumption policies that offer new reduction opportunities which extend to imported emissions. This transition would require standardised accounting guidelines, open access to international production and trade data, appropriate models to enable policy assessments, and the compilation of evidence on different consumption-related policies; some of which are at least partly in place in many developed countries:

- In terms of data requirements the System of national Accounts (United Nations Statistics Division, 2016), the internationally agreed standard set of recommendations on how to compile measures of economic activity, is already a standard which measures how income originating in production, modified by taxes and transfers, flows to consumers, businesses, government and foreign nations and how they allocate income to consumption, saving and investment. This is the basis of data needed to measure consumption. Reported trade data between countries is not currently matched with reported national accounts. For example all imports reported by the UK are not matched exactly to all reported exports destined for the UK. International trade data would need to be reconciled with national accounts, and standardised in order for countries to report 'like-for-like' on their consumption. This would require a central data source such as an international monitoring agency (e.g. the OECD) to oversee data provision, which is already in place for a subset of countries (OECD, 2015). It would also be beneficial to maintain existing global input-output models that perform consumption accounting to be able to validate the data that all countries would be expected to agree upon.
- In terms of modelling, there would need to be a shift from cost-optimal engineering models to at least give similar weight to consumer and behaviour-related policy evidence. The UK Carbon Plan (HM Government, 2011) references evidence from three models (The DECC calculator; ESME; and UK MARKAL, the predecessor to UKTM) all with a foundation in engineering and based on future energy system costs. None consider embodied emissions or the different motivations behind changing consumer practices. For example, in UKTMs the level of final energy demand is determined exogenously and the profile of energy supply technologies is adjusted based on least cost to meet the pre-defined level of demand within an emissions constraint. Demand is therefore not seen as a means of reduction but it is assumed energy supply can adapt to meet the specified demand. Neither does UKTMs consider changing end-user technologies such as mode of transport (from private car to public transport or car-sharing) or buildings designed with less material inputs. Relying on such energy models means that resource consumption measures that target the use of materials and products, offering effective and complementary policies to address the remaining emissions gap, are currently underrepresented in the policy evidence base.
- With the data in place, more policy assessments of consumption-side measures over and above direct energy use from heating, travel and use of appliances, will be needed,

which consider emissions embodied in resources used along product supply chains and their disposal. There is also potentially more scope to target traded products indirectly through changing domestic consumption than to directly target traded products. In the introduction (section 1.1.3.4) I referenced a range of policies influencing consumption, some that exist in practice and others only in theory, from economic and regulatory trading schemes and product standards to information provision, voluntary agreements and non-climate related resource policies. The latter has some promise as resource efficiency is already a central EU agenda, within its Resource Efficiency Roadmap (EC, 2011) and Circular Economy Package (EC, 2015), which have strategies and policies addressing resource consumption in place, albeit these continue to focus on end-of-life strategies and not a reduction in resource use. Therefore, I would suggest that resource efficiency makes up a central pillar of climate change policies, taking advantage of the contribution resource efficiency can make to meeting climate targets.

A potential starting point to get consumption policies on the agenda is to do a cost benefit analysis of consumption-based measures which policy makers are familiar with. Whilst I have raised some drawbacks to relying purely on an economic case to select effective policies, in this case policy makers could at least have a like for like comparison of the different measures to compare with existing production-side ones. This would be interesting to see how consumption policies fair against production ones, and would be easier to attract the attention of policy makers.

However in addition, to be a cost-effective option research needs to frame what a reduction in consumption would look like for the economy and society. It is not yet clear how economic transactions in a more service-driven and less sales-driven economy would be priced. Reducing (UK) demand has been highlighted as being at odds with government objectives on economic growth, yet could have some co-benefits that are aligned with alternative economic, social and environmental indicators measuring progress. Reducing consumption does not automatically mean a reduction in spending as expenditure can be switched from buying products to leasing services, such as switching from private car ownership to car clubs. When there is an aggregate price reduction, literature on the rebound effect says that there needs to be a price adjustment so that the money saved is not used form other emissions-intensive purposes. Therefore prices will need to adjust in line with consumption policies without an alternative no-price option such as a cap on emissions actually aligned with a high probability of not exceeding 1.5 degrees.

Consumption policies tend to require a behavioural response. It will be important to get industry, businesses, governments and the public adopting different business practices and consumption behaviours. Policy mechanisms should be assessed for their social feasibility. For example, product lifetime extensions can be implemented via a number of policy mechanisms such as extended and transferable warrantees, product regulations specifying maximum resource weights or minimum usage, or changes in business practice to leasing products instead of selling final goods. Whilst all three could achieve the same outcome, one may be more acceptable to stakeholders, thereby increasing its implementation scope. Some policies will be easier to extend, for example standards which are part of the current policy landscape, whilst others warrant further attention, for example incentivising a change in business practice. Research needs to move beyond listing the potential barriers to uptake to resolving issues of implementation and aligning policies with a two degree or lower carbon budget. They also need to be evaluated in terms of their interactions and overlap with other policies to ensure they don't undermine existing policies, and to understand the most effective policy package to deliver reduction targets. Energy efficiency and consumer policies have the potential to both undermine the EU Emissions Trading Scheme (and probably other existing policies), and also be undermined by rebound effects. Therefore, policies must be complementary alongside decarbonisation and energy efficiency policies.

Input-output analyses identify actors at a very aggregated and coarse level, without identifying their role in the supply chain. Due to the supply chain nature of potential consumer interventions, methods need to advance the understanding of producer to consumer linkages in commodity supply chains. Enhancing the spatial resolution of supply chains would allow consideration of heterogeneous management practices, actors and governance systems, which will increase understanding of how to govern a diverse set of actors in a more coordinated way. Methods such as agent-based modelling can simulate the role of agents within a system, and how behaviours, and hence uptake, would change under different forms of governance. Co-evolutionary frameworks better understand the interactions of different actors, technologies and ecosystems to enable systematic analysis of influences on the development of consumer policies and changing consumer practices, including the conditions needed for change. Transitions frameworks help understand the conditions for transitioning from niche products and practices to the mainstream, and eventually becoming embedded in the meta-landscape. In particular, I would like to use a form of agent-based modelling as a next step to look at delivering resource consumption policies.

To summarise, the most important next stages of research to realise consumption-based policies in climate mitigation policy include a systemic detailed appraisal of their environmental, political and social feasibility, understood to be ingrained within a system characterised by certain social norms and governance architectures. The social and economic impacts of new user practices need to be more thoroughly investigated. Particularly within the UK there is some, albeit diminishing, political scope to support consumption-accounting as a middle ground mandatory option. Research needs to explore the potential of consumption-based measures beyond theory, to delivering change. This needs to be framed in light of post-Paris and IPCC budgets for a 1.5 degree future. Researchers must take some responsibility for its application, and work with governments to encourage its implementation.

