Structural change for a post-growth economy: The relationships between energy use, labour productivity and economic growth

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The candidate confirms that the work submitted is his 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.

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The thesis contains five chapters. Chapters 2-4 consist of one academic journal article. Chapter 1 provides an introduction to the overall research topic of the thesis. It places the three academic articles in the wider literature and outlines their relevance to the overall research topic of the thesis. Chapter 5 of the thesis synthesises the results presented in the individual academic articles and draws out the overarching implications and conclusions.

The work in Chapter 2 of this thesis has been published as:

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Abstract

To avoid environmental breakdown, high-income countries need to transition to a post-growth economy that can deliver wellbeing within planetary boundaries, independent of GDP growth. The post-growth literature recognises that such a transition will require structural change in the sectoral composition of economic output and demand. But the literature is lacking a systematic analysis of the structural change that is desired and how we can achieve it. In my thesis I address the gap by answering the question how structural change can contribute to the transition to a post-growth economy, focusing on the contribution it can make to reducing final energy demand and to reducing labour productivity growth.

I answer the question by combining two research streams. The first stream uses novel estimates of embodied energy and labour productivity of sectors in the UK and Germany to identify labour-intensive service sectors and test the assumption that they can reduce energy use and labour productivity growth. Building on the results I develop a systematic framework for identifying structural change goals for a post-growth economy. The framework splits the economy into 4 sector groups with similar characteristics and structural change goals. The second stream adds new insights to the literature on structural change drivers with a novel decomposition analysis of final energy demand in the UK. I demonstrate that structural change has only made a relatively small contribution to energy demand reductions and has largely been driven by offshoring.

Combining the two streams I assess historical structural change against the goals for a post-growth economy. I find that it has partially been in the right direction. But, to move to a post-growth economy, more attention needs to be paid to the drivers and consequences of structural change, as the historical drivers are intertwined with growth in GDP, labour productivity, incomes and offshoring.

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Abbreviations

CCCEP	Centre for Climate Change Economics and Policy
CIED	Centre on Innovation and Energy Demand
CO_2	Carbon Dioxide
CREDS	Centre for Research on Energy Demand Solutions
DE	Country code for Germany
DECC	Department of Energy and Climate Change
ECC	Energy Conversion Chain
ECUK	Energy Consumption in the UK
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
EU	The European Union
EUR	Euro
GDP	Gross Domestic Product
GFCF	Gross Fixed Capital Formation
GHD	Gewerbe, Handel, Dienstleistungen
GHG	Greenhouse Gas
GVA	Gross Value Added
h	Hours
HM Government	Her Majesty's Government (i.e. the UK Government)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ktoe	Kilo-tons of oil equivalent
LMDI	Logarithmic Mean Divisia Index
MJ	Megajoules
MRIO	Multi-regional Input-output
NACE	Statistical Classification of Economic Activities
NPISH	Non-profit Institutions Serving Households
ODEX	ODYSEE-MURE Energy Efficiency Index
OECD	Organisation for Economic Co-operation and Development
OPHI	Oxford Poverty and Human Development Initiative
RCUK	Research Councils UK
SIC	Standard Industrial Classification
TFC	Total Final Consumption
UK	United Kingdom
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
US	The United States of America

Chapter 1
Introduction and literature review

1.1 Introduction

Human activities are now breaching several planetary boundaries, for example with regard to climate change, biodiversity loss and the alteration of the nitrogen cycle (Rockström et al., 2009; Steffen et al., 2015; O'Neill et al., 2018). These planetary boundaries define a "safe operating space" for humanity (Rockström et al., 2009). Breaching one or more of them leads to changes in the earth system that will likely make conditions on the planet much less hospitable for human life, with potentially catastrophic effects on human livelihoods (Steffen et al., 2015).

Moving the impacts of human activities back within planetary boundaries will require a fundamental transformation of the economic system, as greenhouse gas (GHG) emissions, energy use and other environmental impacts are intrinsically linked to the way we produce goods and services (Steinberger et al., 2013). At the same time significant parts of the global population live in poverty (OPHI and UNDP, 2019), almost a billion people do not have access to electricity (IEA, 2019) and inequality is increasing both within and between nations (Alvaredo et al., 2018).

The big challenge for the 21st century is to reduce our environmental impacts at the speed and scale necessary to return to within planetary boundaries while simultaneously transforming our economic system to provide for the needs of everyone to flourish under these circumstances. Historically the growth in economic production, as measured by the gross domestic product (GDP), has been closely coupled with the growth in environmental impacts, such as GHG emissions or material use (Hickel and Kallis, 2019). It is therefore likely that effective policy actions to reduce such impacts to levels within planetary boundaries will lead to reductions in GDP, at least in high-income countries. In our current system, such reductions in GDP, or even just in its growth rate, exacerbate many social challenges, such as unemployment, poverty, bankruptcies and inequality (Kallis et al., 2018).

The economic transformation will therefore need to be one towards a post-growth economy, an economy that provides the needs for human flourishing within planetary boundaries, independent of whether GDP is growing or not. With the research presented in my thesis I hope to contribute a small piece to the puzzle of achieving such a transformation.

In my research I will specifically focus on investigating what structural change in the sectoral composition of the economy, in terms of output, demand and labour, is needed for the transition to a post-growth economy. It is widely acknowledged in the literature that the transition to a post-growth economy will be a qualitative transformation, which will have different implications for different sectors. While some activities will need to decline, others will need to grow and others will have to be qualitatively transformed (Kallis, 2011). However, there has been no systematic treatment of structural change in the post-growth literature that identifies the change needed in the sectoral composition and potential ways to achieve it. Such a systematic treatment of structural change, drawing on the insights of the wider economic literature, would be a useful addition to the post-growth literature. It would allow the identification of sector-specific strategies and it would make the post-growth vision more concrete and easier to communicate to policy makers, businesses and the general public, who are often used to discussing the economy in terms of different sectors.

With my thesis I contribute to addressing this gap in the post-growth literature by answering the following research question:

> *How can structural change contribute to the creation of a post-growth economy?*

I particularly focus on the contribution that structural change can make to reductions in final energy demand and to ensuring employment through reductions in labour productivity growth, because the post-growth literature suggests that these are two key objectives that can be potentially and partially achieved through structural change (Jackson, 2017, pp.219–220). I also focus on investigating structural change in high-income countries, because such countries have been the focus of most of the post-growth literature and face a challenge that is distinct from those in low-income countries. However, given the importance of international trade for structural change, I pay particular attention to the insights that can be gained from a supply chain perspective, which considers the interlinkages between production and demand in high-income countries and the global economic system.

I address my overarching research question using a two-streamed approach (Figure 1-1). In the first stream I review the treatment of structural change in the post-growth literature and present new evidence for identifying structural change goals for a post-growth economy. In the second stream I review the literature on structural change in the wider economics literature and present new evidence on

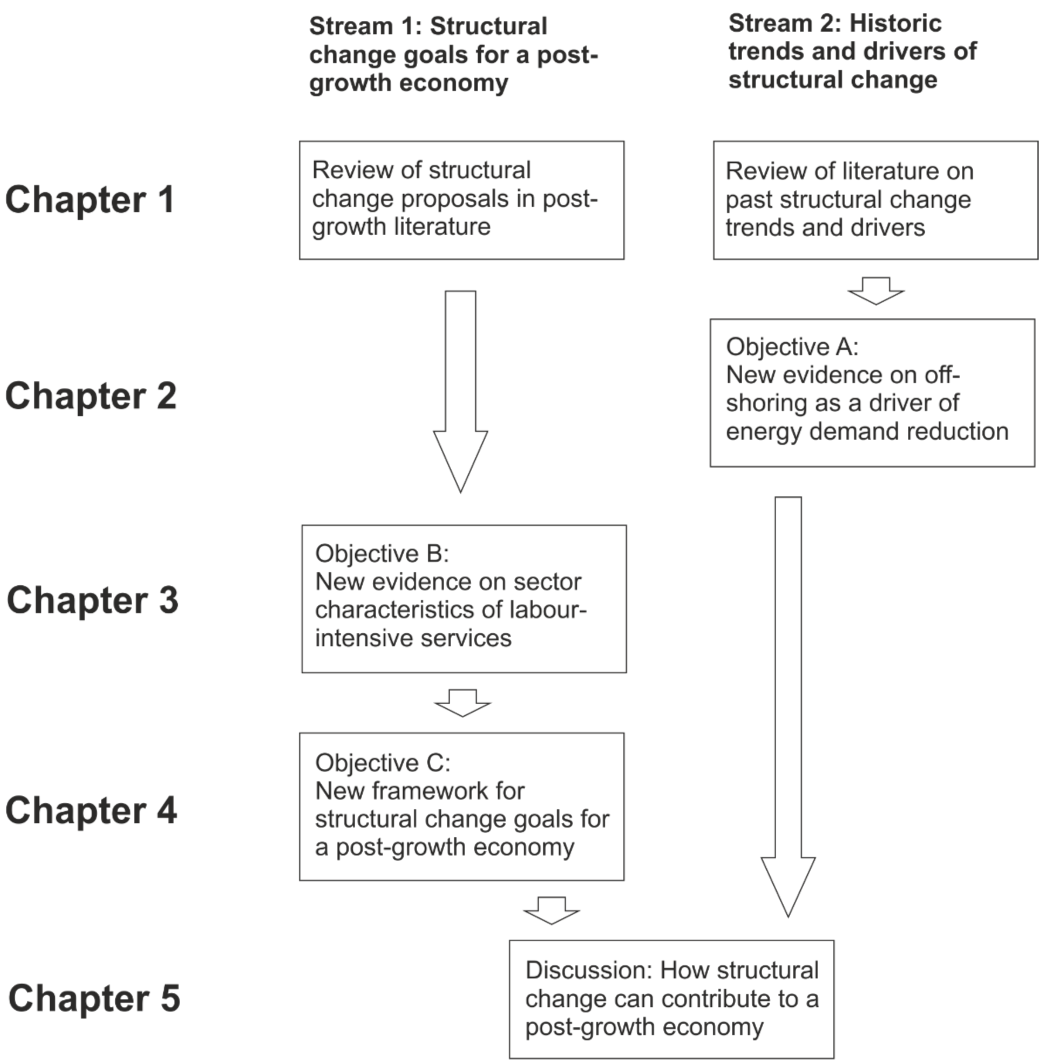

Figure 1-1: Outline of the thesis content

the drivers of structural change and its relationship to energy use. Bringing these two streams together allows me to discuss in how far historical structural change has moved us towards a post-growth economy and what further efforts will be necessary to achieve the structural change desired for a post-growth economy.

In the remainder of this chapter I will review both the literature on post-growth economics and the literature on structural change to discuss, firstly, how structural change has been treated in the post-growth literature, and, secondly, what we can learn about the historical trends and drivers of structural change from the wider economics literature. Based on the review I identify three specific gaps that are important for answering my overarching research question, two related to Stream 1 and one related to Stream 2. From these gaps I derive three specific research objectives for my thesis that are addressed in three academic articles that make up Chapters 2, 3 and 4 (Figure 1-1).

Firstly, there is limited evidence on how the historical relationship between structural change and energy use in high-income countries has been mediated by developments in international trade and the offshoring of specific sectors. A better understanding of this issue is important to determine how far the energy savings achieved from structural change have been desirable from the perspective of a post-growth economy and could provide a plausible route for further energy demand reductions in the future. Therefore the first objective of my research is:

A. To provide evidence on the role of international trade in shaping structural change and energy use in high-income countries.

Secondly, one element of structural change that has been identified explicitly in the post-growth literature is the need to shift the economy towards labour-intensive services. However, there is very little empirical research on the question which sectors in the economy show the desired characteristics of labour-intensive services. The evidence is especially limited when it comes to sector characteristics from an embodied perspective. The second objective of my research is:

B. To provide empirical evidence on sectoral characteristics for the identification of labour-intensive services, focusing on an embodied perspective.

Thirdly, the post-growth literature does not feature a systematic approach for identifying the structural change desired for a post-growth economy. There are some partial ideas, such as the need for more labour-intensive services, but there is no assessment for the whole economy. The third objective of my research is:

C. To develop a systematic approach for determining desirable structural change and sector-specific strategies for a post-growth economy.

Finally, there is also very little discussion in the post-growth literature on how structural change happens in the economy and what strategies could be employed to shape it towards the desired outcomes. Therefore the discussion of potential strategies for achieving structural change for a post-growth economy will be a cross-cutting theme of this thesis that will be discussed in conjunction with all of the three research objectives outlined above.

I outline my approach for achieving the research objectives in Section 1.4.

1.2 Structural change for a post-growth economy

1.2.1 Post-growth economics

The past decades have seen a growing academic literature and advocacy movement arguing that the only realistic and sensible way to avoid catastrophic environmental changes is to adopt new economic approaches that prioritise the delivery of prosperity within planetary boundaries over GDP growth. Such approaches have been called steady-state economics (Daly, 1977; Dietz and O'Neill, 2013), degrowth (Schneider et al., 2010; Kallis, 2018), post-growth economics (Jackson, 2017) or doughnut economics (Raworth, 2017).

Around the approaches described above, a diverse academic literature has developed, which is seeking to develop theories, models and strategies for a sustainable economy not reliant on GDP growth. Despite the use of different terminology and labels, the different approaches are well interconnected, they share many goals and assumptions and there exists a lot of cross-fertilisation. For the purpose of my thesis, the commonalities of these approaches are more important than their differences and I will therefore discuss them as one literature under the label of "post-growth" economics. I choose the term "post-growth" because I consider it the widest and most general term of the ones used.

The arguments in the post-growth literature are particularly founded on two bodies of evidence. The first body of evidence describes the close historical coupling of GDP with energy use, GHG emissions, material use and biodiversity loss (Hickel and Kallis, 2019; Parrique et al., 2019; Haberl et al., 2020; Otero et al., 2020; Vadén et al., 2020). While these environmental impacts have generally been growing more slowly than GDP, the evidence suggests that it is very unlikely that we can decouple GDP growth from its environmental impacts fast enough to avoid catastrophic environmental breakdown.

The second body of evidence relates to the relationship between wellbeing and GDP, which suggests that GDP in itself is not a good indicator of progress (Stiglitz et al., 2010; Costanza et al., 2014). Above a relatively low threshold, measures of life satisfaction, life expectancy or educational attainment are not increasing consistently with GDP (Deaton, 2008; Inglehart et al., 2008; Easterlin et al., 2010; Jackson, 2017, pp.74–76).

Together these two bodies of evidence suggest that continued increases in GDP, especially in high-income countries, are neither compatible with avoiding environmental breakdown, nor necessary for achieving prosperity. Nevertheless, there is also a shared recognition across the post-growth literature that GDP growth is systemically embedded in our current economies. Even though GDP is not a good measure of progress, a stagnating or shrinking GDP is accompanied by undesirable social consequences, such as increasing unemployment, poverty and inequality. Jackson (2017, p.66) refers to this challenge explicitly as the "dilemma of growth", but it is also acknowledged in the wider post-growth literature (Daly, 2008; Schneider et al., 2010; Kallis, 2011; Raworth, 2017). The dilemma of growth demands that the transformation to a post-growth economy needs to be an all-encompassing systemic change, because the treatment of individual problems will always run up against the dilemma. Achieving such a transformation in a socially acceptable way, however, provides a huge challenge.

In contrast to many other economic schools of thought, post-growth economics is not united around specific theories or methods, but instead around a shared framing of the challenge and shared goals for economic transformation. The shared goals become very clear when comparing the descriptions of different post-growth approaches in the literature (Table 1-1). For the purpose of my thesis I define a post-growth economy based on three characteristics derived from the shared goals:

1. In a post-growth economy the environmental impacts of human activities are reduced to levels within planetary boundaries.
2. A post-growth economy provides for human needs and enables flourishing for everyone and the benefits of economic activities are equitably distributed.
3. Continued GDP growth is not seen as a desirable goal in a post-growth economy and it is recognised that the transformation required to achieve the first two characteristics will likely lead to reductions in GDP in high-income countries.

The first two characteristics are explicitly shared in all the three definitions given in Table 1-1. They are also graphically captured in Raworth's "doughnut", which describes a "safe and just space" between the "ecological ceiling" on the outside, defined by the planetary boundaries, and the "social foundations" on the inside, defined by basic human needs (Raworth, 2017). Similarly to the other definitions, she advocates that living within this "doughnut", rather than continued GDP growth, should be the overarching goal for society.

Table 1-1: Definitions of different post-growth approaches

Steady-state Economics	Degrowth	Post-growth economics
"*If an economy manages to achieve relatively constant stocks and flows over the analysis period (…). If the economy also manages to maintain material flows within ecological limits, then it is referred to as a steady-state economy. If, in addition (…), the country manages to achieve a high quality of life for its citizens, then it is referred to as a socially sustainable steady-state economy.*" (O'Neill, 2015, p.1215)	"*We define degrowth as a voluntary transition towards a just, participatory, and ecologically sustainable society. (…) The objectives of degrowth are to meet basic human needs and ensure a high quality of life, while reducing the ecological impact of the global economy to a sustainable level, equitably distributed between nations.*" (Research & Degrowth, 2010, p.524)	A post-growth society is "*one in which neither economic stability nor decent employment rely inherently on relentless consumption growth. One in which economic activity remains within ecological scale. One in which our ability to flourish within ecological limits becomes both a guiding principle for design and a key criterion for success.*" (Jackson, 2017, p.160)

The third characteristic is only implicit in the definitions given in Table 1-1. However, it is an important feature in the post-growth literature, because it is the de-prioritisation of GDP growth that sets the post-growth literature apart from other approaches to sustainable economics, such as green growth. While the necessity of the first two characteristics would probably be widely accepted among economists and policy makers of different backgrounds, the expectation that these two characteristics can, and might have to be, achieved without further GDP growth is much more controversial.