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6 Appendix

Analysis 1: An integration of net imported emissions into climate change targets

6.1 Detailed scenario and projections

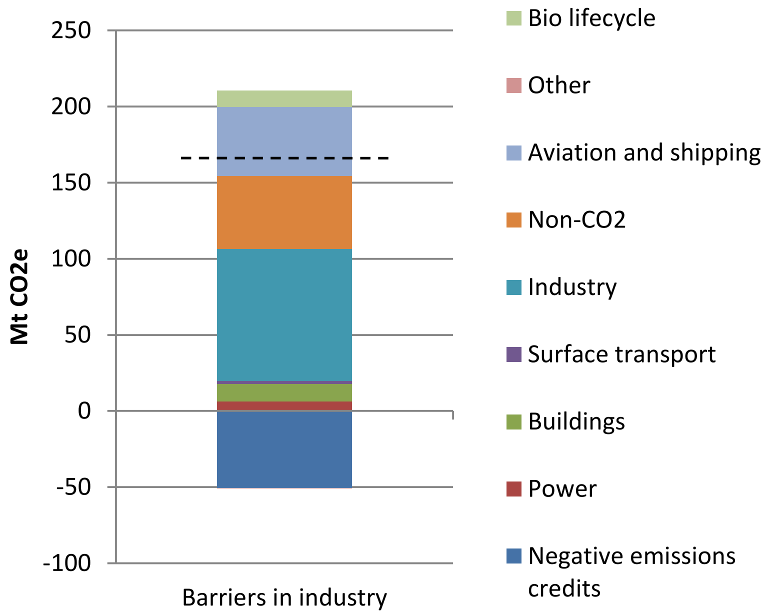
The scenarios were undertaken as part of a project funded in 2013 by the UK Committee on Climate Change who were investigating emissions associated with future UK consumption patterns, documented in the CCC's report *Reducing the UK's carbon footprint and managing competitiveness risks* (CCC, 2013).

Using input-output analysis, consumption emissions (F) are given by $F = f_x Ly$, where f_x is the direct carbon intensity of production sectors, *L* is the effect of trade transactions (known as the Leontief Inverse), and *y* is the volume and composition of final consumption. Each variable is projected from 2010 (the latest year of data available at the time of study) to 2050 using the following data sources and assumptions:

6.2 UK production emissions trajectory (f_{UK})

In line with UK legislated climate targets, UK production emissions are reduced 80% from 1990 levels by 2050 following the "Barriers in industry" scenario defined by the UK Committee on Climate Change (CCC) (pg. 46: CCC (2012)), which acknowledges there are some barriers to maximum deployment of abatement technologies. The CCC investigated the deployment of a range of technology abatement options for UK production sectors which are or are likely to become technologically feasible and cost-effective, with some smaller changes in consumer behaviour, to meet the 80% target. Core strategies include efficiency improvements, decarbonisation of power generation, extensive electrification of heat and surface transport and the use of bioenergy. Emissions remain relatively high in industry as there is limited application of CCS and no electrification (Figure 16). Greater success is achieved in other sectors, with transport, heat and power largely decarbonised (notwithstanding some residual gas use in power and heat), and all but the most challenging abatement options deployed to reduce non-CO_2 emissions. Aviation and shipping emissions are included in the end-point target. The dotted black horizontal line indicates net emissions of 160 Mt CO_2e. Net emissions for UK production (includes exports) reduce to 160 Mt CO_2e by 2050 from 805 Mt CO_2e[1] in 1990. These sector projections are disaggregated to 110 sectors as this is the level of detail in the input-output model.

Figure 16: UK production emissions by sector in 2050



The input-output model defines 110 economic sectors on the basis of Standard Industrial Classification (SIC) codes. The 'Barriers in industry' scenario for meeting the 2050 target in the Climate Change Act examines emissions reductions pathways in the key emitting sectors of the UK's economy: power generation, buildings and industry, surface transport, international aviation and shipping emissions, agriculture and waste. Emissions from this scenario are first attributed to the equivalent high level SIC sectors based on energy use statistics, which enabled us to separate surface transport emissions between services, transport and households (see Table 11).

[1] Production emissions include emissions from international aviation and shipping. Whilst these are not reported in the official UK territorial accounts they are included in the scenario to reduce UK emissions by 80%

Table 11: Mapping of high level UK production emissions classifications

High level SIC sectors	CCC production emission sectors
Agriculture & forestry	Agriculture & forestry emissions
Industry	Industry emissions
Power	Power emissions
Services	20% Surface transport emissions
	All non-residential buildings emissions
Transport	20% Surface transport emissions
	All International aviation & shipping emissions
Direct household transport	60% of Surface transport emissions
Direct household heat	Residential buildings emissions

Proportional analysis was used to disaggregate emissions by sector in Table 11 to the more detailed 110 SIC sectors in the input-output model (Table 12). This means that the proportion of emissions within high level sectors remain the same out to 2050. For example, if coal and lignite made up 5% of industry emissions in 2010, they make up the same proportion of industry emissions in 2050. This mapping was completed by the Committee on Climate Change.

Table 12: Mapping high level UK production emissions to disaggregated SIC sectors

SIC	Description	High level CCC sector allocation
1	Products of agriculture, hunting and related services	Agriculture & forestry
2	Products of forestry, logging and related services	Agriculture & forestry
3	Fish and other fishing products; aquaculture products; support services to fishing	Agriculture & forestry
4	Coal and lignite	Industry
5	Crude petroleum and natural gas & metal ores	Industry
6	Other mining and quarrying products	Industry
7	Mining support services	Industry
8	Preserved meat and meat products	Industry
9	Processed and preserved fish, crustaceans, molluscs, fruit and vegetables	Industry
10	Vegetable and animal oils and fats	Industry
11	Dairy products	Industry
12	Grain mill products, starches and starch products	Industry
13	Bakery and farinaceous products	Industry
14	Other food products	Industry

15	Prepared animal feeds	Industry
16	Alcoholic beverages	Industry
17	Soft drinks	Industry
18	Tobacco products	Industry
19	Textiles	Industry
20	Wearing apparel	Industry
21	Leather and related products	Industry
22	Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	Industry
23	Paper and paper products	Industry
24	Printing and recording services	Industry
25	Coke and refined petroleum products	Industry
26	Paints, varnishes and similar coatings, printing ink and mastics	Industry
27	Soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	Industry
28	Other chemical products	Industry
29	Industrial gases, inorganics and fertilisers (all inorganic chemicals) - 20.11/13/15	Industry
30	Petrochemicals - 20.14/16/17/60	Industry
31	Dyestuffs, agro-chemicals - 20.12/20	Industry
32	Basic pharmaceutical products and pharmaceutical preparations	Industry
33	Rubber and plastic products	Industry
34	Manufacture of cement, lime, plaster and articles of concrete, cement and plaster	Industry
35	Glass, refractory, clay, other porcelain and ceramic, stone and abrasive products - 23.1-4/7-9	Industry
36	Basic iron and steel	Industry
37	Other basic metals and casting	Industry
38	Weapons and ammunition	Industry
39	Fabricated metal products, excl. machinery and equipment and weapons & ammunition - 25.1-3/25.5-9	Industry
40	Computer, electronic and optical products	Industry
41	Electrical equipment	Industry
42	Machinery and equipment n.e.c.	Industry
43	Motor vehicles, trailers and semi-trailers	Industry

44	Ships and boats	Industry
45	Air and spacecraft and related machinery	Industry
46	Other transport equipment - 30.2/4/9	Industry
47	Furniture	Industry
48	Other manufactured goods	Industry
49	Repair and maintenance of ships and boats	Industry
50	Repair and maintenance of aircraft and spacecraft	Industry
51	Rest of repair; Installation - 33.11-14/17/19/20	Industry
52	Electricity, transmission and distribution	Power
53	Gas; distribution of gaseous fuels through mains; steam and air conditioning supply	Power
54	Natural water; water treatment and supply services	Industry
55	Sewerage services; sewage sludge	Industry
56	Waste collection, treatment and disposal services; materials recovery services	Industry
57	Remediation services and other waste management services	Industry
58	Buildings and building construction works	Industry
59	Constructions and construction works for civil engineering	Industry
60	Specialised construction works	Industry
61	Wholesale and retail trade and repair services of motor vehicles and motorcycles	Services
62	Wholesale trade services, except of motor vehicles and motorcycles	Services
63	Retail trade services, except of motor vehicles and motorcycles	Services
64	Rail transport services	Transport
65	Land transport services and transport services via pipelines, excluding rail transport	Transport
66	Water transport services	Transport
67	Air transport services	Transport
68	Warehousing and support services for transportation	Services
69	Postal and courier services	Services
70	Accommodation services	Services
71	Food and beverage serving services	Services
72	Publishing services	Services

73	Motion picture, video and TV programme production services, sound recording & music publishing	Services
74	Programming and broadcasting services	Services
75	Telecommunications services	Services
76	Computer programming, consultancy and related services	Services
77	Information services	Services
78	Financial services, except insurance and pension funding	Services
79	Insurance, reinsurance and pension funding services, except compulsory social security & Pension funding services	Services
80	Services auxiliary to financial services and insurance services	Services
81	Real estate services, excluding on a fee or contract basis and imputed rent	Services
82	Imputed rent services	Services
83	Real estate activities on a fee or contract basis	Services
84	Legal services	Services
85	Accounting, bookkeeping and auditing services; tax consulting services	Services
86	Services of head offices; management consulting services	Services
87	Architectural and engineering services; technical testing and analysis services	Services
88	Scientific research and development services	Services
89	Advertising and market research services	Services
90	Other professional, scientific and technical services	Services
91	Veterinary services	Services
92	Rental and leasing services	Services
93	Employment services	Services
94	Travel agency, tour operator and other reservation services and related services	Services
95	Security and investigation services	Services
96	Services to buildings and landscape	Services
97	Office administrative, office support and other business support services	Services
98	Public administration and defence services; compulsory social security services	Services
99	Education services	Services
100	Human health services	Services

101	Residential care services	Services
102	Social work services without accommodation	Services
103	Creative, arts and entertainment services	Services
104	Libraries, archives, museums and other cultural services	Services
105	Gambling and betting services	Services
106	Sports services and amusement and recreation services	Services
107	Services furnished by membership organisations	Services
108	Repair services of computers and personal and household goods	Services
109	Other personal services	Services
110	Services of households as employers of domestic personnel	Services

6.3 International production emissions trajectories ($f_{overseas}$)

This is where the two and four degree scenarios are distinguished. The IPCC Fifth assessment Report calculates that from 2011 global cumulative emissions cannot exceed around 1,000 Gt CO_2 by 2100 to remain within two degrees of warming (Stocker et al., 2013). If achieved, global emissions would reduce by 60% from 2010 to 2050 to 16 Gt CO_2. This requires carbon intensity improvements of 5 to 6% annually, achieved largely through energy efficiency, decarbonisation and electrification, and carbon capture and storage. Whilst there is international agreement under the UNFCCC to reduce emissions aligned with this objective, current emissions reductions pledged in the Cancun Agreements are so far only consistent with four degrees of temperature rise. Under this case global energy-related emissions will be 40 Gt CO_2 in 2050, similar to the level of global emissions in 2010. The International Energy Agency (International Energy Agency, 2012) has calculated how much emissions are released by which sectors in each country that is compatible with these two futures. UK emissions have been deducted so as not to double count them. As with the UK, the IEA projects emissions by high-level sectors and these have been disaggregated to 26 sectors to align with the sector detail in the input-output model. Not all greenhouse gases are given in the IEA analysis therefore emissions embodied in UK imports are measured as CO_2 only.

The input-output model defines 26 economic sectors for regions outside the UK. The IEA-ETP model explores pathways for reducing emissions in the following high-level sectors: Power generation, Industry (and other transformation), Transport, Residential and commercial buildings and Energy-related emissions from agriculture, fisheries, and other activities. The IEA provided emissions trajectories for the seven trading regions included in this analysis.

To map IEA emissions by sector to 2050 aligned with the Eora input-output classification residential emissions were excluded as these are not part of intermediate production industries that become embodied in products. Transport emissions associated with industry were calculated from transport emissions, which include private household transport that is not an intermediate production activity. Residential emissions from the IEA were subtracted from total household emissions in Eora which includes both housing and transport. This establishes the ratio of emissions for intermediate transport. Proportional analysis was used to disaggregate emissions trajectories for power, industry and a combined sector of agriculture, transport, and services to the more detailed 26 sectors in the input-output model (Table 13). This means that the proportion of emissions within high level sectors remain the same out to 2050. For example, if mining and quarrying made up 5% of industry emissions in 2010, they make up the same proportion of industry emissions in 2050. This mapping was completed by the Committee on Climate Change.

Table 13: Mapping high level global production emissions to disaggregated SIC sectors

No	Eora sector description	High level IEA sector allocation
1	Agriculture	Agriculture, non-private transport, non-res. buildings, services
2	Fishing	Agriculture, non-private transport, non-res. buildings, services
3	Mining and Quarrying	Industry
4	Food & Beverages	Industry
5	Textiles and Wearing Apparel	Industry
6	Wood and Paper	Industry
7	Petroleum, Chemical and Non-Metallic Mineral Products	Industry
8	Metal Products	Industry
9	Electrical and Machinery	Industry
10	Transport Equipment	Industry
11	Other Manufacturing	Industry
12	Recycling	Industry
13	Electricity, Gas and Water	Power
14	Construction	Industry
15	Maintenance and Repair	Industry
16	Wholesale Trade	Agriculture, non-private transport, non-res. buildings, services
17	Retail Trade	Agriculture, non-private transport, non-res. buildings, services
18	Hotels and Restaurants	Agriculture, non-private transport, non-res. buildings, services
19	Transport	Agriculture, non-private transport, non-res. buildings, services

20	Post and Telecommunications	Agriculture, non-private transport, non-res. buildings, services
21	Financial Intermediation and Business Activities	Agriculture, non-private transport, non-res. buildings, services
22	Public Administration	Agriculture, non-private transport, non-res. buildings, services
23	Education, Health and Other Services	Agriculture, non-private transport, non-res. buildings, services
24	Private Households	Agriculture, non-private transport, non-res. buildings, services
25	Others	N/A
26	Re-export & Re-import	N/A

6.4 Direct carbon intensities of production sectors (f_X)

Production emissions by sector are divided by its projected economic output. This describes the carbon intensity generated per unit (£1) of output of each sector. The Office for Budget Responsibility (OBR) projections were used to project UK annual economic growth rates and IMF and other sources were used to project economic output in the seven trading regions. China and India for example are anticipated to have strong annual growth nearing 10% by 2020, reducing gradually thereafter. The UK and OECD Europe are anticipated to experience more steady growth, reaching their yearly highest (2.7% and 2.8%) between 2021 and 2025. The proportion of a given sector to total economic output is assumed to remain the same to 2050 (i.e. a manufacturing-intensive economy is anticipated to remain a manufacturing-intensive economy).

6.5 Global trade transactions (L)

The Eora database developed at the University of Sydney has the world's largest and most detailed map of the structure of the global economy in the form of annual multi-region input-out (MRIO) tables from 1990 to 2011[2] (Lenzen et al., 2012, Lenzen et al., 2013). The economic structure is represented by monetary transactions between a homogenous 26 industry sector classification for 187 countries, which has been aggregated to the UK and 7 trade regions: OECD Europe (excluding UK), non-European OECD, Russia, China, India, Rest of Asia and Rest of World. Both domestic transactions between sectors within countries and their imports and exports sales with sectors in other regions capture the complexity of global supply chains. Domestic, import and export transactions for the UK in Eora have been reconciled with the more detailed

[2] In Lenzen et al. (2012) tables were available to 2009, and 1 further year have been developed at the time of research

110 sector classification from supply and use tables in UK National Accounts. This is consistent with the sector breakdown of the UK consumption-based emissions accounts published by the UK Department for Food and Rural Affairs (Defra, 2015).