Most of the post-growth literature has focused on achieving the goals of a post-growth economy within high-income countries, which are also the focus of my thesis. The reason is that the consumption in high-income countries is associated with much higher environmental impacts per capita (Simas et al., 2015; O'Neill et al., 2018) and it is in high-income countries where continued GDP growth contributes the least to wellbeing (Dietz and O'Neill, 2013, pp.26–27). While low-income countries fundamentally share the same goals, namely the achievement of flourishing within planetary boundaries, they face a different set of challenges for achieving them.

In addition to the shared overarching vision in the post-growth literature, there is also considerable overlap and agreement on the practical policies proposed for the transition to a post-growth economy. Such proposals are rooted in a shared understanding that the economic and social changes envisioned in the post-growth literature cannot be achieved without strong government action (Kallis, 2011; Jackson, 2017, pp.185–209). A full discussion of post-growth policy proposals is beyond the scope of this chapter, but Table 1-2 provides an overview of the most common policy goals and policy instruments proposed across the post-growth literature.

Despite the commonalities with regard to the overarching vision and policy proposals, there remain considerable differences and debates within the post-growth economics literature. Key differences relate to the question of how deep the changes in our economic institutions, norms and lifestyles will have to be to achieve a high quality of life within planetary boundaries.

Table 1-2: Common policy goals and instruments in the post-growth literature

Policy goal	Policy instruments
Limit resource use and emissions	• Cap and trade systems • Environmental taxes • Mandatory warranties and repair services
Provide universal social security	• Universal basic income • Universal basic services • Job guarantee
Reduce inequality	• Minimum and maximum income limits • Progressive taxation, including wealth taxes • Wider distribution of asset ownership
Maintain employment	• Reduced working hours • Support for labour-intensive service sectors
Reform the financial system	• Credit guidance • Public investment banks • Sovereign money
Change policy priorities	• Alternative indicators of progress to replace GDP
Foster local production	• Restrictions on international trade and capital flows • Local currencies
Enable meaning and connection outside consumption-driven market environment	• Support not-for-profit and social enterprises • Creation of common spaces (e.g. libraries, community centres) • Common government of shared resources and spaces

Sources: (Daly, 2008; Dietz and O'Neill, 2013; Cosme et al., 2017; Jackson, 2017; Hardt and O'Neill, 2017; Kallis, 2018)

Many degrowth proponents are very sceptical whether the fundamental dynamics and institutions of our current capitalist economy, such as wage labour, profit, private property, corporations and private credit, are compatible with the achievement of a high quality of life within planetary boundaries (Johanisova et al., 2013; Kallis et al., 2015; Hinton, 2020). They argue that the implementation of the necessary policies will only work if there is a much deeper shift in social values, norms and institutions towards "'sharing', 'simplicity', 'conviviality', 'care' and the 'commons'" (Kallis et al., 2015). Achieving such a shift requires a deconstruction of some of the foundational conceptualisations of the consumer society, including "progress, science and technology" (Latouche, 2010, p.520). Changes proposed in the degrowth literature therefore go considerably beyond what is commonly considered to be part of economics and include, for example, the strengthening and reformation of democracy (Fournier, 2008; Demaria et al., 2013; Kallis et al.,2018), a different governance of technology and innovation focused on simplicity and conviviality (Kerschner et al., 2018) and the establishment of alternatives forms of living (Cattaneo, 2015). A large part of the degrowth literature and movement is not only about transforming economic thinking but also about challenging our societies' focus on economic reasoning and the framing of problems in economic terms as such (Kallis, 2018, p.8). Despite such radical thinking, many of the practical policy proposals in the degrowth literature, such as carbon taxes, are still framed in terms of conventional economic thinking.

Other streams in the post-growth literature are somewhat less radical in their approach to economic transformation, even though they still constitute considerable departures from mainstream thinking. They are more selective in the parts of the economic system that are criticised and see a continued role for existing institutions. For example, Daly's seminal work (1991; 2008), focuses on radical reforms of the economic system, mostly through top-down policies focused on restrictions on resource use, inequality, trade and a redefinition of measures of progress. But compared to the degrowth literature he is less concerned with changes in lifestyles, the meaning and organisation of work and the existence of profit and private property. Similarly, Jackson (2017, p.185) mainly attacks the current system, norms and institutions of "consumer capitalism", which is the part of the system that locks us into a destructive cycle of novelty production and consumption, which entices us to seek meaning through unnecessary material consumption and which exploits and exacerbates our individualistic and self-centred values. He is less critical of markets as an institution per se and considers wage labour as important source of meaning. As a solution he proposes that our economic institutions, specifically work, enterprise, investment and money creation, need to be redesigned around new values, emphasising collective responsibility, long-term commitment, participation and the common good.

Debates on the depth of change required for a post-growth economy are closely intertwined with debates about effective strategies for achieving the desired change. Especially the degrowth proposals and the use of the term "degrowth" have been criticised for being too radical, based on the argument that such language cannot reach beyond a core of people already convinced into other important areas of civil society, governments and businesses (Van den Bergh, 2011).

In response, degrowth proponents argue that, given the power and influence of vested interests benefiting from the current system, necessary policies to achieve a post-growth economy will not be implemented by governments unless radical social movements are effective in shifting the power balance in society (Kallis, 2011). From the beginning the degrowth community has therefore understood itself as a movement for radical social change, based on a combination of grassroots action and academic research (Demaria et al., 2013; Weiss and Cattaneo, 2017).

1.2.2 Structural change for a post-growth economy

1.2.2.1 The case for structural change analysis

The analysis of structural change has a long history in economics. Silva and Teixeira (2008, p.275) broadly define structural change analysis as any approach that divides "the economic system into a limited number of subsystems, in order to analyse the dynamic properties of the economy as a whole". Although the division of economic output into different sectors is one of the most common approaches to structural change analysis, structural change can also be analysed along other dimensions. Ciarli and Savona (2019) identify six aspects of structural change that are especially relevant for climate change mitigation, namely sectors, industrial organisation, technical change, employment, demand and institutions. While the transformation to a post-growth economy will require structural change in all of these aspects, I focus specifically on structural change in the sectoral composition of the economy, in terms of output, demand and employment. For the remainder of this thesis I will therefore use the term structural change to refer to such changes in the sectoral composition of the economy.

There is a general recognition in the post-growth literature that the transition to a post-growth economy is a qualitative change that will require changes in the composition of goods and services that are produced and consumed (Daly, 2008; Schneider et al., 2010). While it is expected that serious efforts to reduce environmental impacts to sustainable levels will reduce the size of GDP, such reductions in GDP are not expected to be equally distributed across the economy. Kallis (2011, p.875), citing Latouche, briefly introduces the idea of "selective degrowth", arguing that there is a need for public debate about which economic activities will have to expand and which will have to be reduced. He argues that such a selection cannot be left to market forces. Similarly, both Cosme et al. (2017) and Hardt and O'Neill (2017) identify shifts in consumption and production between different products as an important theme in the post-growth literature.

Despite this general recognition, however, there is little analysis in the post-growth literature that systematically investigates how the sectoral composition of the economy will have to change, how such change can be achieved and what it implies for differences in sector-specific strategies. Discussions around "selective degrowth" are not continued further in the degrowth literature and the term does not feature in two recent reviews by Weiss and Cattaneo (2017) and Kallis et al. (2018). Similarly, the term "structural change" is virtually absent from the post-growth literature, with very little engagement with the structural change literature in the wider field of economics. The only exception is the discussion of Baumol's cost disease by Jackson (2017, pp.170–174). Structural change has been investigated as part of transition pathways to a sustainable economy, but these usually assume the context of a growing economy (Campiglio, 2014; Ciarli and Savona, 2019).

The absence of a systematic analysis of the structural change needed for a post-growth economy presents an important omission in the post-growth literature. Developing such a structural change analysis can therefore further the transition to a post-growth economy in three important ways.

Firstly, as already outlined above, structural change will be an important part of the transition to a post-growth economy, either as a consequence of other post-growth policies or as the outcome of strategic actions to achieve structural change. It is therefore important to develop an analysis that systematically considers what structural change is necessary and/or desired for a post-growth economy and how these can be achieved. In addition, such an analysis of structural change can form the foundation for the development of sector-specific policies that fill the gap between policies aimed at the whole economy and policies aimed at individual organisations.

Secondly, analysing the structural change desired for a post-growth economy helps to translate the often abstract vision of a post-growth economy into more concrete proposals. By sub-dividing the whole economy into a set of economic sectors, structural change analysis is able to refer to specific areas of economic activity while still offering a comprehensive view of the whole economy. Having a clear picture of the structural change associated with the post-growth transformation helps to determine the social and geographic distribution of changes in income and employment and how these can be managed. It helps to identify sectors and businesses in the economy that are likely to gain from the post-growth transformation, but also those sectors and businesses that are likely to lose out. Such information is vital for the development of effective political strategies to achieve the implementation of a post-growth economy.

Thirdly, the development of a structural change analysis for a post-growth economy is an important tool for communicating the vision for a post-growth economy. Many policy makers, businesses and union leaders are already familiar with a sectoral approach to economic policy-making. For example the UK government has published sector roadmaps for energy efficiency in the past (e.g. Department of Energy & Climate Change, 2015), and has proposed explicit "sector deals" in its recent industrial strategy (HM Government, 2017). Similarly, the German Council of Economic Experts (2019, p.3) suggests that in specific circumstances "there could be justification for a vertical policy intervention that is tailored to individual sectors or technologies". Framing the post-growth transition in sectoral terms therefore makes it easier to communicate the changes that the transition would bring.

I have chosen to focus my thesis on the question of how structural change can contribute to a post-growth transition in order to contribute to the development of a structural change analysis that is so far missing from the post-growth literature.

1.2.2.2 Structural change in the post-growth literature

Even though there is no systematic analysis of structural change in the post-growth literature, we can obtain some ideas of how and why the sectoral composition has to change. These ideas serve as a useful starting point for developing a more systematic analysis.

There are some scattered references to specific sectors that are considered a hindrance to the pursuit of a post-growth economy, including resource extraction, marketing and speculative finance (Daly, 2008; Dietz and O'Neill, 2013; Sekulova et al., 2013).

In terms of sectors that are desired, there is an overarching theme that relational services are seen as more valuable than material products (Research & Degrowth, 2010; Kallis, 2011). The most strongly developed vision of such a structural change can be found in the work by Jackson and co-authors who promote a shift towards labour-intensive services, activities with high social value and potential for creating meaningful work (Jackson and Victor, 2011; Jackson et al., 2014; Jackson, 2017). Jackson (2017) describes such desirable activities as the following:

> *"Community-centred enterprise engaged in delivering local services, such as nutrition, education, care, maintenance and repair, recreation, craft, creativity, culture: these activities contribute to flourishing and are embedded in the community. They have potential for low-carbon footprints and they provide meaningful work." (pp.219-220)*

Although most extensively discussed by Jackson and co-authors the desirability of such shifts towards labour-intensive services has been expressed throughout the post-growth literature (e.g. Kallis et al., 2012; Nørgård, 2013).

Overall it is proposed that there are two important post-growth goals to which structural change can contribute.

The first goal is the reduction of the overall environmental impacts of economic activity. It is proposed that labour-intensive services feature lower environmental impacts and therefore a shift in consumption and production towards such sectors can make a contribution towards moving our economy back to within planetary boundaries. Cosme et al. (2017, p.328) associate the degrowth proposal to "promote changes in consumption patterns" with the goal of reducing the environmental impact of human activities. However, there is also a recognition that there are limits as to how much structural change can contribute to such a goal, for example with regard to GHG emissions (Victor, 2012; Horen Greenford et al., 2020).

For the purpose of my thesis I focus specifically on the final energy use in different sectors as one aspect of environmental impact. Final energy use refers to the use of final energy carriers, such as electricity or petrol, by end users. I choose to focus on final energy use for two reasons.

Firstly, reductions in final energy use in high-income countries will be crucial for achieving the goals of the Paris agreement (Rogelj et al., 2018). Reductions will need to be achieved in both the final energy use within high-income countries as well as the global footprints of final energy use associated with lifestyles in high-income countries. Such reductions will give some room to low-income countries to increase their final energy use and they will make the transition to renewable energy sources more easily achievable (Steckel et al., 2013; Grubler et al., 2018).

Secondly, final energy use is very closely coupled with the process of economic production in general (Haberl et al., 2020) and it is also likely linked to labour productivity growth (Sorman and Giampietro, 2013; Witt and Gross, 2019; Elkomy et al., 2020). As reducing environmental impacts and labour productivity growth are both key objectives for structural change in a post-growth economy, the relationship between the two makes final energy use a very relevant metric of environmental impact for addressing my research question.

The second goal of structural change for a post-growth economy is the creation of meaningful work. One of the key concerns related to the post-growth economy is the loss of employment and income, especially if aggregate labour productivity continues to increase without continued economic growth. A shift towards labour-intensive services has been proposed as one important solution to provide employment in such a situation (Jackson and Victor, 2011), in addition to reductions in working time (Kallis et al., 2013; Antal, 2018).

Jackson (2017, pp.146–149) proposes that sectors such as care, education or art or other personal services, are able to create employment because they have a higher labour intensity than other sectors, meaning that they are associated with more employment per unit of final demand. In addition he also suggests that it is difficult and undesirable to increase labour productivity in such services, because the value of the service delivered is directly related to the time invested. Increasing the share of such sectors in output and demand would therefore not only provide employment but also slow down the aggregate rate of labour productivity growth, which would prevent further unemployment in a non-growing economy.

Increasing the provision of labour-intensive services is not only suggested to maintain employment and income, but also because such work can be an important way to participate in society and to seek fulfilment and well-being (Jackson, 2015). However, in order to increase worker well-being, the post-growth literature stresses that the work created has to be meaningful. Druckman and Mair (2019) provide a review of the factors that can make work meaningful. They identify a number of aspects related to two overarching criteria. The first criterion relates to good working conditions, including aspects such as wages, hours and autonomy. The second criterion relates to the output of the work, which needs to be of high quality and to contribute to the common good.

Considering such criteria, several authors suggest that most of the work available in the current system is not meaningful. For example Klitgaard (2013, p.280) argues that meaningful work is "limited to a small number of professional workers, for example skilled craftworkers, health professionals and college professors". Proponents of the concept of "contributive justice" suggest that the uneven distribution of meaningful work is an important aspect of inequality that needs to be addressed through a fairer distribution of opportunities for meaningful work (Timmermann, 2018; Bottazzi, 2019).

The implicit assumption in the post-growth literature is that a shift towards labour-intensive sectors, such as care and education, can provide meaningful work, because it fulfils the second criterion, namely the contribution to the common good. However, as Druckman and Mair (2019) discuss for the health care sector, contributing to the common good is not a sufficient condition for meaningful work. It is therefore important that work created through structural change towards labour-intensive services is accompanied by improvements in working conditions.

1.2.2.3 Literature gaps

While the post-growth literature therefore shows the beginnings of a vision and discussion of structural change, it is lacking a comprehensive analysis identifying the kind of structural change necessary for the post-growth transition and how to achieve it. In particular, three specific gaps in the literature stand out.

Firstly, while the shift towards labour-intensive services is widely discussed in the literature, there is no detailed empirical investigation into which sectors of the economy actually show the characteristics of labour-intensive services and how a shift in economic output and demand towards such sectors could be achieved. So far the only evidence provided is a brief comparison of sectoral embodied labour and GHG emissions presented in Jackson et al. (2014). This lack of empirical investigation of labour-intensive services has informed my research objective B and is addressed in Chapter 3.

Secondly, the promotion of labour-intensive service sectors only refers to a specific section of the economy. In order to develop a coherent strategy for structural change towards a post-growth economy, it is important to develop a systematic framework that covers the whole economy and locates the shift to labour-intensive services within the wider structural change needed for a post-growth economy. Such a framework would then provide an important starting point for developing sector-specific strategies, for example which sectors would have to grow or reduce output and demand or labour productivity. This gap has informed my research objective C. In Chapter 4 I address this gap in the literature by developing such a framework derived from the two structural change goals identified in Section 1.2.2.2.

Thirdly, the development of successful structural change strategies for the transition to a post-growth economy needs to engage with the existing knowledge on structural change in the economics literature, in order to understand the drivers of structural change in our current system and the potential barriers to desired change. So far the engagement with the structural change literature in post-growth economics is limited. I address this gap in Stream 2 of my thesis, which includes a review of the literature on structural change in Section 1.3 of this chapter and some novel evidence on the drivers of structural change and energy use presented in Chapter 2.

1.2.3 Defining economic sectors

At the heart of any analysis of structural change lies the definition of economic sectors. For the purpose of my thesis I rely on the sector classification system and data from the system of national accounts. I use these definitions of economic sectors to examine the sectoral composition of the economy along a number of different dimensions, including economic output, gross value added (GVA), demand, employment and final energy use. As discussed in Section 1.2.2, these are the aspects of economic composition that are most relevant for the goals that post-growth economists aim to achieve from structural change.

Using the common system of national accounts for the classification of economic sectors has many advantages. It allows me to use the economic data that are widely available in the national accounts and in multi-regional input-output databases. It also allows an easy comparison to other economic studies and it makes it easier to communicate the results, as the system of sectoral classification is widely known and accepted.

However, using the common system of sectoral classification also has some limitations, especially for research in post-growth economics. Firstly, measures of real output in the national accounts, such as GVA, can be difficult to measure in some sectors, especially in many of the sectors that are relevant for the post-growth economy, such as education, care and other service sectors (Eurostat, 2016, pp.34–38). Secondly, the sectoral classification in the national accounts excludes many activities that are important for the transition to a post-growth economy, such as unpaid care work or voluntary work. Shifts in the balance between formal, paid work and informal, unpaid work will likely play a part in the transition to a post-growth economy (Nørgård, 2013; Kallis et al., 2018). However, these are not captured by my analysis looking at structural change between sectors in the formal economy.

Nevertheless, keeping these limitations in mind, I consider that an analysis of structural change for a post-growth economy, conducted within the framework of national accounts, constitutes a valuable addition to the literature for the reasons outlined in Section 1.2.2.1.

Using the national accounts, economic sectors can still be conceptualised in two different ways, both of which are important for analysing structural change for a post-growth economy. Firstly, in conventional reporting, sectors classify economic production by the type of product that is produced. For example the sector "vehicles", would include all the firms that assemble vehicles from intermediate inputs. When the energy use of the sector is considered from this perspective, it includes all the energy that is directly used by the firms producing vehicles, but not the energy used in producing the intermediate inputs, such as steel or plastic. I refer to this approach as the "direct" perspective and to sectors conceptualised in this way as "direct sectors". Such a direct perspective for sector classification has the advantage that it is relatively easy to link sectors to real firms and that the type of production activities are relatively homogeneous throughout a sector. However, the perspective is less suited to assess the complex interlinkages between sectors.

The second way of conceptualising sectors starts with the type of product that is consumed and then defines the sector to include all production activities that are part of the supply chain and therefore embodied in the product and services delivered to final demand. Sectors defined in this way have been referred to as "vertically-integrated" and, conceptually, they are completely self-sufficient and are not directly connected to any other sector (Pasinetti, 1981). Defining sectors in this way has the advantage that it takes into account the interconnectedness within the economic system. For example such a perspective allows estimation of the impacts that any changes in demand have throughout the whole economy. In ecological economics such a perspective has a long history for the estimation of the energy and material requirements, as well as the emissions, that are embodied in the supply chains of different end products (e.g. Cleveland et al., 1984). Since the development of multi-regional input-output (MRIO) models, which cover the global economy, another prominent research topic has been the comparison of carbon emissions or energy use within specific countries with the carbon emissions or energy use that are associated with the global supply chains that serve the final demand in specific countries (Minx et al., 2009; Inomata and Owen, 2014). When this approach has been used to investigate the global energy use and emissions of whole countries, it has been referred to as consumption-based accounts (Barrett et al., 2013; Owen et al., 2017) or as footprints (Lan et al., 2016; Akizu-Gardoki et al., 2018). The energy use or emissions associated with the supply chain of a specific demand sector or product are often referred to as "embodied" energy use or emissions (e.g. Hammond, 2007; Skelton et al., 2011; Simas et al., 2015). I therefore refer to this perspective as an "embodied" perspective, which describes the embodied inputs associated with different "demand sectors".

The disadvantage of the embodied perspective is that it is in many ways an abstract concept that is difficult to link to real companies and parts of the production system. In reality, most companies will be part of the supply chains of a number of different demand sectors. Nevertheless, it is very important to include the embodied perspective when studying structural change for a post-growth economy, because the challenges that the transition to a post-growth economy aims to address are inherently global in nature. Structural change and its impact on energy use and employment therefore has to be evaluated in the global context and not only in individual countries.

Sectors classified from the two perspectives are inherently linked through the accounting structure of the national accounts and input-output tables. In my thesis, the set of direct sectors and demand sectors is the always the same. That means for each direct sector there is a corresponding demand sector which describes the final demand for the output from the direct sector. The embodied perspective then provides the inputs needed to produce that demand along the supply chain. These embodied inputs associated with the demand sectors are made up of bits of direct output or GVA, direct energy use or direct labour use from different direct sectors. On a global level, the total direct energy use and total direct labour use are the same as the total embodied energy use and total embodied labour use. The characteristics of the direct inputs into direct sectors and the embodied inputs associated with the corresponding demand sectors are often related, because in most cases a large part of the supply chain inputs into a specific demand sector is made up of output from the corresponding direct sector (Schettkat and Yocarini, 2006). For example, the supply chain inputs in the production of the “vehicles” demand sector contain a large proportion of output from the “vehicles” direct sector, even though they also include output from other direct sectors, such as “iron and steel”.

Given the close connection between the direct sector and the corresponding demand sector, I often discuss the two perspectives together, for example in the sector classification in Chapter 4. I therefore use the term “sector” in my thesis when I refer to the corresponding direct and demand sectors together. I use the term “direct sector” and associated “direct” inputs of energy and labour when I refer specifically to a sector from a direct perspective. I use the term “demand sector” when I refer specifically to a sector from the embodied perspective, with its associated “embodied” inputs of energy and labour.

Both sectors and demand sectors can be represented at different levels of aggregation. For example the literature on structural change often describes the stylised development path of countries using three highly aggregated sectors, such as agriculture, manufacturing and services. In my thesis I will use different levels of sector aggregation, which are dependent on the requirements of the analysis and are described in detail in each chapter.

In the context of input-output analysis, sectors are often referred to as “industries” (e.g. Stadler et al., 2018). However, in my thesis I do not adopt this language and continue to refer to them as “sectors” in order to avoid confusion with the term industry as used in the structural change literature (and in common language), which distinguishes industrial sectors from other types of sectors, such as services.

It is worth noting that my thesis is only concerned with the energy use of sectors that are featured in the national accounts. I do not investigate the energy use for non-commercial purposes, such as residential or private transport. Any country totals of embodied energy reported in my thesis therefore do not constitute the total energy footprint or the total consumption-based energy use of the country as commonly defined in the literature, because such measures would include energy use for residential purposes and private transport within the country (e.g. Lan et al.,2016; Owen et al., 2017).

1.3 Evidence on structural change

In order to investigate how structural change can contribute to the transition to a post-growth economy, it is useful to examine the patterns and drivers of structural change in the past and how they are related to energy use.

1.3.1 Historical patterns of structural change

Long-term structural change in growing economies is often described as a stylised fact using a model of three highly aggregated sectors (Kuznets, 1966; Kuznets, 1973; Krüger, 2008). In the first stage economies are dominated by a large agricultural (or primary) sector. In the second stage the share of the industry (or secondary) sector in the economy rises rapidly while the agricultural sector share declines. In the final stage the share of the industry sector declines again at the expense of an expanding services (or tertiary) sector, while the share of the agricultural sector remains at a low level.

For the purpose of this thesis I focus on the last stage of this stylised pattern, the rise of the service sectors that has been observed in industrialised countries during the 20th century (Kongsamut et al., 1997). As this process of structural change has been most important in the more recent past and is still unfolding in many high-income countries I consider it as most relevant for understanding structural change towards a post-growth economy in high-income countries. I do not consider here the contributions to the understanding of structural change that have been developed in the literature on development economics, which has largely focused on the transition from agricultural to industrial economies (e.g. Storm, 2015).

Structural change between the three highly aggregate sectors has been described in terms of shares in direct employment, nominal GVA or real GVA.

When considering the sectoral composition of direct employment, the structural change observed over the last decades has shown a remarkable regularity across high-income countries. Two important trends have been discussed. Firstly, for all of the 20th century, increasing GDP has been closely coupled with an increasing share of direct employment in the service sectors (Fuchs, 1980; Kongsamut et al., 1997; Schettkat and Yocarini, 2006). Secondly, after the share of direct industry employment rose with increasing GDP for the first two thirds of the century, there has been a consistent fall in the direct employment share of industry since the 1970s (Saeger, 1997; Rowthorn and Coutts, 2004; Kollmeyer, 2009; Tregenna, 2009; van Neuss, 2019). The trend of falling direct employment shares in industry, and especially manufacturing, has been discussed under the term of deindustrialisation. This trend constitutes a relative effect; in some countries declining direct employment shares in industry have been associated with increases in absolute direct employment in industry (Rowthorn and Coutts, 2004; Tregenna, 2009; Sarra et al., 2019). The process of deindustrialisation over the past decades is not restricted to high-income countries, but can also be observed in many low-income countries (Rodrik, 2016; van Neuss, 2019).

The stylised pattern of structural change observed in employment shares has largely been mirrored when the sectoral composition of the economy is considered in terms of nominal valued added (van Neuss, 2019). However, when the sectoral composition of value added is considered in real terms, corrected using sector-specific price indices, the observed patterns of structural change are less consistent with the stylised pattern of direct employment shares. While there is still an increase in the service sector share and a decline in the industry sector share over the last decades, this change is much smaller than the one observed for direct employment shares and nominal output (Rowthorn and Coutts, 2004; Tregenna, 2009; Henriques and Kander, 2010). In addition, the pattern is much less consistent across countries, with some showing increasing industry shares in real output (Tregenna, 2009; Henriques and Kander, 2010). It is also worth highlighting that in many countries where the share of the industry sector in real value added has been falling, the real output of the industry sector has still been growing in absolute terms (Tregenna, 2009).

The process of deindustrialisation has received considerable attention in the academic literature and in policy circles (Sarra et al., 2019). The attention is driven by concerns about the rise of unemployment caused by deindustrialisation, which has not been large in absolute terms but has been concentrated heavily in specific regions (Rowthorn and Coutts, 2004). In addition there are concerns about the impact of deindustrialisation on economic growth, as some economic theories suggest that the industry sector, particularly the manufacturing sector, is an important driver of economic growth, because it is disproportionally responsible for innovation, exports and is related to a strong demand for services (Tregenna, 2009; Sarra et al., 2019).

1.3.2 Drivers of structural change

Structural change represents a complex phenomenon that can be measured in different ways and is influenced by a wide range of factors. A sizeable literature discusses the drivers that have produced the stylised patterns of structural change observed in high-income countries over the past decades. The literature generally identifies four different types of drivers. These include, firstly, the outsourcing of service sector tasks from industry firms to specialised service sector firms, secondly, the differential rates of labour productivity growth in different sectors, thirdly, changes in the structure of demand and fourthly, increasing international trade and international division of labour (Schettkat and Yocarini, 2006; Kollmeyer, 2009; van Neuss, 2019). While there is some consensus that all these drivers play a role in driving structural change, their relative importance is debated.

1.3.2.1 Inter-sector outsourcing

The first mechanism that has been considered for explaining the shifts in employment structure from industry to services has been the increasing specialisation of the economy. It has been argued that many service-type functions that were previously performed within industry sector companies are now being outsourced to specialised service sector companies, leading to an increase in the direct employment share in the service sector (van Neuss, 2019). In some ways, any observed structural change produced by this process represents a statistical artefact, as it is not related to real change in the types of goods and services that are produced and consumed in the economy (Schettkat and Yocarini, 2006). Nevertheless, Peneder et al. (2003) suggest that this effect does highlight some important changes in the real economy, namely an increasing demand and market size for specific services that allows for increasing returns on specialisation.

Overall, there is some evidence that this effect is happening and partially responsible for the increase in direct service sector employment, especially in those direct service sectors that produce intermediate inputs, such as business and professional services (van Neuss, 2019). However, the importance of this effect for explaining observed structural change is likely to be small (Rowthorn and Coutts, 2004; Schettkat and Yocarini, 2006; Sarra et al., 2019). For the remainder of my thesis I therefore concentrate on the remaining three drivers discussed below. Nevertheless, the discussions around inter-sector outsourcing highlight the inherent challenges to adequately classify business activities in the national accounts, especially in an environment where the distinction between industry and service sectors is becoming increasingly blurred (Christensen, 2013).

1.3.2.2 Differential rates of labour productivity growth

A second important driver of structural change are differential rates of productivity increases, especially of labour productivity. An important contribution to this literature has been the theories of William Baumol and his co-authors (Baumol and Bowen, 1965; Baumol, 1967; Baumol et al., 1985; Baumol, 2012). They observe that some sectors in the economy have faster labour productivity growth (progressive sectors) than others (stagnant sectors). Assuming that wages across sectors cannot diverge to strongly, they propose that labour costs in the stagnant sectors rise in comparison to the progressive sectors, which leads to similar trends in relative prices. The fate of the stagnant sectors is then determined by the price-elasticity of demand for their products and services. Those of the stagnant sectors for which demand is price elastic shrink, while those of the stagnant sectors for which demand is inelastic take up increasing shares in employment and nominal output (but not in real output). Finally, assuming that the majority of demand in the stagnant sectors is not price elastic, for example in health care and education, they hypothesise that the share of these sectors in public expenditure as well as in overall employment and nominal output continually rises. The increasing share of the stagnant sectors in demand, employment and output might then lower the aggregate growth in labour productivity and GDP in the economy, a phenomenon that has been termed "Baumol's Cost Disease". However, Baumol (2012, pp.69–76) identifies the potential environmental and social impacts of continuously cheapening manufactured goods and weapons as the most important drawbacks of the cost disease.

In Baumol's theory, the increase of the service sector share in employment and nominal output and nominal demand represents a pure price effect. It is assumed that the shares of the stagnant and progressive sectors in real output and real demand stay the same. The change is caused solely by the progressive products becoming less labour intensive and therefore cheaper.

In a similar fashion, differential rates of labour productivity growth are a key component of Pasinetti's theoretical treatment of structural change (Pasinetti, 1981; Pasinetti, 1993). Pasinetti (1993) presents an accounting framework of a pure labour economy with vertically integrated sectors with a constant wage rate across the economy. In his stylised framework the differential rates of change in sectoral embodied labour productivity determine relative prices and relative shares of demand sectors in embodied employment. However, in contrast to Baumol's theory, the sector shares in real demand are not constant but instead change with rising income as the demand for some demand sectors becomes saturated. He uses this framework to argue that the independent changes in sectoral embodied labour productivity and sectoral demand shares continuously create new situations of unemployment that require an active management of the system as the market alone cannot ensure full employment.

Both Baumol's and Pasinetti's theories are highly stylised to provide clarity on their key messages. These key messages are, firstly, that differential rates of labour productivity growth are an integral part of economic growth and, secondly, that they are important for influencing the relative prices of products and the distribution of employment in the economy.

Despite being highly stylised, Baumol's and Pasinetti's theories are supported by empirical observations that structural change towards the direct service sector has been much stronger and more consistent when measured in terms of direct employment or nominal output, than in real output (Henriques and Kander, 2010; Tregenna, 2011). In addition, there is considerable evidence from the literature that Baumol's cost disease plays a role in shaping the economy in the US (Nordhaus, 2006; Duernecker et al., 2017), the EU (Hartwig, 2011; Fernandez and Palazuelos, 2012), South Korea (Oh and Kim, 2015) and across the OECD (Maroto and Rubalcaba, 2008; Hartwig, 2012; Hartwig, 2015). However, the strength of the effect varies in line with different contexts. For example Oh and Kim (2015) find that the effect of Baumol's cost disease in South Korea is only small, due to a large reliance on exports. Hartwig (2012) only finds evidence for Baumol's cost disease across the OECD when Japan is excluded from the analysis.

Similarly, the deindustrialisation literature recognises that relatively higher rates of direct labour productivity growth in the industry sectors are a key driver of reduced direct employment shares in industry (Kollmeyer, 2009; van Neuss, 2019). However, there is no agreement how important this effect is in comparison to other drivers, especially the effect of changes in the composition of demand (see Section 1.3.2.3). Tregenna (2011) and Święcki (2017) suggest that relative direct labour productivity increases in the manufacturing sectors have been more important than shifts in demand for reducing the share of direct manufacturing employment in many high-income countries. In contrast, Kollmeyer (2009) argues that rising affluence and associated shifts in demand have been more important than differential rates of productivity growth in explaining the declining direct employment share of manufacturing across OECD countries.

While the literature highlights the importance of differential rates of productivity growth, there is very little discussion about the sources of productivity growth and why it differs between different sectors. There are different bodies of literature that have been investigating the drivers of labour productivity growth in the economy.

Economists in the Kaldorian tradition have emphasised the special role of manufacturing as a driver of economic growth. It is argued that the manufacturing sector has a higher potential for labour productivity growth compared to other sectors, because of increasing returns to scale, and that growth of manufacturing output therefore induces higher productivity growth in the sector (Thirlwall, 1983; Tregenna, 2009; Marconi et al., 2016). As a result growth in the manufacturing sector is considered a key driver of growth in the economy as a whole.

The literature on evolutionary economics is explicitly concerned with the processes through which innovation and technological change occur, diffuse and shape the structure and development of the economy. In their seminal contribution, Nelson and Winter (1982) propose a dynamic model in which firms search for innovations and process improvements. Market forces, especially differences in unit costs, lead to a selection of some technologies and firms over others. Firms and sectors that can exploit new innovations get ahead while those firms that cannot fall behind. While market forces and profitability influence the choice of technologies they do not necessarily lead to the optimal choice as the selection process is characterised by uncertainty, path-dependency, institutional contexts and chance. These theories have been translated into a range of models that try to capture the relationship between technological innovation and structural change (e.g. Andersen, 2001; Montobbio, 2002; Saviotti and Pyka, 2004; Ciarli et al., 2010). Important technological innovations, such as the steam engine, can lead to an all-encompassing transformation of the economy, but the transformation takes time as it requires institutional adaptation and reorganisation until the full benefits of the technology are reaped (Perez, 2013).

Ecological economists have proposed that a key driver of increasing labour productivity has been the replacement of energy for labour. This relationship is discussed specifically in Section 1.3.3.2.