The transactions matrix representing trade between 292 sectors[3] is kept constant (i.e. the manufacture of goods in 2050 will require the same mix of inputs as 2010; however the carbon efficiency of production and demand for goods will change). We recognise that there will be changes in the production structure, however modelling approaches to 2050 would fail to predict the complexity of 292 sectors interacting. Keeping the detail at this level provides further insights into the potential breakdown of future emissions, and production structure changes in the last 20 years have shown to contribute only marginal changes in the UK's carbon footprint compared to changes driven by increased final demand and carbon intensity improvements (Baiocchi and Minx, 2010b).

6.6 UK final demand (*y*)

Final demand is recorded as final consumer spending on product groups determined as the finished goods and services produced by each production sector. Final demand categories are those that do not sell goods: households, government and Not for Profit Institutions Serving Households (NPISH). UK final consumers purchase products both domestically and directly from overseas. It is assumed that the level of final demand grows in line with trends over the past 20 years and that this growth is met increasingly by imports. Demand for imported products increase at the average annual growth rate of the past 20 years (2.75%) informed by the 20 year time series in Eora (MRIO), and growth in domestic demand for domestic consumption equates to an average 1.9% growth per annum. The import share of GDP would increase to around 40% by 2050. 50% of this share is from emerging economies, compared to 29% in 2010. Additionally expenditure on fossil fuels is reduced and redistributed proportionally to all other product groups.

Analysis 2: National climate policy implications of mitigating embodied energy system emissions

6.7 Method summary

This section provides a summary of the method to derive indirect emissions factors. Refer to (Daly et al., 2015) for full details of the method, data sources and modelling assumptions.

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[3] UK 110 sectors and 7 trading regions represented by 26 sectors each

Indirect emissions factors (IEFs) are generated, which measure the physical output of CO_2 emissions on the basis of activity of different economic sectors (CO_2/£). This is done similar to Nansai (2012) using environmentally-extended multi-regional input-output (EE-MRIO) analysis (Miller and Blair, 2009), which is a peer reviewed method for calculating consumption-based emissions for the purpose of global sustainability analysis (Wiedmann, 2009). The MRIO model was selected for its system completeness and ability to account for traded emissions i.e. it captures the full supply-chain emissions of products depending on the emission intensity of generation in the country of production. System completeness does come at the expense of detail as sectors are highly aggregated, however the specific model selected has a disaggregated energy sector (Wiedmann et al., 2011). In the EE-MRIO model, emissions directly emitted by industry sectors are reallocated through complex supply chains to the finished products in which they become embodied. National consumption-based emissions are the sum of embodied carbon along these complex supply chains to meet absolute demand for finished products.

IEFs are generated for each technology and fuel in the energy supply sectors of UKTM by allocating each element of UKTM to a sector in EE-MRIO. The EE-MRIO model generates emission factors for the whole lifecycle of economic activity, and since UKTM describes several stages of fuel production, double-counting is identified and removed. We convert this for UKTM using the capital cost of technologies in £M per unit of capacity (MW for power generation; PJ_a for other technologies and infrastructure) divided by the technology lifetime, to generate IEFs in terms of PJ_a and gCO_2/MW for installed capacity, and gCO_2/PJ for fuel imports and extraction.

Because EE-MRIO describes two regions (UK and the rest of the world), the IEFs distinguish between emissions produced domestically and those generated abroad. Assumptions regarding the future emissions intensities for domestic and rest of world economic activity and the import dependency of the UK economy are developed.

Indirect emissions, from both UK and overseas industry, were added to each stage of the energy system up to the point of use (i.e. demand technologies). The model integration captures the embodied emissions coming into the UK as well as those going out. If emissions embodied in imports are more than those embodied in exports there is a net positive indirect emissions budget.

Analysis 3: Addressing globally traded emissions through domestic consumption policies

6.8 Emissions accounting principles

Under the UNFCCC, countries submit annual greenhouse gas emissions inventories from a territorial perspective, with a two year time lag before publication. If the territorial emissions from the 28 countries that make up the European Union (EU) are summed, this equals the emissions released directly by sources within EU territory. In 2012 these were reported as 4,544 Mt CO_2e, with aviation and shipping recorded as a memorandum, at 281 Mt CO_2e (European Environment Agency, 2014a). A production accounting approach is similar, however instead of summing emissions occurring within national territories, it sums emissions the emissions produced by all institutional units resident in the economy that contribute to the country/ regions' GDP (Peters, 2008). For example, aviation emissions are attributed to the country registered as operating the flights. Consumption-based emissions are equal to production emissions plus emissions embodied in imports minus emissions embodied in exports (Peters and Hertwich, 2008a). Exported emissions are attributed to the destination country. Using input-output analysis we calculate EU consumption emissions as 7,222 Mt CO_2e in 2007, the latest year available using the EXIOIBASE v2.2.0 MRIO database. For comparison, production emissions were 5,187 Mt in 2007.

Kander et al. (2015) suggest that a technology-adjusted consumption-based emissions account is most adequate to measure climate mitigation progress. They argue that production-based accounting enables countries to reduce emissions within their territories whilst compensating by shifting carbon-intensive production abroad and taking a consumption approach does not credit countries for cleaning up their export production. A reduction in the carbon intensity of exports would be attributed to the country for which the exports are destined. Kander et al. propose a technology adjustment is applied to exports. Instead of subtracting exported emissions based on the carbon intensity of the exporting region, export-related emissions are subtracted based on the average carbon intensity for the relevant sector on the world market. In other words, if EU exports are less carbon intensive than the world average, the emissions subtracted from the technology-adjusted account would be greater than the pure consumption-based one, attributing less total emissions to the EU. However, we argue that this ignores the historic processes of industrialisation that by-and-large enabled developed countries to specialise in low carbon activities, which is balanced by material and carbon intensive production in industrialising countries. Therefore, in line with attempts to present a fairness-based climate regime (Raupach et al., 2014, Grasso and Roberts, 2014, Steininger et al., 2014) we do not adjust for the carbon intensity of EU exports.

6.9 Emissions-extended multi-region input-output analysis (EE-MRIOA)

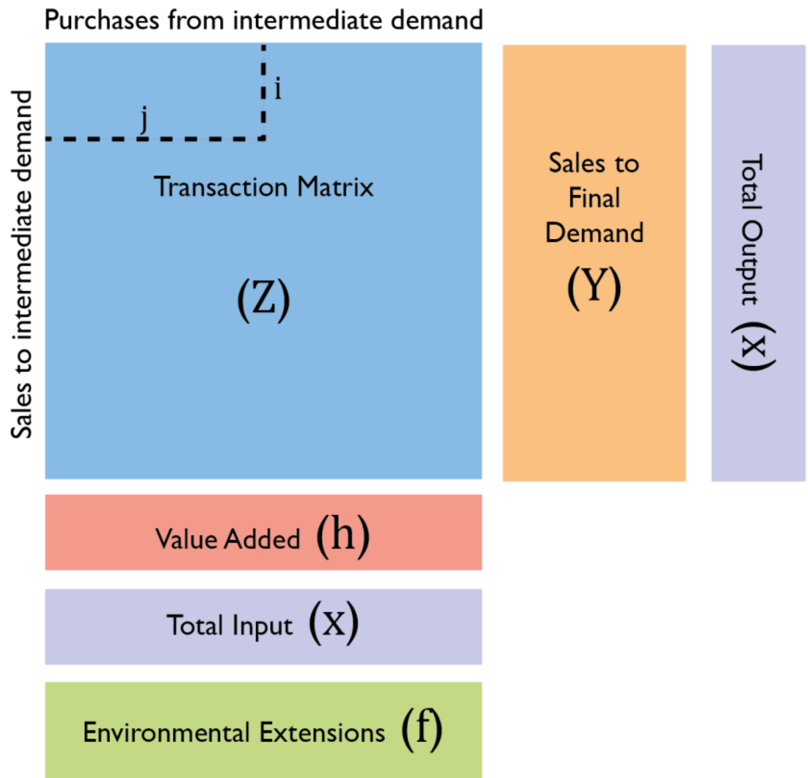
At the macro level EE-MRIOA is a well-established method to re-allocate emissions associated with production activities to the final demand of products i.e. consumption-based emissions (Wiedmann, 2009). In the 1930s Wassily Leontief developed a series of linear equations that describe how producing a single unit of final demand requires inputs from all sectors of the economy. The economic framework was later extended to include a vector of 'externalities' which measured tonnes of pollution per unit of output for each industrial sector (e.g. CO_2/ £).