1.3.2.3 Changes in the structure of demand

A third important driver of structural change is the change in the composition of real demand. The conceptualisation of this change is based on an extension of Engel's law, considering that the demand for products is somewhat hierarchical (Schettkat and Yocarini, 2006). As a result the structure of demand changes with rising income as demand for essential products saturates and the demand for luxury products rises. It is generally considered that the demand share of services rises with rising income, while the demand share for agricultural products and, ultimately, manufactured goods decreases, leading to structural change in demand away from the industry and manufacturing sectors and towards the service sectors. Implicit in this theory is the assumption that demand sectors and direct sectors are closely connected, so that a shift in demand between demand sectors leads to similar shifts in value added or output from a direct perspective.

The importance of this effect is debated. Baumol's theory, as outlined above, does not feature any changes in demand composition as it assumes constant shares of the progressive and stagnant sectors in real demand. Pasinetti's theory, in contrast, features a version of different income elasticities for different demand sectors, which are the main driver shaping the structure of the economy. Similarly, evolutionary models of structural change feature a sorting process relying on different income elasticities for different demand sectors (Montobbio, 2002).

Baumol et al. (1985) present some empirical evidence that service sector shares in output are constant across countries with different levels of per-capita GDP. However, Schettkat and Yocarini (2006) argue that this constancy is only evident if national prices are adjusted by purchasing power parities. They argue that longitudinal studies in individual countries provide better evidence and suggest that the share of service sectors in real final demand has increased in many high-income countries between 1972 and 1990. The shift to services is even stronger and more consistent when only the private consumption component of final demand is considered. They also review evidence of studies investigating household expenditures, which come to a similar conclusion. Kollmeyer (2009) and Comin et al. (2015) similarly conclude that shifts in demand towards service sectors have been an important driver of structural change even after relative price effects are accounted for.

Of course, it is difficult to disentangle the effects of differential rates of productivity growth and changes in demand. As differential rates of productivity growth change relative prices, they might also influence the structure of demand, not only in nominal but also in real terms (Rowthorn and Ramaswamy, 1999). Baumol (2012, pp.71–73) acknowledges this connection implicitly when he argues that falling relative prices of manufactured goods might contribute to the environmental crisis, because they might increase demand for such goods.

Despite the recognition of the importance of the demand side, the literature dealing explicitly with structural change features relatively little discussion of what drives the structure of demand beyond the existence of different income elasticities for different products (Silva and Teixeira, 2008). In reality, the structure of demand is not only influenced by changes in overall income or GDP, but also by many other factors. For example, such factors include changing preferences, changes in the income distribution, changes in age structure or the level of public intervention (van Neuss, 2019).

Another important aspect on the demand side is the development of new products and sectors. In Pasinetti's framework, high rates of unemployment can only be avoided if new products and sectors are added regularly to the economy. Similarly, Montobbio (2002, p.405) explicitly states that his evolutionary model describes a transitory process which would lead to strong centralisation of firms and that in the "long run the evolutionary process of structural change is nurtured by the emergence of new sectors and firms." However, neither of the two authors discuss how the emergence of new sectors and firms comes about.

A good understanding of what is driving the structure of demand is crucial for the advancement of a post-growth economy, given that the consumerist logic and institutions are one of the main drivers of environmental destruction (Jackson, 2017, pp.103–117). Beyond the structural change literature there does exist a range of research investigating the drivers, patterns and motivations of consumption that can provide insights into this question. A comprehensive review of this literature is beyond the scope of this thesis. However, it is worth highlighting that the literature in evolutionary economics has made some progress in the direction of investigating the drivers of consumption and demand structures and incorporating them into wider theories of economic development and structural change (Safarzyńska, 2013). For example Witt (2001; 2011) explores how consumption patterns are influenced by innate needs and acquired wants. Ciarli et al. (2010) present a model of evolutionary economic change to explore how microeconomic behaviours can produce different patterns of structural change at the macro level, depending on the interplay between technical change, firm structure, income distribution and consumption.

Other authors have developed theoretical, evolutionary models that represent the endogenous emergence of new products and sectors. Andersen (2001) develops a theoretical evolutionary model of a simple economy in which consumption and labour coefficients as well as the emergence of new sectors is endogenised. These changes happen as a result of different search activities that are performed by economic agents depending on their situation. Saviotti and Pyka (2004; 2013; 2017) also develop an evolutionary, endogenous growth model in which the creation of new sectors is endogenous and interacts with the supply side of the economy. Demand saturation stimulates the development of new sectors which is a key driver of continued economic growth.

1.3.2.4 International trade

The last important driver of structural change is the rise of international trade over the last decades. Especially in the literature on deindustrialisation, the topic has received considerable attention. As the deindustrialisation in high-income countries over the past five decades has coincided with increasing trade and imports of manufactured goods from low-income countries, the latter has often been used as an explanation for the former in policy discourse (Saeger, 1997).

It has been suggested that the production of low-skilled, labour-intensive manufactured goods, which were previously produced domestically in high-income countries, has been moved to low-income countries which feature lower labour costs (Kollmeyer, 2009). In high-income countries, the increasing imports from those low-income countries have been partially off-set by increases in exports of more high-skilled manufactured goods. However, the latter is generally less labour intensive, so that even if trade remains balanced, there is a loss of employment in the high-income countries (Rowthorn and Coutts, 2004). In addition to this direct effect, increasing trade can also influence structural change indirectly by increasing the other effects. For example international trade can raise overall income leading to changes in the structure of demand, international competition stimulates productivity improvements and changes relative prices, while more integrated markets offer more opportunities for inter-sector outsourcing (Peneder and Streicher, 2018).

Despite the importance attached to trade and comparative advantage as a driver of deindustrialisation, there is an emerging consensus in the literature that international trade does play a role in structural change but that it is not as important as is often claimed in political discourse.

Econometric studies indicate that international trade has reduced the direct employment share of manufacturing in high-income countries, but is less important than the internal effects discussed in the previous sections (Saeger, 1997; Alderson, 1999; Rowthorn and Coutts, 2004; Kollmeyer, 2009). Similar results have been obtained using general equilibrium models (Święcki, 2017) and decomposition analyses (Tregenna, 2011). Using a MRIO model, Peneder and Streicher (2018) also find that the main driver of deindustrialisation with regard to value added has been the global decline in relative prices of manufactured products. They highlight the paradoxical effect of industrial policies which increase productivity and international competitiveness at the national level but contribute to the overall effect of deindustrialisation at the global level. They also highlight, however, that the employment share of manufacturing has been reduced as a result of international trade in many high-income countries.

While international trade might not have been the most important driver of structural change in direct employment and value added from industry to service sectors, it did lead to some losses of employment in high-income countries. As a result, most high-income countries now show a considerable discrepancy between the total labour embodied in their final demand and the direct labour employed within the country, with the former exceeding the latter, especially within industry sectors (Simas et al., 2015; Sakai et al., 2017).

1.3.3 Structural change and energy use

In order to explore how structural change can contribute to the transition towards a post-growth economy it is important to understand how the patterns and drivers of structural change discussed in Sections 1.3.1 and 1.3.2 are linked to energy use. There are two relevant questions. The first is concerned with the relationship between the overarching patterns of structural change in employment and output and its relation to energy use. The second refers to the specific relationship between energy use and labour productivity.

1.3.3.1 The relationship between structural change and energy use

Since the 1950s most high-income countries have shown considerable reductions in the direct energy intensity of GDP that have led to relative decoupling but not absolute reductions in energy use (Csereklyei et al., 2016). There are propositions in the literature on environmental Kuznets curves that structural change in economic output and value added from direct industry to service sectors is one of the drivers of the observed reductions in direct energy intensity (Dinda, 2004; Stern, 2004).

However, the literature does not provide evidence for a strong effect of structural change in economic output or value added reducing the energy intensity across high-income countries. Even though structural change often contributes to direct energy intensity reductions, these contributions are usually small compared to the effect of energy intensity reductions within direct sectors and are not evident across all countries.

Structural change towards service sectors has been much stronger and more consistent when measured in terms of direct employment or nominal output and value added. But Henriques and Kander (2010) and Kander (2005) argue that it is structural change in real output that is relevant for direct energy use. They calculate sector shares in real output for a number of high-income countries using sector-specific price indices and find that the increase in direct service sector share is either absent or considerably smaller than in nominal output. While structural change still contributed to reductions in direct energy intensity in most countries, it also increased direct energy intensity in some. In those countries where structural change has contributed to reductions in aggregate direct energy intensity, these contributions are small, falling in the range of 2% to 9% between 1971 and 2005 (Henriques and Kander, 2010). This compares to contributions of 13% to 37% reductions from direct energy intensity reductions within individual sectors.

Their findings are also supported by a large literature conducting decomposition analyses of energy use across a range of different countries. These analyses conventionally allocate the change in a country's direct final or primary energy use to three effects, namely changes in direct sectoral energy intensities, changes in the structure (sectoral composition) of economic output or GVA and changes in overall output or GVA. These studies find that the contribution of structural change to energy intensity reductions varies widely across countries and time periods.

Some high-income countries, like the US, the UK and Germany show relatively consistent patterns where structural change has reduced the direct energy intensity of the economy, but has generally been less important than reductions in direct sectoral energy intensities (Henriques and Kander, 2010; Mulder and de Groot, 2013; Marrero and Ramos-Real, 2013; Fernández González et al., 2013). For other countries, such as Italy, Spain or Sweden, the evidence is much more mixed with structural change reportedly contributing to increases or reductions in direct energy intensity depending on the time period and method of analysis (Henriques and Kander, 2010; Mendiluce et al., 2010; Andreoni and Galmarini, 2012; Fernández González et al., 2013; Cruz and Dias, 2016). Torrie, Stone and Layzell (2016) report a rare case in which structural change contributed more to reductions in overall direct energy intensity than direct sectoral energy intensity reductions in Canada between 1995 and 2010.

The wide variety in results highlight that decomposition analyses are sensitive to the decomposition index used, the time period studied and the sectoral resolution of underlying data (Ang and Wang, 2015). Especially the sectoral resolution can have a strong impact on the reported effects of structural change, with a more detailed sectoral resolution leading to stronger structural change effects in the decomposition (Weber, 2009). Most of the studies cited above rely on a very coarse resolution of sectors. While the evidence therefore seems robust that high-level structural change from industry to services had a small but non-negligible impact on the energy intensity in many high-income countries, it is less clear in how far structural change within these sectors has contributed to energy intensity reductions.

The studies discussed above all estimate the impact of structural change on direct energy use within countries and focus on the sectoral composition of the economy from a direct perspective. However, for the transition to a post-growth economy it is important to consider the relationship between structural change and energy use in a global context, as the objective to stay within planetary boundaries can only be evaluated at the planetary level. The important question is in how far the contributions from structural change to direct energy intensity reductions in high-income countries have been driven by international trade and the off-shoring of energy-intensive production to other countries.

The literature gives some indications that offshoring has been an important factor, mainly based on MRIO analysis. Most high-income countries are now net importers of energy use, meaning that the energy use embodied in their final demand exceeds the direct energy use within the country (Chen and Chen, 2011; Simas et al., 2015). The UK has shown increases in net imports of embodied energy use until the financial crisis, but decreases thereafter (Owen et al., 2017). Assuming that high-income countries have not always been net-importers of embodied energy use, the existence of such net-imports indicate that structural change in the past has led to a shift of energy-intensive production away from high-income countries towards the rest of the world. Jiborn et al. (2018) suggest that this shift has been driven by trade specialisation rather than overall increases in the trade deficit of high-income countries, meaning that energy-intensive imports have largely been replaced by less energy-intensive exports. This effect is similar to the one that has been described for the decreasing share of direct manufacturing employment driven by international trade (Section 1.3.2.4). Such a combination is especially evident in the case of Germany, which features large net-exports in monetary terms but net-imports of energy and labour (Simas et al., 2015).

Lan et al. (2016) provide a structural decomposition analysis of energy footprints for countries around the world using a global MRIO model. They estimate that between 1990 and 2010 changes in the structure of the production system and the structure of final demand have only played a minor role in influencing the development of energy footprints around the world. These results provide another indication that energy demand reductions from structural change within high-income countries is likely a reflection of off-shoring.

Gaining a better understanding of how structural change and energy use within high-income countries is driven by global trade presents an important piece of the puzzle for developing viable strategies for structural change for a post-growth economy. This gap in the literature has informed my research objective A and I address this gap in the article presented in Chapter 2.

1.3.3.2 The relationship between energy use and labour productivity

In addition to the direct effects of structural change on energy use, there is also a potentially important connection between the two via their respective linkages to labour productivity. As discussed in Section 1.3.2.2, differential rates of labour productivity growth in different sectors are an important driver of structural change, at least in terms of employment, nominal output and nominal demand. Ecological economists argue that high rates of labour productivity growth in the past were only possible through increases in the amount of energy that was made available to workers. As a result reductions in the availability of high quality fossil fuels might reduce the potential for labour productivity growth (Tverberg, 2012; Kaufmann, 2014; Jackson, 2019). Some even argue that future energy constraints will not only reduce the rate of labour productivity growth but also the level, suggesting that unemployment in a post-growth economy will not be as much of a problem as is often claimed (Sorman and Giampietro, 2013). Degrowth scholars have responded by arguing that degrowth does not aim to maintain the same level of production and instead aims to systematically change lifestyles, production and consumption systems, which would reduce the level of production and allow for lighter workloads, even in an energy-constrained future (Kallis, 2013; Sekulova et al., 2013).

Elkomy et al. (2020) provide an extensive review of the literature on the relationship between energy and productivity. They conclude that there is evidence for a long-term link between energy use and productivity, but that there is very little clarity on how this link operates. Kander et al. (2013) argue that it was the overall availability of energy per worker, linked to the capital deepening of the economy, that has been an important enabler of increasing labour productivity since the beginning of the industrial revolution. Focusing on more recent times, Semieniuk (2016) decomposes the growth rate of fossil energy productivity into the growth rate of direct labour productivity and the growth rate of the direct energy-labour ratio. He then compares the growth rates of the two components for a large number of countries and for each decade from 1950 to 2012. He finds that, with the exception of the 1980s, there is a close relationship between the growth rates in the two ratios for most decades, with the direct energy-labour ratio growing at very similar rates to direct labour productivity. In addition, there is also evidence that it is not only the quantity but also the quality of energy inputs into production that is important for labour productivity. Especially the increasing share of electricity in the energy mix is considered to have played an important role in productivity growth, both in the manufacturing sector and the aggregate economy (Jorgenson, 1984; Beaudreau, 1995; Murillo-Zamorano, 2005).

The reliance of labour productivity growth on increases in the energy-labour ratio does not necessarily mean that there is a trade-off between the growth in energy and labour productivity, as overall energy intensity often declines at the same time as labour productivity rises. Jorgensen (1984) argues that this reflects the situation where increases in energy use stimulate growth in labour productivity above and beyond their own rate so that energy use increases while energy intensity falls or stagnates. This positive relationship between increasing energy efficiency and increasing labour productivity has more recently been used to strengthen the political case for energy efficiency improvements (Boyd and Pang, 2000; Worell, 2011; Baptist and Hepburn, 2013).

The discussions in the literature have mostly remained at the level of direct aggregate energy and labour productivity, sometimes also looking at the direct manufacturing sector on its own. However, in order to gain insights into the relationship between structural change and energy use it is important to know how the relationship between direct and embodied energy use and labour productivity differs between different economic sectors.

Mulder and de Groot (2004; 2007) provide one of the few systematic comparisons of direct labour productivity and direct energy productivity growth across four sectors (agriculture, manufacturing, services and transport) and across several OECD countries, covering the time period from 1970 to 1997. They find a positive relationship between growth rates in direct energy productivity and direct labour productivity in the manufacturing sector, and to a lesser extent, in the transport sector. In almost all of the countries and in both sectors, the growth rate of direct labour productivity exceeds the growth rate of direct energy productivity, indicating an increasing direct energy-labour ratio. However, in the services and agriculture sectors, the relationship between the growth rates of direct energy and labour productivity is less consistent.

Witt and Gross (2019) explicitly link the relationship between energy and productivity to structural change. They hypothesise that it is possible to raise direct labour productivity by substituting cheap energy for labour in the industry and transport sectors but not in the service sectors. They test their hypothesis using a co-integration model of US sectoral data between 1970 and 2005. They find that direct labour productivity is co-integrated with the direct energy-labour ratio only in the industry and transport sectors, but not in the services sector.

The two studies indicate that one of the drivers of differential rates of direct labour productivity growth could be the better ability of some direct sectors, especially the industry and transport sectors, to harness energy to replace labour. While the two studies show consistent results, it is difficult to assess whether such sector-specific relationships between direct energy use and labour productivity will hold in the future. It is generally expected that many labour productivity increases in the future will come from automation and information processing technologies (Frey and Osborne, 2017; Spencer, 2018). Such technologies could change the sector-specific patterns of the relationship between labour-productivity growth and energy use observed in the past, although there is currently not enough evidence to assess such impacts (Lange et al., 2020).

If some sectors, like the manufacturing and transport sectors, have indeed a higher potential for direct or embodied labour productivity growth based on a better ability to exploit energy sources, it would have implications for structural change in the transition to a post-growth economy. Firstly, any constraints on energy use might diminish the ability of the industry and transport sectors to increase labour productivity compared to other sectors, reducing one of the key drivers of structural change, in particular Baumol's cost disease. Secondly, the relationship between labour productivity growth and the energy-labour ratio might determine whether it is desirable to increase labour productivity in a sector or not.

However, so far there is not sufficient evidence on the relationship between energy use and labour productivity at the sectoral level in order to gauge the implications for structural change in the transition to a post-growth economy. To get a comprehensive picture it would be especially useful to compare direct and embodied measures of energy use and labour productivity, to gain additional insights into the drivers that have been responsible for shaping the relationship. For example, reductions in the direct energy-labour ratio in industry might be caused by improvements in technology or by the off-shoring of industrial sectors with a low energy-labour ratio.

The lack of evidence on the relationship between labour productivity and energy use at a sectoral level presents an important gap in the literature on post-growth economics and structural change. In Chapter 4, I present some new evidence on the direct and embodied energy-labour ratio of different sectors and their relationship to labour productivity as a part of a wider framework for identifying structural change goals for a post-growth economy.

1.4 Research approach

1.4.1 Overall approach

In the previous sections I have set out the overall research question I am addressing in my thesis, namely:

> *How can structural change contribute to the creation of a post-growth economy?*

In order to do so I have identified three research objectives that address specific gaps in the literature:

A. To provide evidence on the role of international trade in shaping structural change and energy use in high-income countries.
B. To provide empirical evidence on sectoral characteristics for the identification of labour-intensive services, focusing on an embodied perspective.
C. To develop a systematic approach for determining desirable structural change and sector-specific strategies for a post-growth economy.

My research is grounded in the perspective of post-growth economics and ecological macroeconomics. These approaches to economic analysis are highly sceptical of mainstream approaches based on marginalist substitution of production factors and consumer products and the analysis of markets as optimising systems (Rezai et al., 2013; Jackson et al., 2014; Rezai and Stagl, 2016; Hardt and O'Neill, 2017). Instead post-growth and ecological macroeconomic thinking has been drawing on ecological economics, which highlights the embeddedness of the economy in biophysical processes, and heterodox approaches to economic analysis, such as post-Keynesian, evolutionary and Marxian thinking, which are concerned with disequilibrium dynamics, non-optimisation models, path-dependency, uncertainty and power relations (Kronenberg, 2010; Foxon, 2011; Hardt and O'Neill, 2017; Pirgmaier and Steinberger, 2019; Jackson and Victor, 2020; Stratford, 2020).

Given the lack of structural change analysis in the post-growth literature, my research objectives aim to establish an empirical and theoretical foundation for a structural change analysis for the post-growth transition. As a result, the empirical analysis presented throughout my thesis is focused on structural change developments and sectoral characteristics derived from historical data, rather than dynamic modelling of future scenarios.

The most important method I employ in order to achieve my research objectives is MRIO analysis, which forms an integral component in the analysis performed for each of the three research objectives. MRIO models are particularly well placed for analysing structural change in the economy and for achieving my research objectives. Firstly, the MRIO framework is specifically built around a representation of the economy as a set of interconnected economic sectors

(Leontief, 1974; Miller and Blair, 2009). It therefore allows for the analysis of structural change while maintaining a comprehensive view of the aggregate economy. Secondly, MRIO models explicitly describe trade flows between sectors and can link them to the final demand for goods and services on one end, and the environmental impacts and labour inputs associated with economic production on the other end. MRIO models can therefore provide the link between the direct and embodied perspectives of sectoral structure (Owen et al., 2017). As outlined in Section 1.2.3, the consideration of both of these perspectives is an important requirement for analysing structural change for a post-growth economy. Lastly, MRIO models cover the whole global economy in a consistent manner that satisfies accounting balances. MRIO models therefore allow for an explicit assessment of how global trade has been related to structural change in individual countries (Minx et al., 2009; Peters et al., 2011; Timmer et al., 2013). Given the important role of international trade in shaping structural change, any analysis of structural change for a post-growth economy is incomplete without the consideration of international trade.

I address each of my three research objectives in an academic journal article, which make up Chapters 2-4 of my thesis.

1.4.2 Untangling the drivers of energy reduction in the UK economic sectors: Efficiency or offshoring?

The article in Chapter 2 addresses research objective A. It is part of Stream 2, which is concerned with the historical relationship between structural change and energy use. The objective is specifically concerned with obtaining new evidence on the link between structural change impacts on energy use in high-income countries and the development of international trade.

In order to address this research objective I perform an index decomposition analysis of direct final energy use in the UK between 1997 and 2013. The index decomposition builds on the approaches used in the literature on energy decomposition analysis, as discussed in Section 1.3.3.1. However, I add a novel element that utilises MRIO data to determine whether structural change in the UK is related to the off-shoring of industries to other countries. In this way the decomposition analysis specifically addresses the gap in the literature, which, so far, does not link structural change within countries to international trade.

In addition I also provide some novel insights on the drivers of another important decomposition factor, namely the direct energy intensity within sectors. Using data on the useful exergy consumption in the UK, I investigate the role that increases in the thermodynamic conversion efficiency from final energy to useful exergy have played in driving changes in the direct energy intensity of output in different sectors. Useful exergy measures the amount of useful work (in thermodynamic terms) that is delivered by energy carriers to the economy, such as the movement of a car or the light emitted by a light bulb (Brockway et al., 2014; Sousa et al., 2017). It is useful to investigate the role of useful exergy conversion, because there is some evidence that the amount of useful exergy used is even more strongly coupled with GDP than primary and final energy use (Warr et al., 2010; Serrenho et al., 2014; Guevara et al., 2016).

I focus on the UK as a relevant case study for the research objective because it is one of the few countries that has achieved absolute reductions in direct final energy use in combination with increasing GDP since the early 2000s (Csereklyei et al., 2016; Department for Business Energy & Industrial Strategy, 2018). Given the importance of reducing final energy use for the transition to a post-growth economy, it is useful to examine the case of the UK in order to gain better insights into how the reductions in direct final energy use were achieved.

1.4.3 Structural change for a post-growth economy: Investigating the relationship between embodied energy intensity and labour productivity

The article in Chapter 3 addresses research objective B. It is part of Stream 1, which is focused on the transition to a post-growth economy. Objective B is specifically concerned with the shift towards labour-intensive services that is advocated in the post-growth literature. It addresses the gap in the literature that is the lack of an empirical analysis identifying labour-intensive services and the lack of a discussion of the challenges of achieving such a shift.

I identify two characteristics of labour-intensive services, namely a low energy intensity and a low rate of labour productivity growth. The lack of empirical evidence on such sector characteristics is especially prevalent for data from an embodied perspective, as data on direct energy intensity and direct labour productivity growth are widely available. Although the latter have not been used specifically for the identification of labour-intensive services from a post-growth perspective.

Given the international nature of our global economy and supply chains, the estimation of embodied energy intensity and labour productivity requires an MRIO model. To address my research objective I therefore use the EXIOBASE MRIO model (Stadler et al., 2018) to estimate novel results for the embodied final energy intensity and embodied labour productivity associated with demand sectors in the UK and Germany between 1995 and 2011. In order to do so, I develop a new extension to the EXIOBASE MRIO model describing direct final energy inputs in economic sectors across the world. The new empirical evidence I provide allows me to identify a subset of demand sectors that show the characteristics of labour-intensive services.

In order to gain more insights into the potential challenges surrounding the promotion of such labour-intensive services, specifically from Baumol's cost disease, I also link the analysis of embodied energy intensity and labour productivity to the changes in prices in different sectors.

While the MRIO model takes into account final energy use and labour inputs along the global supply chain, I focus on the final demand in the UK and Germany. Focussing on these two case studies allows me to strike a balance between providing the necessary detail on final energy use, especially in the service sectors, while also allowing for some international comparison.

I have chosen the UK and Germany as case study countries, because they are both high-income countries with similar income levels but important differences in sectoral structure, both in terms value added and demand, and economic dynamics. Since the 1990s, the UK has experienced considerable reductions in the share of direct output, labour and energy use in the industrial sectors, with an increasing share in the service sectors (Department for Business Energy &

Industrial Strategy, 2018; Office for National Statistics, 2019). In contrast, Germany has experienced deindustrialisation to a lesser degree and has retained a greater share of the industry sectors in direct employment and output (Statistisches Bundesamt, 2019; AG Energiebilanzen, 2020). The two countries therefore provide a useful contrast for the investigation of structural change.

1.4.4 What structural change is needed for a post-growth economy: A framework of analysis and empirical evidence

The article in Chapter 4 addresses research objective C. It is also part of Stream 1 and is concerned with the development of a systematic approach for identifying structural change goals and sector-specific strategies for a post-growth economy, an important gap in the post-growth literature (see Section 1.2.2.3).

In order to address this gap I develop a novel framework that allows for identification of structural change goals for different sectors based on sector characteristics in three dimensions, namely the sectoral energy intensity, the potential for labour productivity growth, and the relationship between labour productivity and the energy-labour ratio. The structural change goals for individual sectors are derived by combining the sector characteristics in these three dimensions with the two overarching structural change goals for the whole economy identified in Section 1.2.2.2. Overall this framework allows me to identify a number of sector groups that share the same combination of characteristics and therefore the same structural change goals.

I apply the framework by estimating values for the sector characteristics for economic sectors in the UK and Germany. As outlined before, it is important that sector characteristics are considered both from a direct and embodied perspective. The empirical analysis I conduct for this purpose builds on the one conducted for objective B using the EXIOBASE MRIO model and my own extension describing direct final energy use. However, it expands the analysis by adding new results with regard to the relationship between the energy-labour ratio and labour productivity and by comparing direct and embodied values for the sector characteristics in all three dimensions.

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Chapter 2

Untangling the drivers of energy reduction in the UK economic sectors: Efficiency or offshoring?

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Abstract:

The UK has been one of the few countries that has successfully decoupled final energy consumption from economic growth over the past 15 years. This study investigates the drivers of direct final energy consumption in the UK economic sectors between 1997 and 2013 using a decomposition analysis that incorporates two novel features. Firstly, it investigates to what extent changes in the thermodynamic conversion efficiency from final energy to useful exergy have contributed to overall changes in direct sectoral energy intensities. Secondly, it analyses how much of the structural change in the UK economy is driven by the offshoring of energy-intensive production overseas. The results show that direct energy intensity reductions are the strongest factor reducing energy consumption. However, only a third of the energy savings from energy intensity reductions can be attributed to increases in the final-to-useful conversion efficiency, with reductions in the useful exergy intensity of monetary output making up the reminder. In addition the majority of energy savings from structural change are a result of offshoring, which constitutes the second biggest factor reducing energy consumption. In recent years the contributions of all decomposition factors have been declining with very little change in energy consumption after 2009. This suggests that a return to the strong reductions in direct energy consumption observed between 2001 and 2009 in the UK economic sectors should not be taken for granted. Given that further reductions in UK final energy consumption are needed to achieve global targets for climate change mitigation, additional policy interventions are needed. Such policies should

adopt a holistic approach, taking into account all direct sectors in the UK economy as well as the relationship between the structural change in the UK and in the global supply chains delivering the goods and service for demand in the UK.

Keywords: Energy consumption; Decomposition; UK; Exergy; Multiregional input-output databases; Offshoring

2.1 Introduction

Most of the IPCC scenarios aiming to limit global warming to 2°C result in a stabilisation of energy consumption at the global level (Clarke et al., 2014). This requirement for stabilisation should be considered as an optimistic requirement as most of the scenarios also rely on large quantities of unproven negative emission technologies (Anderson and Peters, 2016; Peters et al., 2017). If such technologies do not materialise at sufficient scale, stabilisation of global energy consumption might not be sufficient and absolute reductions might be needed to avoid dangerous climate change. At the same time global population is predicted to increase over the period to 2050 by about 30% compared to current levels in the UN's medium variant (United Nations, Department of Economic and Social Affairs, 2017) and many less-developed countries will need to increase their energy consumption to reduce poverty and social hardships, especially given that 16% of the global population currently do not have access to energy (International Energy Agency, 2017). Increasing energy consumption in developing countries combined with a need to stabilise (let alone reduce) global energy use therefore implies the need for absolute reductions in direct energy consumption in developed countries, potentially exceeding 50% for per capita energy-use.

However, only very few developed countries have so far achieved an absolute decoupling of direct final energy consumption and economic growth over extended periods of time (Csereklyei et al., 2016). One of the few examples where this has happened is the UK. Despite a 19% growth in real GDP, direct final energy consumption (excluding non-energy use) declined by 11% between 2001 and 2013 (Figure 2-1). However, to meet climate change targets direct energy

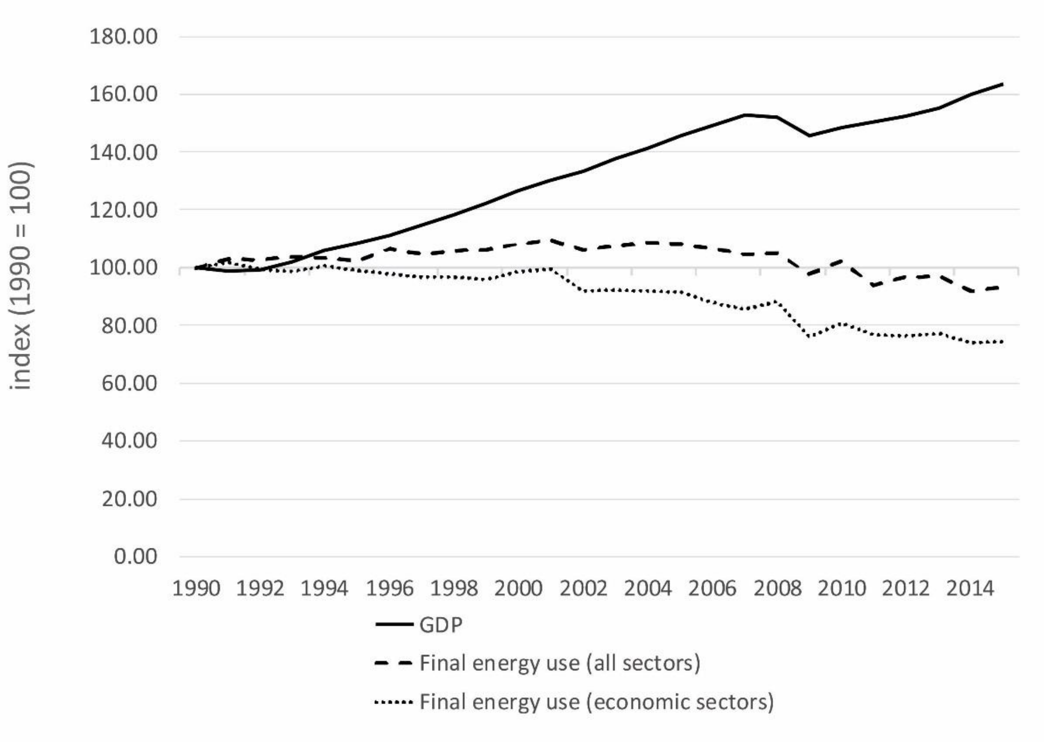

Figure 2-1: UK GDP and final energy consumption (excluding non-energy use) between 1990 and 2015. Values are indexed with 1990 = 100. Economic sectors include the industry and non-industrial sectors but excludes energy consumption for domestic and transport purposes. GDP and energy data were obtained from the UK Office for National Statistics (Office for National Statistics, 2017) and the Energy Consumption in the UK data collection (Department for Business Energy & Industrial Strategy, 2016b) respectively.

consumption will most probably need to be reduced even further. To assess the need for further policy interventions and to see whether lessons from the UK can be applied in other countries, it is important to understand what has been driving the reduction in direct energy consumption in the UK and whether the trends are likely to continue into the future.

This study will contribute to this understanding by providing an analysis of the direct final energy consumption in the UK economic sectors between 1997 and 2013. We refer to economic sectors as those direct sectors that use final energy carriers for commercial purposes and record economic output in the national accounts, including industrial and non-industrial sectors, but excluding the direct final energy used in the commercial transport sector for reasons discussed in Section 2.2. By focusing on economic sectors we exclude final energy used for non-commercial domestic (i.e. residential) and transport use. This study is also exclusively concerned with the direct energy intensity of different direct sectors in the UK. It does not investigate the embodied energy intensity associated with different demand sectors, although it assesses the global output of different sectors that is embodied in the total final demand in the UK. The term "sector" therefore exclusively refers to direct sectors in this chapter.