The different sectors of an economy not only require natural resources in order to produce different goods and services, but they also generate several by-products (e.g. pollution and waste) during their production processes. Calculations could then determine how pollution originating from producing sectors could be reallocated to the final users of goods and services.

6.9.1 Input-Output (IO) Calculations

Consider a transactions matrix **Z** (**Figure 17**), showing sales by each sector (rows) and the purchases by each sector (columns). Reading across a row reveals which other sectors a single industry sells to and reading down a column reveals who a single sector buys from in order to make its product output. A single element, $\mathbf{z_{ij}}$, within $\mathbf{Z}$ represents the contributions from the i[th] supplying sector to the j[th] producing sector in an economy. The $\mathbf{Z}$ matrix is in monetary units.

Figure 17: Components used for environmentally-extended input-output analysis



Reading across the table, the total output ($\mathbf{x_i}$) of a particular sector can be expressed as:

$$\mathbf{x_{i=}z_{i1}} + \mathbf{z_{i2}} + \cdots + \mathbf{z_{in}} + \mathbf{y_i} \qquad (1)$$

where $\mathbf{y_i}$ is the final demand for that product produced by the particular sector. The IO framework shows that the total output of a sector is the sum of its intermediate and final demand. Similarly if a column of the IO table is considered, the total input of a sector is the sum of its intermediate demand and value added in profits and wages ($\mathbf{h}$).

If each element, $\mathbf{z_{ij}}$, along row i is divided by the output $\mathbf{x_j}$, associated with the corresponding column j it is found in, then each element in $\mathbf{Z}$ can be replaced with:

$$\mathbf{a_{ij}} = \frac{\mathbf{z_{ij}}}{\mathbf{x_j}} \tag{2}$$

forming a new matrix $\mathbf{A}$, known as the direct requirements matrix. Element $\mathbf{a_{ij}}$ is therefore the input as a proportion of all the inputs in the production recipe of that product.

(2) can be re-written as:

$$\mathbf{z_{ij}} = \mathbf{a_{ij}x_j} \tag{3}$$

Substituting for (3) in (1) forms:

$$\mathbf{x_{i=}a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n + y_i} \tag{4}$$

Which, in matrix notation is $+\,\mathbf{y}$. Solving for $\mathbf{x}$ gives:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{5}$$

(5) is known as the Leontief equation and describes output $\mathbf{x}$ as a function of final demand $\mathbf{y}$. $\mathbf{I}$ is the identity matrix, and $\mathbf{A}$ shows the inter-industry requirements. $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse (denoted hereafter as $\mathbf{L}$). (5) can be re-written as:

$$\mathbf{x} = \mathbf{Ly} \tag{6}$$

Consider a row vector $\mathbf{f}$ of annual greenhouse gas (GHG) emissions emitted by each production sector. It is possible to calculate emissions intensity ($\mathbf{e}$) by dividing the total emissions of each sector by total sector output ($\mathbf{x}$).

$$\mathbf{e} = \mathbf{f}\hat{\mathbf{x}}^{-1} \tag{7}$$

In other words, $\mathbf{e}$ is the coefficient vector representing emissions per unit of output.

Multiplying both sides of (6) by $\mathbf{e}$ gives:

$$\mathbf{ex} = \mathbf{eLy} \tag{8}$$

and from (7) we simplify (8) to:

$$\mathbf{f} = \mathbf{eLy} \tag{9}$$

However, we need the result ($\mathbf{f}$) as a flow matrix ($\mathbf{Q}$), showing the source sector and region of emissions embodied in all products, and so we use the diagonalised $\hat{\mathbf{e}}$ and $\hat{\mathbf{y}}$:

$$\mathbf{Q} = \hat{\mathbf{e}}\mathbf{L}\hat{\mathbf{y}} \tag{10}$$

$\mathbf{Q}$ is the consumption based emissions account calculated by pre-multiplying $\mathbf{L}$ by emissions per unit of output and post-multiplying by final demand. Emissions are reallocated from production sectors to final products.

6.9.2 Data sources

We use the 2007 Symmetric EXIOBASE v2.2.0 database (Tukker et al., 2013) representing 163 production sectors and product groups, and 7 final consumers, aggregated from 48 countries/ regions to 3 regions: the EU, non-EU Annex I countries and non-Annex countries. We distinguish between imports from Annex I and non-Annex I countries, as Annex I have existing quantified emissions reductions targets and whilst outside the EU ETS, they are being addressed by an emissions cap. This is expected to change as countries prepare their intended nationally determined contributions (INDCs) to climate actions to be negotiated at the 2015 UNFCCC climate summit. Only final demand by EU consumers is considered i.e. we exclude final demand outside the EU. We use the greenhouse gas emissions extension. The results matrix shows the sector and regional source of emissions embodied in 163 sectors across 3 regions. The 163 sectors are aggregated into 6 high-level sectors for Figure 12 in chapter 4, listed in **Table 14**. Operational emissions released directly by households for heating and travel sit outside the IO database as they do not flow through an intermediate sector. Operational EU emissions are also sourced from the EXIOBASE v2.2.0 database (Tukker 2013), and only the embodied emissions are calculated using EE-MRIOA.

Table 14: Results sectors and aggregation

Sector no.	Sector name	Aggregation
0	Cultivation of paddy rice	Agriculture
1	Cultivation of wheat	Agriculture
2	Cultivation of cereal grains nec	Agriculture
3	Cultivation of vegetables, fruit, nuts	Agriculture
4	Cultivation of oil seeds	Agriculture
5	Cultivation of sugar cane, sugar beet	Agriculture
6	Cultivation of plant-based fibers	Agriculture
7	Cultivation of crops nec	Agriculture
8	Cattle farming	Agriculture
9	Pigs farming	Agriculture
10	Poultry farming	Agriculture
11	Meat animals nec	Agriculture

12	Animal products nec	Agriculture
13	Raw milk	Agriculture
14	Wool, silk-worm cocoons	Agriculture
15	Manure treatment (conventional), storage and land application	Agriculture
16	Manure treatment (biogas), storage and land application	Agriculture
17	Forestry, logging and related service activities	Agriculture
18	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing	Agriculture
19	Mining of coal and lignite; extraction of peat	Prim. materials
20	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	Prim. materials
21	Extraction of natural gas and services related to natural gas extraction, excluding surveying	Prim. materials
22	Extraction, liquefaction, and regasification of other petroleum and gaseous materials	Prim. materials
23	Mining of uranium and thorium ores	Prim. materials
24	Mining of iron ores	Prim. materials
25	Mining of copper ores and concentrates	Prim. materials
26	Mining of nickel ores and concentrates	Prim. materials
27	Mining of aluminium ores and concentrates	Prim. materials
28	Mining of precious metal ores and concentrates	Prim. materials
29	Mining of lead, zinc and tin ores and concentrates	Prim. materials
30	Mining of other non-ferrous metal ores and concentrates	Prim. materials
31	Quarrying of stone	Prim. materials
32	Quarrying of sand and clay	Prim. materials
33	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.	Prim. materials
34	Processing of meat cattle	Agriculture
35	Processing of meat pigs	Agriculture
36	Processing of meat poultry	Agriculture
37	Production of meat products nec	Agriculture
38	Processing vegetable oils and fats	Agriculture
39	Processing of dairy products	Agriculture
40	Processed rice	Agriculture