While non-transport, final energy consumption in the economic sectors only accounted for 31% of all direct final energy consumption in the UK in 2013 (Figure 2-2), the reductions in direct final energy consumption in these sectors account for about two thirds of the overall reductions in direct UK final energy consumption since 2001. To investigate the drivers of energy consumption in the economic sectors this study employs an index decomposition analysis with two novel features. Firstly, it draws on energy conversion chain (ECC) analysis that allows the estimation of the conversion efficiencies from final energy to useful exergy (Heun et al., 2017). In this way direct energy intensity reductions can be broken down into a component representing the conversion efficiency from final energy to useful exergy (hereafter final-to-useful efficiency) and a component

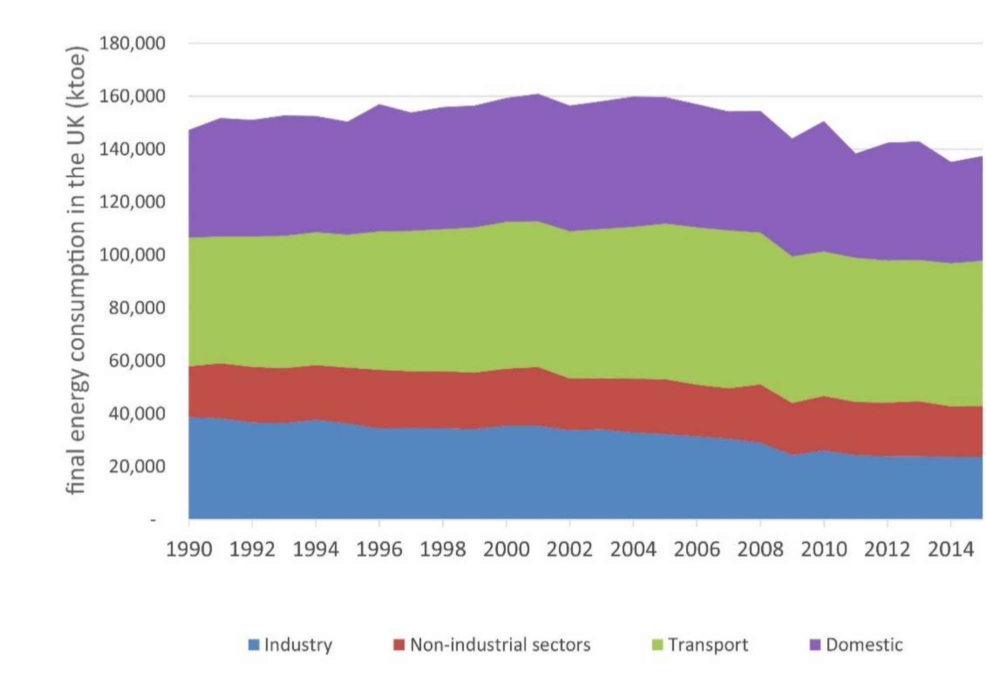

Figure 2-2: Final energy consumption in the UK by purpose. This article only investigates energy use in the economic sectors which include the industry and non-industrial sectors shown here. Energy data were obtained from the Energy Consumption in the UK data collection (Department for Business Energy & Industrial Strategy, 2016b).

representing the changing monetary output per unit of useful exergy. Secondly, it employs data from a multi-regional input-output (MRIO) model to investigate how much of the direct energy savings resulting from structural change can be attributed to offshoring. The results of this decomposition analysis are also compared to the results of a conventional approach featuring only direct energy intensity and structural change factors.

Index decomposition analysis is a widely-used tool to identify the drivers of change in direct energy use and carbon emissions (Liu and Ang, 2003; Ang, 2004). It has been applied to study aggregate direct energy consumption in countries (Fernández González et al., 2013; Xu et al., 2014), as well as energy consumption for particular purposes, such as domestic (i.e. residential) energy use (Nie and Kemp, 2014; Xu and Ang, 2014) and transport energy use (Sorrell et al., 2009; Zhang et al., 2011). Index decomposition analysis of energy use in economic sectors commonly decomposes energy use according to three factors, namely direct energy intensity, structural change and output (Liu and Ang, 2007). In such an approach direct energy intensity describes the energy used per unit of monetary output in each sector, structural change describes the sectoral composition of economic output and output describes the change in the aggregate output of the economy. Such decomposition analyses for the UK generally conclude that direct energy intensity reductions have been the major driver of reductions in direct UK final energy consumption over the last two decades, even though structural change has also been important (Liu and Ang, 2007; Hammond and Norman, 2012; Fernández González et al., 2013; Mulder and de Groot, 2013; Marrero and Ramos-Real, 2013; Gynther et al., 2015; Obadi and Korček, 2015; Cruz and Dias, 2016). However, most of these studies only pay brief attention to the UK as part of a multi-country study and there has not been a comprehensive analysis of the drivers of direct final energy consumption in the UK economic sectors in the past two decades. Hammond & Norman (2012) decompose trends in direct energy use and CO_2 emissions in the UK, but focus exclusively on the manufacturing sectors between 1990 and 2006. Reports from the ODYSEE-MURE project present detailed analyses of the ODEX efficiency indicator, but pay less attention to structural change (Ricardo Energy & Environment et al., 2015).

The conventional decomposition approach focusing on direct energy intensity, structure and output provides important insights, but it leaves important questions unanswered about the underlying drivers of changes in direct energy intensity and economic structure. Firstly, the measure of direct energy intensity does not answer the question of whether changes have been driven by an increasing final-to-useful efficiency of energy conversion or by other effects influencing monetary output. Secondly, looking at structural change within a country does not indicate whether this structural change is a reflection of offshoring, (i.e. a shift of energy-intensive production to other countries) or whether it is due to changed economic demands and the production structure that satisfies them. Whether structural change is due to offshoring is important, because it determines in how far direct energy savings from structural change have contributed to global climate change mitigation efforts. There are studies that have used input-output models to investigate changes in the energy-footprint of countries, including the UK (Lan et al., 2016; Owen et al., 2017). However, these studies do not link the changes in the footprint to the changes in domestic structure of economic output to assess in how far domestic structural change has been a result of offshoring. Other studies specifically study the economic impacts of environmental improvements along the whole supply chain of products, focussing on specific companies or sectors (Savino et al., 2015; Savino et al., 2017). The two novel features employed in this study provide new insights into the underlying drivers of direct energy intensity reductions and structural change across the whole of the UK economic sectors.

2.2 Data and methods

2.2.1 The decomposition factors

This study investigates the drivers of the change in direct final energy consumption (excluding non-energy use) in the UK economic sectors between 1997 and 2013. Direct final energy excludes energy consumed by those economic sectors that produce primary energy carriers (e.g. the extraction of oil & gas) or transform primary energy into final energy carriers for sale (e.g. oil refineries). For brevity the word energy always refers to final energy in this article. The economic sectors include only those direct sectors that use final energy consumption for commercial purposes and record economic output in the national accounts. The energy used for personal transport and domestic uses is not investigated. The commercial transport sector is also not analysed in this study, because it is difficult to disentangle the energy consumption for private and commercial transport and transport energy use is a complex issue that would not be well served by the approach applied here to the other sectors (for a good analysis of UK road freight energy use see (Sorrell et al., 2009). The economic sectors analysed are subdivided into fifteen direct sectors including twelve industrial and three non-industrial sectors (Table 2-1). This is the most disaggregated level of energy data available from 1997. These sectors cover all sectors in the national accounts excluding the transport and energy producing sectors. For ease of presentation many of the results will be aggregated as

Table 2-1: Sector split used in the conventional and extended decomposition analysis, based on the classification used in the Digest of the United Kingdom energy statistics (Department for Business Energy & Industrial Strategy, 2016a).

Sector name	SIC 2007 code
Industrial Sectors	
Iron & Steel	24.1 – 24.3
Non-ferrous Metals	24.4 – 24.5
Mineral Products	08, 23
Chemicals	20 - 21
Mechanical Engineering and Metal Products	25, 28
Electrical and Instrument Engineering	26 - 27
Vehicles	29 - 30
Food, Beverages & Tobacco	10 - 12
Textiles, Clothing, Leather & Footwear	13 - 15
Paper, Printing and Publishing	17 - 18
Other Industries	16, 22, 31-33, 36-39
Construction	41-43
Non-industrial sectors	
Public Administration	84 - 88
Commercial Services	45-47, 52-53, 55-56, 58-66, 68-75, 77-82, 90-99
Agriculture	01-03

"industrial" and "non-industrial" sectors, in which the latter contains the direct public and commercials services and agriculture sectors.

To analyse the change in direct final energy consumption in the UK economic sectors two decomposition analyses are presented. The first decomposition analysis follows the conventional approach to estimate the role that changes in the direct energy intensity and structure of the economy have contributed to the observed change in direct final energy consumption in the UK economic sectors.

The main purpose of this conventional decomposition is to serve as a comparison to the new and extended approach. Specifically, this comparison was used to verify that the treatment of structural change in the newly developed extended approach is comparable to the conventional approach, because the extended approach uses slightly different decomposition factors to describe structural change. For the purpose of the conventional decomposition analysis, direct final energy consumption in the economic sectors (E) is expressed as the combination of an intensity effect (I), a structural change effect (S), an output effect (O) and a population effect (P) (Table 2-2):

$$E = \sum_i I_i \, S_i \, O \, P = \sum_i \frac{E_i}{X_i} \frac{X_i}{X} \frac{X}{P} P \qquad \text{(2-1)}$$

where E_i is the direct sectoral energy consumption in the UK, X_i is sector output in the UK, X is total output of the UK and P is UK population. The subscript i denotes the economic sectors studied, which are presented in Table 2-1.

The extended analysis introduces two novel features that further investigate the intensity and structural change effects. While the direct final energy use (E) is the same as in the conventional approach, the extended approach includes more factors in the identity used to decompose direct final energy consumption. These six factors are a final-to-useful efficiency effect (FUE), a useful exergy intensity effect (UEI) an offshoring effect (OS), an embodied output effect (EO), a final demand effect (DM) and a population effect (P) (Table 2-2):

$$E = \sum_i FUE_i \, UEI_i \, OS_i \, EO_i \, DM \, P = \sum_i \frac{E_i}{UE_i} \frac{UE_i}{X_i} \frac{X_i}{XG_i} \frac{XG_i}{Y} \frac{Y}{P} P \qquad \text{(2-2)}$$

Table 2-2: Summary of the decomposition factors used in the conventional and extended decomposition analysis. More detailed descriptions are provided in Section 2.2.1. Data sources used to construct the factors are outlined in Section 2.2.3.

Decomposition factor		**Description**	**Units**
Conventional decomposition			
Intensity	I_i	Final energy used in each UK sector (E_i) divided by the monetary output of the sector (X_i)	ktoe/ million £
Structural change	S_i	Monetary output of each UK sector (X_i) divided by the total output of the UK economy (X)	million £/ million £
Output	O	Total output of the UK economy (X) divided by the UK population (P)	million £/ person
Population	P	UK population (P)	person
Extended decomposition			
Final-to-useful efficiency	$FUCE_i$	Final energy used in each UK sector (E_i) divided by the useful exergy used in the sector (UE_i)	ktoe/ ktoe
Useful Exergy intensity	UEI_i	Useful exergy used in each UK sector (UE_i) divided by the monetary output of the sector (X_i)	ktoe/ million £
Offshoring	OS_i	Monetary output of each UK sector (X_i) divided by the sector's global output embodied in UK final demand (XG_i)	million £/ million £
Embodied Output	$ECON_i$	Global sector output embodied in UK final demand (XG_i) divided by the total amount of UK final demand (Y)	million £/ million £
Demand	DM	Total amount of UK final demand (Y) divided by UK population (P)	million £/ person
Population	P	UK population (P)	person

where E_i is direct sectoral energy consumption in the UK, UE_i is the useful exergy consumed in each direct sector, X_i is sector output in the UK, XG_i is the global output of the sector embodied in UK final demand, Y is UK final demand and P is UK population.

The first two factors subdivide the energy intensity effect in the conventional decomposition into two separate effects, namely the final-to-useful efficiency effect and the useful exergy intensity effect. These two factors sum exactly to the energy intensity effect in the conventional decomposition. The final-to-useful efficiency effect describes the efficiency with which direct final energy is transformed into direct useful exergy in each sector as obtained from ECC analysis (Heun et al., 2017). Useful exergy describes the work that is delivered at the last stage of the energy conversion chain that can still be measured in energy units, for example useful heat, mechanical drive, or light. Useful exergy can therefore be considered to be most closely related to the energy services delivered (Sousa et al., 2017). The final-to-useful efficiency effect is calculated as direct final energy per unit of direct useful exergy used in each sector. This factor presents a purely thermodynamic measure of energy efficiency, because it is a ratio of two energy measures.

In contrast, the useful exergy intensity effect is a mixed measure as the ratio includes monetary and energy measures. The effect captures the changes in the monetary output that is produced for each unit of direct useful exergy. These can include changes in the physical efficiency of the production process that are not captured by the final-to-useful efficiency effect, but also changes in the monetary value of production, imperfect deflation and structural change within sectors. For example the conventional approach applied to the steel sector would describe the energy intensity of the sector as the direct final energy used in the sector divided by the output of steel (in monetary terms). The extended version splits this ratio into a ratio describing the direct final energy used per unit of direct useful exergy used (i.e. the mechanical drive, heat and light used) and a ratio describing the direct useful exergy used divided by the output of steel (in monetary terms). This can provide new insights into whether reductions in direct energy intensity have come from increases in in final-to-useful conversion efficiencies or changes in the monetary value of the output produced.

The offshoring and embodied output effects allow further examination of the drivers of structural change. The two effects do not exactly sum to the structural change effect in the conventional decomposition because the extended decomposition uses final demand per capita as its fifth decomposition factor, rather than total output per capita, which is used in the conventional decomposition. Final demand describes all the goods and services bought in the UK, whether for the purpose of consumption or investment. The use of final demand in the analysis is required to incorporate the global supply chains that are associated with final demand in the UK. Since total final demand and total output generally develop in a similar fashion, the results of the conventional and extended decomposition analysis remain comparable.

The offshoring effect describes the ratio of domestic sector output divided by the global sector output embodied in UK demand. The global output embodied in UK final demand is obtained from the UKMRIO model (Owen et al., 2017) and describes the total monetary output (in each sector) that is used globally to satisfy the final demand of goods and services in the UK, taking into account intermediate consumption along the whole supply chain. For the steel sector this includes all steel used at some point in the supply chain of the products bought in the UK. For example this could be steel that is produced in China, if it is then made into a car in Germany and sold in the UK. The embodied output effect in turn describes the global sector output embodied in each unit of final demand in the UK, for instance how much steel has been used in the world for each £ of goods bought for UK final demand. The terms offshoring and embodied output are used here as a convenient shorthand. The offshoring effect does not exclusively capture the deliberate movement of industry from the UK to other countries. Instead it can be interpreted as an indicator of the potential direct sectoral capacity that the UK economy possesses to satisfy the final demand for goods and services in the UK. For example it compares the amount of steel embodied in UK final demand to the steel produced in the UK, even if the latter is not necessarily used for products sold in the UK. Similarly the embodied output effect captures a variety of potential changes both in the composition of UK final demand as well as in the structure of the global supply chains satisfying this demand. In effect, the offshoring and embodied output effects determine whether structural changes in the UK have been matched by structural changes in the economic output embodied in UK final demand. If the structural change in the UK (e.g. a relative decline of manufacturing) is not matched by changes in the embodied output it is considered to constitute a type of offshoring.

2.2.2 The decomposition index

This study employs the Logarithmic Mean Divisia Index (LMDI). The LMDI method has been identified as one of the most suitable methods for energy decomposition because it gives complete decomposition without residuals, it has a sound theoretical foundation, it passes the test of time reversal and factor reversal and is easy to implement (Hoekstra and van den Bergh, 2003; Ang, 2004; Su and Ang, 2012). It is also well suited to multidimensional and multilevel energy data, as used for this study, because it gives perfect decomposition at the sub-category level and is consistent in aggregation (Ang and Wang, 2015). The

LMDI index can be used in two different ways, either in an additive or in multiplicative form. This choice does not affect the conclusions from the study because the results from either method can be transformed into the other by a simple formula (Ang, 2004). In this study the additive version of the LMDI index is used as it was considered that its results are easier to interpret.

The subject of this study is the decomposition of the total direct final energy consumption in the UK economic sectors (E) which is subdivided into the direct energy consumption of economic sectors, denoted by subscript i. For the purpose of the decomposition analysis E is expressed as a product of n factors, $E = \sum_i E_i = \sum_i x_{1,i} * x_{2,i} * x_{3,i} * \ldots * x_{n,i}$. The factors used in this analysis are described in Section 2.2.1.

The additive LMDI method is then used to allocate the overall difference in energy consumption between a time period 0 and a time period T (ΔE) to the respective factors:

$$\Delta E = E^T - E^0 = \Delta E_{x_1} + \Delta E_{x_2} + \Delta E_{x_3} + \cdots + \Delta E_{x_n} \qquad (2\text{-}3)$$

Drawing on Ang (2004) the following LMDI formula was used to determine the contribution of the k^{th} factor to the change in energy consumption (version LMDI-I):

$$\Delta E_{x_k} = \sum_i \frac{E_i^T - E_i^0}{\ln(E_i^T) - \ln(E_i^0)} * ln\left(\frac{x_{k,i}^T}{x_{k,i}^0}\right) \qquad (2\text{-}4)$$

This study uses decomposition analysis to investigate the change in energy consumption over a multi-year time period. As annual data are available this study employs a chained decomposition methodology. This means that the change of direct energy consumption is always decomposed for two consecutive years rather than comparing each year to a common base-year. The chaining method should be preferred when annual data are available as it better represents the true change and the results are independent from a choice of base year (Ang et al., 2010).

2.2.3 Data

Data describing the direct final energy consumption in the UK economic sectors were obtained from the Digest of UK Energy Statistics and the Energy Consumption in the UK data collection (Department for Business Energy & Industrial Strategy, 2016b). The Digest of UK Energy Statistics (Department for Business Energy & Industrial Strategy, 2016a) contains a category of "unclassified industrial energy use" which introduces an element of uncertainty into the analysis. For this article the "unclassified industrial energy use" was allocated to the Other Industries sector. The data showed that significant decreases in one of the two categories was often accompanied by significant increases in the other category. This suggests that the data in both categories are strongly influenced by statistical re-classifications of different energy uses between the two sectors. Therefore it was considered most consistent to add the unclassified energy use to the direct energy use in the Other Industries sector, although this is likely to overestimate the direct energy use in the latter. While results for the Other Industries sector should therefore be interpreted with caution, this treatment does not affect the results for the industrial sector as a whole.