41	Sugar refining	Agriculture
42	Processing of Food products nec	Agriculture
43	Manufacture of beverages	Agriculture
44	Manufacture of fish products	Agriculture
45	Manufacture of tobacco products	Agriculture
46	Manufacture of textiles	Prim. materials
47	Manufacture of wearing apparel; dressing and dyeing of fur	Prim. materials
48	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear	Prim. materials
49	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	Prim. materials
50	Re-processing of secondary wood material into new wood material	Prim. materials
51	Pulp	Prim. materials
52	Re-processing of secondary paper into new pulp	Prim. materials
53	Paper	Prim. materials
54	Publishing, printing and reproduction of recorded media	Prim. materials
55	Manufacture of coke oven products	Prim. materials
56	Petroleum Refinery	Prim. materials
57	Processing of nuclear fuel	Prim. materials
58	Plastics, basic	Prim. materials
59	Re-processing of secondary plastic into new plastic	Prim. materials
60	N-fertiliser	Prim. materials
61	P- and other fertiliser	Prim. materials
62	Chemicals nec	Prim. materials
63	Manufacture of rubber and plastic products	Prim. materials
64	Manufacture of glass and glass products	Prim. materials
65	Re-processing of secondary glass into new glass	Prim. materials
66	Manufacture of ceramic goods	Prim. materials
67	Manufacture of bricks, tiles and construction products, in baked clay	Prim. materials
68	Manufacture of cement, lime and plaster	Prim. materials
69	Re-processing of ash into clinker	Prim. materials

70	Manufacture of other non-metallic mineral products n.e.c.	Prim. materials
71	Manufacture of basic iron and steel and of ferro-alloys and first products thereof	Prim. materials
72	Re-processing of secondary steel into new steel	Prim. materials
73	Precious metals production	Prim. materials
74	Re-processing of secondary preciuos metals into new preciuos metals	Prim. materials
75	Aluminium production	Prim. materials
76	Re-processing of secondary aluminium into new aluminium	Prim. materials
77	Lead, zinc and tin production	Prim. materials
78	Re-processing of secondary lead into new lead	Prim. materials
79	Copper production	Prim. materials
80	Re-processing of secondary copper into new copper	Prim. materials
81	Other non-ferrous metal production	Prim. materials
82	Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	Prim. materials
83	Casting of metals	Prim. materials
84	Manufacture of fabricated metal products, except machinery and equipment	Manuf. goods
85	Manufacture of machinery and equipment n.e.c.	Manuf. goods
86	Manufacture of office machinery and computers	Manuf. goods
87	Manufacture of electrical machinery and apparatus n.e.c.	Manuf. goods
88	Manufacture of radio, television and communication equipment and apparatus	Manuf. goods
89	Manufacture of medical, precision and optical instruments, watches and clocks	Manuf. goods
90	Manufacture of motor vehicles, trailers and semi-trailers	Manuf. goods
91	Manufacture of other transport equipment	Manuf. goods
92	Manufacture of furniture; manufacturing n.e.c.	Manuf. goods
93	Recycling of waste and scrap	Manuf. goods
94	Recycling of bottles by direct reuse	Manuf. goods
95	Production of electricity by coal	Power
96	Production of electricity by gas	Power
97	Production of electricity by nuclear	Power

98	Production of electricity by hydro	Power
99	Production of electricity by wind	Power
100	Production of electricity by petroleum and other oil derivatives	Power
101	Production of electricity by biomass and waste	Power
102	Production of electricity by solar photovoltaic	Power
103	Production of electricity by solar thermal	Power
104	Production of electricity by tide, wave, ocean	Power
105	Production of electricity by Geothermal	Power
106	Production of electricity nec	Power
107	Transmission of electricity	Power
108	Distribution and trade of electricity	Power
109	Manufacture of gas; distribution of gaseous fuels through mains	Prim. materials
110	Steam and hot water supply	Prim. materials
111	Collection, purification and distribution of water	Prim. materials
112	Construction	Manuf. goods
113	Re-processing of secondary construction material into aggregates	Manuf. goods
114	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessories	Transport
115	Retail sale of automotive fuel	Transport
116	Wholesale trade and commission trade, except of motor vehicles and motorcycles	Services
117	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods	Services
118	Hotels and restaurants	Services
119	Transport via railways	Transport
120	Other land transport	Transport
121	Transport via pipelines	Transport
122	Sea and coastal water transport	Transport
123	Inland water transport	Transport
124	Air transport	Transport
125	Supporting and auxiliary transport activities; activities of travel agencies	Transport
126	Post and telecommunications	Services

127	Financial intermediation, except insurance and pension funding	Services
128	Insurance and pension funding, except compulsory social security	Services
129	Activities auxiliary to financial intermediation	Services
130	Real estate activities	Services
131	Renting of machinery and equipment without operator and of personal and household goods	Services
132	Computer and related activities	Services
133	Research and development	Services
134	Other business activities	Services
135	Public administration and defence; compulsory social security	Services
136	Education	Services
137	Health and social work	Services
138	Incineration of waste: Food	Manuf. goods
139	Incineration of waste: Paper	Manuf. goods
140	Incineration of waste: Plastic	Manuf. goods
141	Incineration of waste: Metals and Inert materials	Manuf. goods
142	Incineration of waste: Textiles	Manuf. goods
143	Incineration of waste: Wood	Manuf. goods
144	Incineration of waste: Oil/Hazardous waste	Manuf. goods
145	Biogasification of food waste, incl. land application	Manuf. goods
146	Biogasification of paper, incl. land application	Manuf. goods
147	Biogasification of sewage slugde, incl. land application	Manuf. goods
148	Composting of food waste, incl. land application	Manuf. goods
149	Composting of paper and wood, incl. land application	Manuf. goods
150	Waste water treatment, food	Manuf. goods
151	Waste water treatment, other	Manuf. goods
152	Landfill of waste: Food	Manuf. goods
153	Landfill of waste: Paper	Manuf. goods
154	Landfill of waste: Plastic	Manuf. goods
155	Landfill of waste: Inert/metal/hazardous	Manuf. goods
156	Landfill of waste: Textiles	Manuf. goods
157	Landfill of waste: Wood	Manuf. goods
158	Activities of membership organisation n.e.c.	Services

159	Recreational, cultural and sporting activities	Services
160	Other service activities	Services
161	Private households with employed persons	Services
162	Extra-territorial organizations and bodies	Services

6.9.3 Data validation

The choice of data used has implications for the results. In the last five years, several MRIO databases with an emissions extension have been developed described in Table 15. Limitations in the availability, consistency and quality of global trade data has meant tables are constructed using various approaches (Inomata and Owen, 2014). The MRIO databases differ in their geographical, sectoral and temporal coverage. Eora has the longest annual time series from 1990 to 2012 and the largest geographical scope covering 186 world regions. EXIOBASE uses the most detailed sector classification, displaying each region's economy in 163 production sectors.

Table 15: EE-MRIO models

Model	Sector coverage	Country coverage	Years available	Potential updates	Reference(s)
Eora	Varies by country from 26 to 515 sectors[4]	187	1990 – 2012	Annual updates with 2 year time lag	(Lenzen et al., 2012, Lenzen et al., 2013)
GTAP	57	129 (yr '07); 113 (yr '04); 87 (yr '01)	2001, 2004, 2007	3 year intervals with a 4 year time lag	(Narayanan et al., 2012, Peters et al., 2011)
EXIOBASE	163	44 (EU27, 16 others + ROW)	2000, 2007	Funding dependent	(Tukker et al., 2013, Wood et al., 2015)
WIOD	35 industries, 59 products	41 (27 EU, 13 others + RoW)	1995 – 2011	Funding dependent	(Dietzenbacher et al., 2013)

We selected to use the Exiobase (v2.2.0) MRIO model as it has the greatest sector disaggregation. This gives us the greatest scope to isolate material and product groups more readily, and sectors that are capped within the EU ETS. Table 16 compares the production and consumption emissions of different MRIO models. We also compare the original Exiobase results with our aggregated 3 region model. Consumption emissions in the aggregated model are within 1.5% of the original 48 region model.

[4] The original database has heterogeneous country sector classification systems, however a harmonised 26 sector model is available

Table 16: Comparison of greenhouse gas emissions data across MRIO models for 2007, unless specified otherwise

MRIO database/ project	Production emissions (Mt CO_2e)	Consumption emissions (Mt CO_2e)
EXIOBASE v2.2.0 (3 region)	5213	7256
EXIOBASE v2.2.0 (original)	5213	7369
Eora	5184	7369
Eureapa	5093 [2004]	6568 [2004]
Global carbon atlas	4028 [only CO_2]	5120 [only CO_2]
WIOD	5246	6867

Understanding uncertainties in the data gives an indication of the robustness of outcomes (Inomata and Owen, 2014) for use in policy making. Environmentally extended-MRIO analysis relies on the compilation of secondary economic, environmental and trade data into a MRIO framework. As shown by Peters et al. (2012a) different results across different models and studies can be attributed to the use of different production emissions data sources, different definitions of consumption and different economic and trade structures (supported by (Lenzen et al., 2010, Wiedmann et al., 2008, Wilting, 2012)).There are many ways in which the data can be assembled and adjusted (Inomata and Owen, 2014) and each alteration to the original source data introduces a layer of uncertainty. National economic data needs to be converted into a common currency and monetary transactions converted into basic prices. This requires price conversion statistics and taxes and subsidies to be re-distributed from a product to a value added sector. Where national data is missing, estimations are required such as the use of a representative average. MRIO tables must also adhere to a number of properties such as inputs must equal outputs and the sum of value added must equal the sum of the final demand. If these conditions are not met in the raw data, then the table is subjected to a number of balancing iterations until a table is produced that satisfies these constraints. Balancing methods vary and there are numerous techniques for table construction which leads to uncertainty in the final result.

In addition, the aggregation of economic sectors introduces uncertainty. Firms are grouped into broader economic sectors, each representing a weighted average of the characteristics of the firms within them (Steen-Olsen et al., 2014). Steen-Olsen et al. (2014) show that this is more of a problem for environmental analyses, as industries within a sector can exhibit different emissions profiles with an order of magnitude difference. For example, a carbon intensity is often applied to the agricultural sector when calculating consumption emissions. This aggregated sector includes a wide range of crops, animals, practices and so forth. However, cattle farming are considerably more carbon intensive than other types of agriculture. The choice of aggregation can therefore lead to different impact results. Grouping data together that exhibit very different emission intensities will lead to calculations containing more uncertainty.

In a comparison of the main databases, Owen et al. (2014) find that differences in national consumption emissions accounts across the models are largely explained by differences in total global emissions from different data sources, differences in the trade structures, and differences in total final demand. (Peters et al., 2012a) found that consumption-based emissions are broadly consistent across studies and MRIO databases, despite some differences in the model compilation, and that the difference didn't necessarily translate into uncertainty but were a result of several data sources and definitions of consumption. Variation in the territorial emissions accounts, and the attribution of these emissions to countries and sectors, was found to be much larger than the variation in economic and trade input data. Transport and energy intensive sectors exhibited the most variation in results along with small trade dependant countries and countries with poor data quality.

6.9.4 Isolating the emissions associated with energy-using products

We calculate the total emissions embodied in products regulated by existing EU directives, which currently focus on energy, and not resource, efficiency. This measures the maximum reach of emissions of adopting resource efficiency standards that address the fully supply chain inputs of products. At EU level, the Energy Efficiency Directive, the Ecodesign Directive, and the Energy Performance of Buildings Directive are the main elements of energy efficiency policy, and we include obligatory vehicle emissions standards. The general energy efficiency targets do not relate to a specific product(s) and therefore we investigate the following:

- The Ecodesign Directive - sets design requirements for energy-related products e.g. televisions, washing machines and electric motors.
- Energy Performance of Buildings Directive - aims at improving energy efficiency in the building sector, both for the existing building stock as well as for the newly-constructed buildings.
- Obligatory vehicle emissions standards - EU Regulation No 443/2009 sets an average CO_2 emissions target for new passenger cars and light commercial vehicles, getting tighter with time.

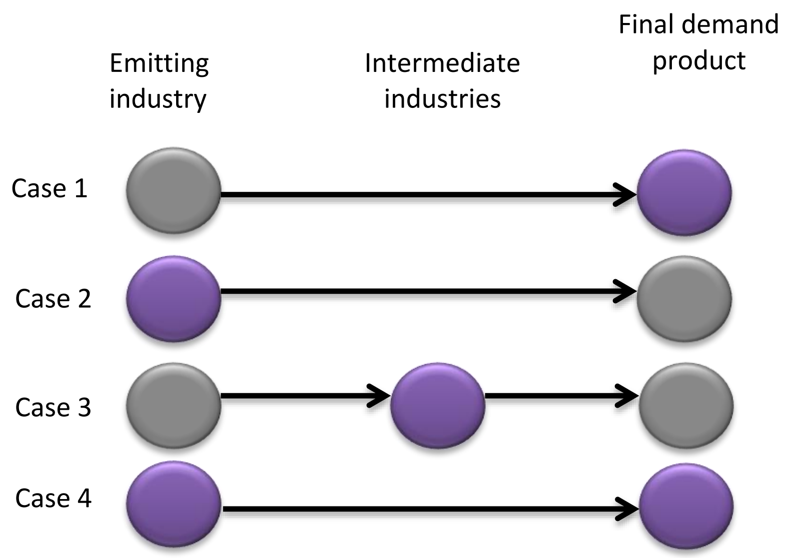
Each energy-using product group captured by the three EU directives are assigned a representative sector(s) in Exiobase, shown in Table 17. The embodied greenhouse gas emissions associated with both intermediate and final demand are calculated. This section explains how to use input-output analysis to identify the sum of the emissions flows that are associated with products using the example of vehicles. The same logic applies for buildings and appliances.

Table 17: Product mapping

Energy-using products captured by EU directives	Exiobase production sector(s)
Vehicles	Manufacture of motor vehicles, trailers and semi-trailers
Buildings	Construction
Appliances	Manufacture of office machinery and computers; Manufacture of electrical machinery and apparatus n.e.c.; Manufacture of radio, television and communication equipment and apparatus

The supply chain emissions associated with vehicles can take one of four forms (see Figure 18). Case 1 is the emissions associated with any industry that ends up embodied in a vehicle purchased by an EU final consumer, e.g. emissions from the steel industry that make a car bought by a household. Case 2 is the emissions associated with the vehicle industry that ends up in a final demand product, e.g. the on-site emissions from a car making factory and the car is then bought by a delivery service which is used by a household. Case 3 is the emissions associated with any supply chain that involves the vehicle sector, e.g. the emissions associated with the steel industry that go into a car used for delivery services bought by a household. Case 4 are emissions associated with an industry that makes a product that goes directly to final demand without being part of any intermediate stages. E.g. emissions associated with a vehicle factory making cars bought by households. It is argued that EU resource efficiency policy on vehicles will reduce the emissions in each of the four cases.