There has been some discussion in the literature about the measure of economic output that is best used to measure the energy intensity of direct economic sectors (Patterson, 1996). This literature is mainly concerned with the question whether it is better to use physical or monetary values, and, if the latter are used, which kind of monetary value to use (for a good summary see Hammond and Norman, 2012). In this study only monetary output measures are used, as this allows a comparable and consistent treatment of all sectors. There are different monetary output measures that can be used, including value added and total value of production. While value added is most frequently used, Hammond & Norman (2012) concluded that there is no evidence that one measure is superior. In this study the total value of production is used to measure output, as given in the national supply and use tables. This measure was chosen because it fits better into the input-output framework used in the extended decomposition.

All the economic data were obtained from the UKMRIO model, which is based on the national accounts produced by the UK Office for National Statistics

(Owen et al., 2017). The economic data obtained include figures for the annual production of the fifteen investigated sectors, production of the UK economy as a whole, levels of final demand in the UK as well as the global output of each sector embodied in UK demand. Monetary variables in the UKMRIO model were converted into constant prices by applying the double deflation method (Lan et al., 2016). As is conventional in input-output analysis, the sector output embodied in UK final demand was obtained by multiplying the Leontief inverse of the input-output table with the vector of UK final demand for each year. A more detailed description is available in Owen et al. (2017). This method implies that the boundary for calculating embodied sector outputs includes only the intermediate demand of goods and services in each year, but not capital expenditures.

The analysis in this article is restricted to the time period from 1997 to 2013, because the input data obtained from the UK MRIO model are only available for this time period. However, the time period is adequate as it captures the change in trend from stagnating to decreasing direct final energy consumption in the UK economic sectors observed around 2001 (Figure 2-1).

Data on the direct useful exergy used in each sector was produced by the authors. The useful exergy data are calculated in three steps. First the direct final energy used in each sector is mapped to the main useful work categories (heat, mechanical drive, electricity and muscle work) and then to individual task levels within these categories (e.g. work done by cars, light bulbs, etc.). Second, for each individual task level conversion efficiencies (final energy to useful exergy) are estimated based on the literature or new calculations. Third, the task-level final energy values and final-to-useful conversion efficiencies are then multiplied together, and summed to obtain the direct useful exergy used in each sector. A more detailed description of the methodology can be found in Brockway et al. (2014; 2015).

2.3 Results

The conventional decomposition shows that reductions in direct final energy consumption in the UK economic sectors between 1997 and 2013 were achieved despite significant upward pressures on energy consumption from increased output per capita and population growth (Figure 2-3a). Direct energy consumption declined because these upward pressures were more than offset by reductions from the energy intensity and structural change effects, with the reductions allocated to the energy intensity effect being significantly bigger than the reductions allocated to the structural change effect.

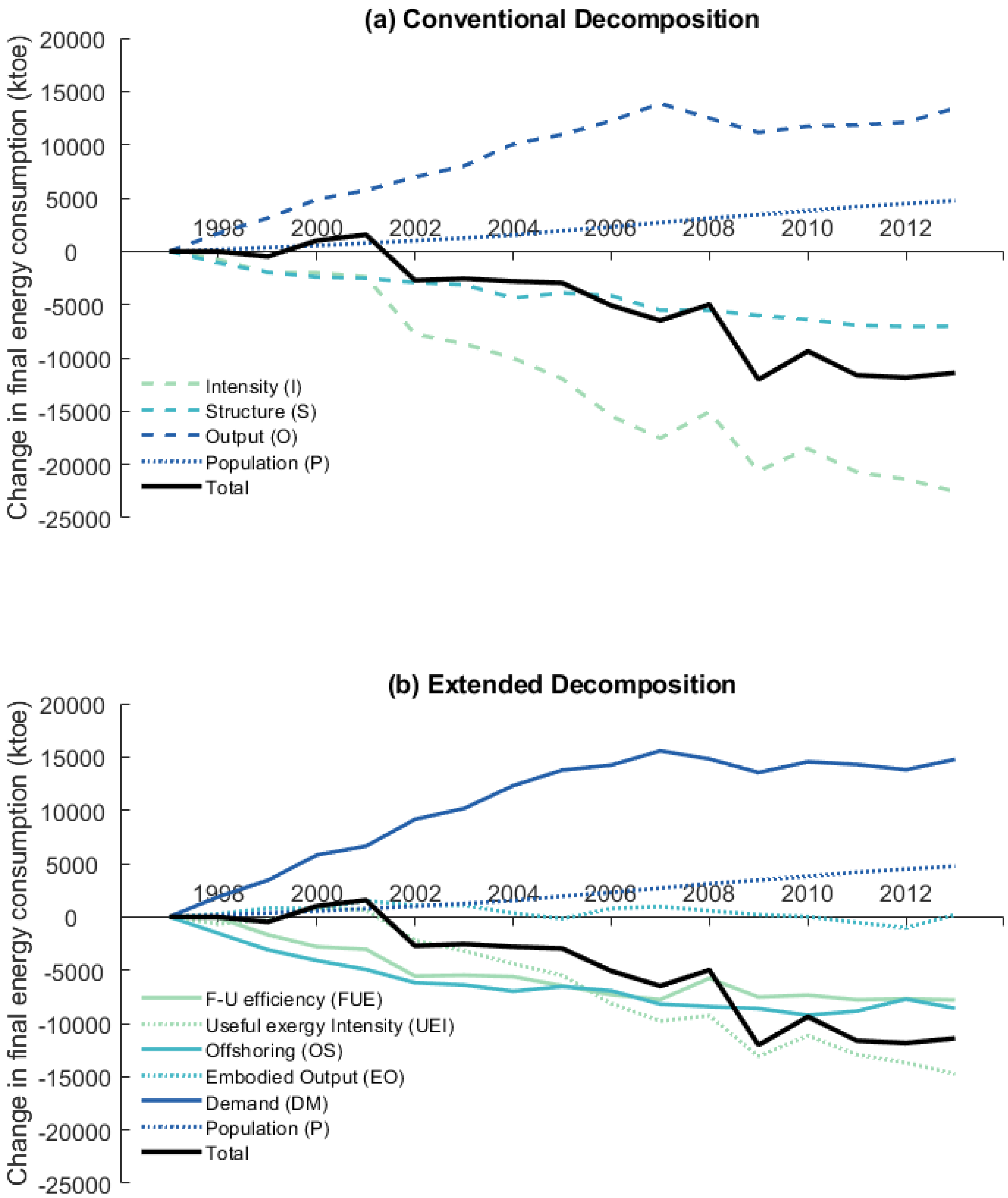

Figure 2-3: Aggregate results showing the allocation of change in final energy consumption in the economic sectors to the decomposition factors in (a) the conventional decomposition analysis and (b) the extended decomposition analysis. For each year the cumulative change since 1997 is shown.

Despite using more and slightly different factors, the extended decomposition analysis produces very similar results (Figure 2-3b). There are no differences in the qualitative patterns and the quantitative differences between the output and demand effects as well as between the structural change effect and the combined offshoring and embodied output effects are small. This gives confidence that the results are comparable. A number of interesting observations stand out.

Firstly, the useful exergy intensity effect is larger than the final-to-useful efficiency effect, when the whole time period is considered (Figure 2-3b). However, up to 2005 the final-to-useful efficiency effect contributes more reductions in direct energy consumption. The relationship between the useful exergy intensity effect and the final-to-useful efficiency effect differs between sectors. While the two are of equal magnitude in the industrial sectors, the useful exergy intensity effect is significantly larger in the non-industrial sectors. Within the industrial sectors the bulk of reductions in energy consumption is very much concentrated in two sectors, namely Iron & Steel and Chemicals. These two sectors account for over 60% of reductions in direct energy use in the industrial sectors and 60% of the reductions assigned to the energy intensity effect in industry, even though they only used 32% of all direct industrial energy in 1997. An important contributor to this concentration is the useful exergy intensity effect. Almost 75% of the direct energy savings allocated to this effect in the industrial sectors occur in the Iron & Steel and the Chemicals sectors (detailed sectoral results are provided in Table A1 in Appendix A).

Secondly, the direct energy savings attributed to the offshoring effect are much bigger than the energy savings attributed to the embodied output effect, with virtually no reductions in direct energy consumption due to the embodied output effect at the aggregate level (Figure 2-3b). This pattern is the result of direct energy savings attributed to the embodied output effect in the industrial sectors (Figure 2-4a) being cancelled out by increases in direct energy consumption attributed to the embodied output effect in the non-industrial sectors (Figure 2-4b). All the energy savings from the offshoring effect occur in the industrial sector with no changes in direct energy consumption in the non-industrial sectors attributed to the offshoring effect. While the Agriculture sector shows a

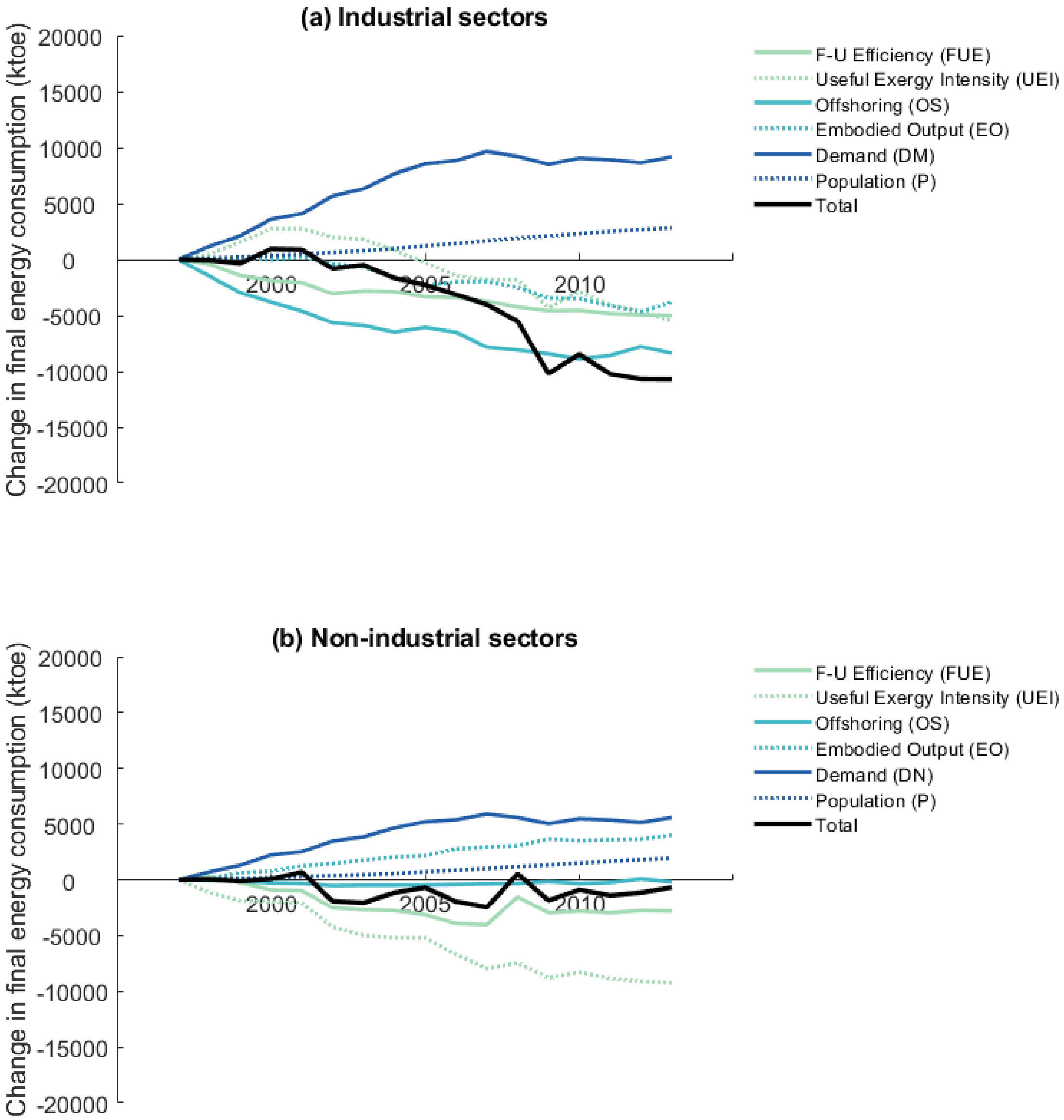

Figure 2-4: Results of the extended decomposition analysis showing the allocation of change in final energy consumption to the decomposition factors for (a) the industrial sectors and (b) the non-industrial sectors. For each year the cumulative change since 1997 is shown.

significant reduction in direct energy use due to the offshoring effect, the size of the sector is so small that it hardly shows up in the aggregate total for the non-industrial sectors.

Lastly, the importance of the different effects varies significantly over time (Table 2-3). Both the final-to-useful efficiency effect and the offshoring effect contribute to direct energy savings but at declining rates, with very low contributions after 2009. The useful exergy intensity effect contributes strongly to reductions in direct energy consumption between 2001 and 2009 and also at a more moderate

rate thereafter. The demand effect increases direct energy use except for the time of the crises. However, even after 2009 contributions from the demand effect remain subdued. This means that after 2009 the contributions from all factors are significantly smaller than they were in the time before the crisis (Table 2-3).

Table 2-3: Results of the extended decomposition analysis for different time periods and decomposition factors. The results are obtained by first applying equation 2-4 to each effect, sector and year and then summing the results across all sectors and over the relevant time periods.

ktoe	**1997-2001**	**2001-2005**	**2005-2009**	**2009-2013**	**Total**
Final-to-useful efficiency	-3046	-3418	-1061	-272	**-7797**
Useful exergy intensity	653	-6139	-7591	-1660	**-14737**
Offshoring	-4939	-1602	-2066	25	**-8582**
Embodied output	1501	-1671	375	-13	**191**
Demand	6630	7130	-220	1233	**14773**
Population	767	1168	1505	1313	**4754**
Total	**1566**	**-4533**	**-9057**	**626**	**-11398**

2.4 Discussion

2.4.1 The role of final-to-useful efficiency in energy intensity

The significant reductions in energy intensity identified in this study present an encouraging trend and have been the key driver in reducing direct final energy consumption in the UK despite significant increases in output. Direct energy intensity reductions have been happening across the whole time period studied and across virtually all sectors, with the Textiles, Clothing, Leather & Footwear sector presenting the only exception. However, when interpreting the results it needs to be considered that a decomposition analysis cannot determine whether the trends in the different factors are independent from each other. For example the analysis cannot indicate whether direct energy intensity reductions (or structural changes) would have been similar without growth in output leading to even larger reductions in energy use. For example there is some evidence that output growth and reductions in direct energy efficiency are interlinked (Brockway et al., 2017).

The novel features employed in this article have produced more detailed in insights into the underlying drivers of improved direct energy intensity. Unexpectedly, the reductions in the final-to-useful conversion efficiency have contributed much less to energy savings than reductions in the useful exergy intensity of production. This finding suggests that direct energy intensity is not necessarily a good proxy for the direct final-to-useful energy efficiency.

In the non-industrial sectors this result is not so surprising because in these sectors monetary output is less related to the production of physical products. However, even in the industrial sectors, the relative proportions of direct energy savings allocated to the final-to-useful efficiency and useful exergy intensity effects vary widely between sectors. In the Construction and Textiles, Clothing, Leather & Footwear sectors, the two effects even have opposite signs, with one effect increasing direct energy use and one effect reducing direct energy use. The inconsistent contributions of the final-to-useful conversion efficiency to direct energy intensity reductions make it difficult to assess what has been driving the reductions in direct energy intensity in the UK. The useful exergy intensity effect captures the components of direct energy intensity reductions that are not attributed to an increasing direct final-to-useful conversion efficiency. It incorporates many factors not captured elsewhere. This makes it difficult to determine what has been driving the reductions in direct useful exergy intensity.

On the one hand the useful exergy intensity effect might capture real reductions in the ratio of the direct useful exergy needed to produce the monetary output of a sector. For example, if higher quality products are produced using similar conversion processes and similar amounts of useful exergy. Another source of reductions in the ratio could be structural change within sectors. The structural change effect in this study only captures shifts in output between the 15 sectors analysed. Any energy savings produced by output shifts within the 15 sectors would therefore show up in the useful exergy intensity effects. Using very detailed data for the US, Weber (2009) shows that energy savings can shift significantly from the energy intensity to the structural change effect if a more detailed resolution of sectors is employed. In the UK economic sectors the Chemicals sector provides the largest share of direct energy savings allocated to the useful exergy intensity effect in the industrial sectors, accounting for 45%. Some of these reductions in useful exergy intensity are almost certainly due to structural changes within the sector as the output share of the pharmaceutical sector within chemicals, which has a relatively low direct energy-intensity, has significantly risen. However, the lack of detailed sectoral energy data for the UK makes it difficult to assess how important this effect could be across all the sectors.

On the other hand the useful exergy intensity effect might also be influenced by inaccuracies in the data. For example increases in sector output might not be related to increased physical production if the monetary production data are not appropriately corrected for inflation. Similarly uncertainties in the energy data would influence the energy intensity effect. For example a key uncertainty in this analysis is the treatment of the industrial energy consumption that is "unclassified" and hence not allocated to a specific industrial sector. This category of direct energy use was added to the energy consumed by the Other Industries sector because there was some evidence that the changes of the two were inversely related. However, this presents a very crude assumption. Despite accounting for 20% of all direct industrial energy consumption in 1997, the Other Industries sector only contributes 2% of the reductions in direct industrial energy use between 1997 and 2013. This disproportionally small contribution might indicate that some of the direct energy intensity reductions in the other sectors have been exaggerated by the reallocation of direct energy consumption from specific sectors to the "unclassified" category. However, such a reallocation would not affect the direct energy intensity values for the industrial sectors as a whole.