Figure 18: Supply chain emissions associated with vehicles (purple represents vehicles and grey represents any other industry)



Let $\mathbf{Z}$ be the MRIO table containing three regions (European Union (EU) and Annex I and non-Annex I countries) and 163 industrial sectors and $\mathbf{A}$ is the corresponding direct requirements matrix. To calculate the emissions that are associated with any supply chain involving vehicles that are a result of EU final demand we first calculate $\mathbf{Q_{EU}} = \mathbf{eLy_{EU}}$, the EU consumption-based account. We next calculate $\mathbf{Q^0_{EU}}$**,** the EU consumption-based account if there were no flows involving vehicles. The emissions associated with any supply chain involving vehicles that result from EU final demand is $\mathbf{Q^v_{EU}}$, which is the difference between $\mathbf{Q_{EU}}$ and $\mathbf{Q^0_{EU}}$. However, this only captures emissions that are involved in a flow between one industry and another—i.e. cases 1 to 3 from Figure 18. Those emissions that go directly from the vehicle sector to final demand of vehicles (case 4) need to also be included in $\mathbf{Q^v_{EU}}$. These 'direct path' emissions are denoted $\mathbf{f^v}$. Thus

$$\mathbf{Q^v_{EU}} = \mathbf{Q_{EU}} - \mathbf{Q^0_{EU}} + \mathbf{f^v} \tag{11}$$

We next discuss how to isolate the individual parts of equation 11, starting with $\mathbf{f^v}$, the 'direct paths'.

Let M be the set of 163 industrial sectors denoted 1 to m and including sector v, which is the vehicles sector.

$$\{M \mid M \in \mathbb{N}_1, M = 1,2, \dots v, \dots, m\} \tag{12}$$

Let N be the set of regions drawn from numbers 1 to n and including region k representing the EU.

$$\{N \mid N \in \mathbb{N}_1, N = 1,2, \dots, k, \dots, n\} \tag{13}$$

The dimensions of $\mathbf{Z}$ are $mn \times mn$, where i represents the set of row numbers from 1 to mn and j represents the set of column numbers from 1 to mn. The dimensions of $\mathbf{y}$ are $mn \times n$. In this example, there is only a single demand category per country. The final demand has been aggregated.

$$\{i \mid i \in \mathbb{N}_1, i = 1,2, \dots, mn\} \tag{14}$$

$$\{j \mid j \in \mathbb{N}_1, j = 1,2, \dots, mn\} \tag{15}$$

Let i^0 be a subset of i such that it contains those row elements that represent the vehicle sector from the EU.

$$\{i^0 \subset i \mid i^0 = v + (k-1)m\} \tag{16}$$

Let j^0 be a subset of j such that it only contains those column elements that represent the EU vehicle sectors.

$$\{j^0 \subset j | \, j^0 = v + (k-1)m\} \tag{17}$$

To calculate the sum of the 'direct paths', $\mathbf{f^v}$, we first find the direct EU emissions emitted to satisfy total EU final demand for vehicle products. To do this we multiply only those elements in $\mathbf{y}$ that represent EU final demand for vehicles with the corresponding EU vehicle emissions intensity element from $\mathbf{e}$. The simplest way of achieive this is to generate a new final demand matrix $\mathbf{y^0}$ containing zeros in all cells except the EU final demand for EU vehicles. The non-zero element will be in the cell in position $(v + (k-1)m, k)$.

Element y^0_{in} from the matrix $\mathbf{y^0}$ is zero when i is not in the set of i^0 and n is not equal to k. Otherwise, y^0_{in} is the same as y_{in}.

$$\begin{Bmatrix} y^0_{ij} = y_{ij} \ \leftrightarrow i \in i^0 \cap n = k \\ y^0_{in} = 0 \ \leftrightarrow i \notin i^0 \cup n \neq k \end{Bmatrix} \tag{18}$$

Then

$$\mathbf{f^v} = \mathbf{ey^0} \tag{19}$$

Next we need to calculate the EU consumption-based account if there were no flows involving vehicles. This is $\mathbf{Q^0_{EU}} = \mathbf{eL_0y_{EU}}$ where $\mathbf{L^0} = \left(\mathbf{I} - \mathbf{A^0}\right)^{-1}$. $\mathbf{A^0}$ is the same as $\mathbf{A}$ but contains zeros in the rows and columns that represent EU vehicle industries. Thus:

$$\begin{Bmatrix} a^0_{ij} = a_{ij} \ \leftrightarrow i \notin i^0 \cap j \notin j^0 \\ a^0_{ij} = 0 \ \leftrightarrow i \in i^0 \cup j \in j^0 \end{Bmatrix} \tag{20}$$

Once $\mathbf{A^0}$has been calculated, we can then calculate $\mathbf{L^0}$ and $\mathbf{Q^0_{EU}}$. Finally, now $\mathbf{Q_{EU}}$, $\mathbf{Q^0_{EU}}$ and $\mathbf{f^v}$ are known, the final calculation of $\mathbf{Q^v_{EU}}$ can be made following equation 11.

To calculate the total potential across all manufactured groups you cannot sum the emissions as calculated above for each product as there will be some overlap. For example, the emissions reach of EU vehicles includes all sectors that purchase vehicles from the EU at some point along their supply chain. Both the construction and appliances sectors will have purchased from the vehicles sector e.g. for product distribution and staff travel. These emissions are therefore calculated to be within the scope of all three's influence. To estimate the emissions within the reach of all manufactured goods with any double counting removed, we also calculated a 'total scope' where all sectors defined as material-intensive manufacturing were included in the one calculation, and hence double counting between products was removed.

6.9.5 Emissions capped within the EU ETS

We evaluate how many of the embodied emissions in the products analysed are produced in sectors capped under the EU ETS, and therefore are within the scope of existing EU climate policy. From the emissions results matrix we can identify the source of emissions (region and sector) embodied in the products analysed. For each product we measure the emissions produced in economic sectors which we identify as being included in the EU ETS (Table 18).

Table 18: Mapping EU ETS sectors with Exiobase sectors

EU	Pulp	Pulp
EU	Paper	Paper
EU	Manufacture of coke oven products	Coke ovens
EU	Petroleum Refinery	Oil refineries
EU	Plastics, basic	Petrochemicals
EU	N-fertiliser	Petrochemicals
EU	P- and other fertiliser	Petrochemicals
EU	Chemicals nec	Petrochemicals
EU	Manufacture of rubber and plastic products	Petrochemicals
EU	Manufacture of glass and glass products	Glass
EU	Manufacture of ceramic goods	Ceramics
EU	Manufacture of bricks, tiles and construction products, in baked clay	Bricks
EU	Manufacture of cement, lime and plaster	Cement and lime
EU	Re-processing of ash into clinker	Clinker
EU	Manufacture of basic iron and steel and of ferro-alloys and first products thereof	Iron and steel plants
EU	Aluminium production	Aluminium
EU	Production of electricity by coal	Power stations
EU	Production of electricity by gas	Power stations
EU	Production of electricity by nuclear	Power stations
EU	Production of electricity by petroleum and other oil derivatives	Power stations

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