2.4.2 The role of offshoring in structural change

The MRIO model results used in this study have allowed a more detailed investigation of the drivers of structural change, which are generally not considered in other decomposition analyses. Three key results stand out from the analysis.

Firstly, the direct energy savings attributed to the offshoring effect are a lot larger than the direct energy savings attributed to the embodied output effect, even within the industrial sectors. Interestingly, this result is not caused by a general divergence between the shares of industrial output in the UK and in the output embodied in UK final demand. In fact, the relative decline of industrial output in the UK has been mirrored by a similar decline in the industrial output embodied in UK final demand. This decline in the industrial output embodied in UK demand produces the direct energy savings associated with the embodied output effect in the industrial sectors (Figure 2-4a). However, the direct energy savings assigned to the offshoring effect are significantly bigger than the savings assigned to the embodied output effect, because of different structural changes within the industrial sectors. While industrial sector output in the UK has, in relative terms, moved away from high-energy sectors such as Iron & Steel, Chemicals or Textiles, Leather & Clothing, this trend has been less strong or even reversed for the industrial output embodied in UK final demand.

The second key result is the fact that the direct energy savings from the embodied output effect in the industrial sectors are completely offset by increased direct energy use associated with the embodied output effect in the non-industrial sectors. Given that the non-industrial sectors have a lower direct energy intensity this result is somewhat counterintuitive. This result can be explained by the fact that the sectors analysed in this study do not constitute the total economy. Specifically the transport and fuel-producing sectors are excluded. Both of the excluded sectors show declining shares in total UK output, with the changes being especially pronounced in the fuel producing sector which declines from 10% to 5% in total output over the period of the study. The overall neutral contribution of the embodied output effect in this analysis is therefore the result of two different structural changes in the UK economy. Firstly, there is a shift from industrial to non-industrial sectors, which should yield a net reduction in direct final energy consumption as non-industrial sectors are less energy intensive. Secondly, however, the overall output of the economic sectors analysed in this study is increasing its share in total UK output, as the shares of the transport and fuel producing sectors are declining. This reduces the observed impact of the structural change effect on direct final energy consumption. Both of these changes happen similarly in the UK economy as well as in the output embodied in UK consumption so that they only show up in the embodied output effect but not in the offshoring effect.

The third key result is the strong decline in the rate of direct energy savings attributed to the offshoring effect. This temporal pattern of the offshoring effect essentially reflects the change in the gap between industrial output in the UK and the industrial output embodied in UK demand. Up to 2009 UK industrial output generally grew more slowly (or declined more strongly) than the industrial output embodied in UK demand leading to direct energy savings from the offshoring effect. However, this trend was reversed between 2009 and 2013 as industry output in the UK grew slightly more than the industrial output embodied in UK final demand. However, while the level of offshoring is no longer increasing, the production of the goods and services embodied in UK demand is still highly dependent on industrial production in other countries. For all industrial sectors, except construction, the ratio of output in the UK to global output embodied in UK demand is below 1 in 2013. For four sectors it is even below 0.5, namely in the Iron & Steel, Non-ferrous metals, Electrical & Instrument Engineering sectors as well as the Textiles, Clothing, Leather & Footwear sector.

The observed results are supported by the results of other studies investigating the UK energy, carbon and material footprints, which generally show a widening gap between consumption and production-based accounts up to the financial crisis and a change in trend thereafter (Barrett et al., 2013; Wiedmann et al., 2015; Lan et al., 2016; Owen et al., 2017; Owen et al., 2018). However most of these studies do not extend far beyond the financial crises. It is interesting to see that there has been no return to regular direct energy savings from the offshoring effect up to 2013.

2.4.3 Implications for the future of final energy consumption in the UK

Overall the reduction in direct final energy consumption in the UK economic sectors has been driven by some trends that can be considered desirable from the perspective of climate change mitigation. There have been significant reductions in direct energy intensity across sectors and there have also been direct energy savings from a reduced dependence on industrial production, both in the UK and in the output embodied in UK final demand.

However, in spite of these encouraging trends, this analysis has highlighted several features that question whether there will be an imminent return to the rates of reduction in direct energy consumption that were observed between 2001 and 2009:

1. Rates of increase in the final-to-useful conversion efficiency and of reduction in the useful exergy intensity of production have been slowing down and are very small between 2009 and 2013. In addition direct energy savings from the two effects before 2009 were very concentrated in the Iron & Steel and Chemicals sectors. Although there remains some potential for further savings it is unlikely that these two sectors can contribute further direct energy savings at the same magnitude as observed before 2009 (Allwood, 2013; Griffin et al., 2018).
2. Energy savings from structural change have been very important and absolute reductions in direct final energy consumption in the economic sectors would have been much smaller without these contributions. However, it is questionable whether further direct energy savings from structural change are forthcoming and whether these are desirable from the perspective of climate change mitigation, as outlined in points 3 and 4.
3. The UK government is currently pursuing an active industrial strategy with the aim of increasing labour productivity and competitiveness of the economy and ending the period of low growth after the crisis (HM Government, 2017). While the strategy explicitly refers to the whole economy and not only the sectors conventionally considered to be "industrial", it is difficult to imagine that it can achieve its aims while continuing the trend of deindustrialisation that the UK has seen over the past decades. This is likely to reduce further direct energy savings from structural change in the UK.
4. To contribute to global efforts of climate change mitigation any direct energy savings from structural change in the UK would have to be matched by similar structural changes in the economic output embodied

in UK final demand. The magnitude of the offshoring effect in this article as well as other evidence suggests that such an alignment has been very limited in the past (Barrett et al., 2013; Owen et al., 2017). Hence a return to higher growth rates of GDP and final demand is likely to lead to renewed growth in the embodied energy use associated with UK final demand.

These findings point to three key implications for energy and economic policy in the UK.

Firstly, efforts to further reduce direct energy consumption in the UK will need to target a wide range of sectors. One interesting option would be to explore how the materials produced by energy-intensive sectors could be more efficiently used in later stages of the industrial supply chain (Barrett and Scott, 2012). In addition there also needs to be a strong focus on non-industrial sectors of the economy. After years of reduction in direct energy consumption in the industrial sectors, the non-industrial sectors now account for almost half the total direct energy consumption in the UK economic sectors. The Public Administration sector in the UK presents an encouraging example, as direct energy consumption was reduced by 25% between 1997 and 2010 even though sector output grew by 79%. The UK government has had carbon reduction targets for the Public Administration sector in place for several years (The Carbon Trust, 2012). The results of this study suggest that these targets have been effective, but further research would be useful to determine how the Public Administration sector in the UK has achieved its reductions in direct energy consumption.

Secondly, it should be a priority for policy makers to ensure that the industrial strategy will shape the UK economy towards a low-energy structure. If past trends continue, increasing efficiency on its own is unlikely to lead to substantive reductions in direct final energy consumption in the economic sectors, especially in combination with economic growth.

Thirdly, in order to effectively contribute to global climate change mitigation efforts, energy and economic policy in the UK needs to consider the energy consumption in other countries that is associated with UK final demand. This is not an easy task, as the interconnected and globalised nature of the economy means that there are very different forces shaping the structure of the UK economy and the structure of output embodied in UK final demand.

Overall, the future development of direct final energy consumption in the UK economic sectors is very uncertain. Between 2009 and 2013 direct energy consumption in the economic sectors was characterised by a peculiar phase of stagnation with very little change in the decomposition factors investigated in this study (Table 2-3). This is a reflection of the wider economic stagnation. More recent data on direct final energy consumption suggest that there also have only been very small further reductions in direct final energy consumption in 2014 and 2015 and that direct final energy consumption in the economic sectors (as well as in the transport and domestic sectors) has actually slightly increased in 2016 (Department for Business Energy & Industrial Strategy, 2017). Whether and how this period of stagnation ends, and the nature of economic development that will follow, will be crucial in determining whether the UK can continue to reduce direct final energy consumption and achieve its climate change targets.

This article has focused its attention on direct energy consumption in the economic sectors. These sectors are only responsible for a part of final energy consumption in the UK with large amounts of energy used for transport and residential purposes. While the latter two purposes are often treated separately, energy use for transport and residential purposes is related to wider economic developments, such as growth and structural change. These links are complex and work through a variety of mechanisms. For example energy use for personal transport and residential purposes is linked to growth in income and associated changes in lifestyle. Similarly, all the technological devices that consume energy for transport or in homes are ultimately produced in the economic sectors (e.g. cars, houses, TVs). The widespread adoption of new technologies and shifts in behaviour intended to reduce energy consumption will therefore have significant impacts on the economic sectors. Such interlinkages between the sectors would provide a fruitful avenue for further research.

2.5 Conclusion

This study has introduced two novel features into a decomposition analysis of the direct final energy consumption in the UK economic sectors. These features have provided new insights into the drivers of direct energy savings. Estimates of the conversion efficiency from final energy to useful exergy have been included to further break down the measure of direct energy intensity and multi-regional input-output analysis has been employed to assess the contribution of offshoring to structural change in the UK. The analysis has revealed some trends between 1997 and 2013 that are encouraging with regard to climate change mitigation. Direct energy intensity reductions have been the biggest contributor to the reductions in direct energy consumption and are driven by both increasing conversion efficiency from final energy to useful exergy as well as from reductions in the ratio of useful exergy used per unit of monetary output. In addition there are some indications of desirable structural change with a slight de-industrialisation of the economic output embodied in the goods and services produced for final demand in the UK. However, the analysis also highlights several issues suggesting that further reductions in direct energy consumption at the rate seen between 2001 and 2009 cannot be taken for granted. Firstly, rates of increase in the final-to-useful conversion efficiency as well as rates of reduction in the useful exergy intensity have been slowing down. Secondly, savings from direct energy intensity reductions have only slightly exceeded increases in direct energy use from increased output. Hence, direct energy savings from structural change have played a key role in delivering absolute reductions in direct energy consumption. However, this analysis suggest that almost all these savings from structural change are a result of offshoring as they have not been matched by a similar change in the structure of economic output embodied in UK final demand.

The trends in energy consumption strongly reflect the economic stagnation between 2009 and 2013, with a significant slow-down in the growth rates of output and final demand, as well as in the rates of direct energy savings from structural change, final-to-useful efficiency and useful exergy intensity. How the ongoing economic stagnation is resolved will have significant impacts on the direct energy consumption in the UK. Therefore the industrial strategy currently developed by the UK government presents a unique opportunity to shape the economic development in the UK for a low-energy future. However, to take up this opportunity, policy aimed at reducing energy consumption has to be rethought in a more holistic way. It needs to go way beyond the energy-intensive industrial sectors and pay equal attention to the less energy-intensive industries as well as the non-industrial sectors, such as public administration and commercial services. In addition energy policy needs to go beyond the UK borders and consider how energy consumption in the UK and abroad is driven by the growth and changing nature of UK final demand.

More research is needed to support the development of effective policy interventions for reducing energy consumption. This article has studied the effect of offshoring on direct energy consumption in the UK but it has not investigated the change in the embodied energy associated with UK final demand. Gaining a better understanding of what is driving changes in the embodied energy of UK final demand would be a fruitful area for further research. Another interesting avenue would be the relationship between changes in energy intensity and economic structure on the one hand and prices and costs in the economy on the other. Research on this topic would be useful to assess the potential economic impacts of policies intended to significantly reduce energy consumption. This topic is also related to the question of how energy consumption in the transport and domestic sector might be linked to energy consumption in the economic sectors studied here.

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Chapter 3

Structural change for a post-growth economy: Investigating the relationship between embodied energy intensity and labour productivity

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Abstract:

Post-growth economists propose structural changes towards labour-intensive services, such as care or education, to make our economy more sustainable by providing meaningful work and reducing the environmentally damaging production of material goods. Our study investigates the assumption underlying such proposals. Using a multi-regional input-output model we compare the embodied energy intensity and embodied labour productivity across economic demand sectors in the UK and Germany between 1995 and 2011. We identify five labour-intensive service demand sectors, which combine low embodied energy intensity with low growth in embodied labour productivity. However, despite their lower embodied energy intensities, our results indicate that large structural changes towards these demand sectors would only lead to small reductions in overall embodied energy. Our results also suggest that labour-intensive service sectors in the UK have been characterised by higher rates of price inflation than other sectors. This supports suggestions from the literature that labour-intensive services face challenges from increasing relative prices and costs. We do not find similar results for Germany, which is the result of low overall growth in embodied labour productivity and prices. This highlights that structural change is closely associated with economic growth, which raises the question of how structural changes can be achieved in a non-growing economy.

Keywords: post-growth economics; degrowth; structural change; energy footprint; multiregional input-output databases

3.1 Introduction

Sustainable development requires us to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987) and this principle has been enshrined in the United Nations Sustainable Development Goals (United Nations General Assembly, 2015). However, human activities are currently breaching several planetary boundaries, threatening to destroy the ecological life-support systems of our planet for future generations (Rockström et al., 2009; Steffen et al., 2015). These planetary boundaries represent thresholds in Earth-system processes "which, if crossed, could generate unacceptable environmental change" (Rockström et al., 2009, p.472). Avoiding large-scale environmental crises will require the elimination of greenhouse gas (GHG) emissions, significant reductions in energy use and material throughput, as well as the reversal of trends in land-use change and biodiversity loss over the space of mere decades (Opršal et al., 2018; Hickel and Kallis, 2019). The critical challenge of sustainability is therefore how we can provide for human needs while reversing our environmental impacts to stay within the planetary boundaries (O'Neill et al., 2018).

One of the key drivers of environmental degradation has been the growth in economic activities, measured by GDP (Raupach et al., 2007; Peters et al., 2017). Therefore, ecological economists propose that we have to transform the economies of developed countries towards post-growth approaches to address the sustainability challenge (Jackson, 2017). Such post-growth economies are defined as economies that prioritise the reduction of environmental impacts and the enhancements of other measures of prosperity over GDP growth. Similar proposals have been discussed under different names such as degrowth (Kallis, 2011; D'Alisa et al., 2015) or a steady-state economy (Daly, 1990; O'Neill, 2015). While these approaches feature some important differences, we focus on their commonalities in this study and will therefore refer to them collectively as post-growth approaches.

One important part of the proposed strategies for achieving the post-growth economy is structural change in economic output and employment away from material production and consumption and towards labour-intensive services such as education, care or repair (Kallis et al., 2012; Jackson, 2015). Labour-intensive services are considered to be those services where the value of the service provided is inextricably linked to the labour time invested, so that it is difficult or undesirable to increase labour productivity in these services. We distinguish such labour-intensive services from labour-light services that feature a higher potential for labour productivity growth, such as communication services. The objective for such a structural change towards labour-intensive services in a post-growth economy is two-fold (Jackson, 2017). Firstly, these labour-intensive services are important for human flourishing and can provide meaningful jobs. As it is undesirable and difficult to improve labour productivity in such services, they can reduce the threat of unemployment in a non-growing economy. Secondly, it is considered that such labour-intensive services have lower environmental impact than material goods. However, so far, there has been very little empirical investigation in the post-growth economics literature of which sectors in the economy show the characteristics of labour-intensive services and whether structural change in output, employment and demand towards such sectors can contribute to the desired objectives.

In this study, we address this gap in the literature by investigating the relationship between the embodied final energy intensity and embodied labour productivity across economic demand sectors in the UK and Germany. The adoption of an embodied perspective, which allows us to examine the embodied energy and labour inputs, is one of the key novelties of our analysis. To our knowledge, we provide the first study that compares embodied energy intensity and embodied labour productivity for different demand sectors, although there are a few examples of similar approaches used to examine the relationship between embodied labour and GHG intensities (Jackson et al., 2014; Gazheli et al., 2016; Sakai et al., 2017). The embodied approach, which is based on input-output analysis, takes into account the labour and energy inputs along the whole global supply chain involved in the production for the demand in different sectors. We refer to the calculated measures as “embodied” energy intensity and “embodied” labour productivity of different demand sectors, to distinguish them from conventional measures, which we will refer to as "direct" energy intensity and labour productivity. We consider an embodied perspective important for investigating structural change for a post-growth transition, because it allows us to examine whether changes in energy intensity and labour productivity are consistent with the overall goals of the post-growth economy. For example, a conventional perspective cannot show whether changes in direct energy intensity or direct labour productivity in specific sectors have been achieved at the expense of changes in energy or labour inputs in other parts of the supply chain.

Using an embodied perspective has a long tradition in ecological economics for the calculation of energy, GHG and material footprints associated with the final demand in a particular country (Wiedmann et al., 2006; Barrett et al., 2013; Wiedmann et al., 2015; Lan et al., 2016). Supply chain approaches have also been used in the economics literature on structural change, for example, to investigate the implications of diverging levels of embodied labour-productivity in different sectors for overall economic stability (Pasinetti, 1981; Pasinetti, 1993). Our study combines these two strands of literature.

Our approach allows us to investigate three important topics regarding the assumptions and feasibility of structural change towards labour-intensive services for a post-growth economy. Firstly, it is generally assumed that service sectors, including labour-intensive services, have a lower energy intensity than other sectors. There is evidence that this is the case when measuring the direct energy intensity without taking into account the supply chain (Mulder and de Groot, 2004; Mulder et al., 2014). However, it is debated how much structural change in economic output towards service sectors in developed countries over the past decades have contributed to reducing the overall direct energy intensity of economies (Henriques and Kander, 2010; Mulder et al., 2014). We investigate whether the assumption of lower energy intensity in service sectors holds when an embodied perspective is used. In addition, we estimate a second measure of energy use that we consider relevant from a post-growth perspective, namely the embodied energy-labour ratio. We use these measures to answer our first research question:

1. Do service demand sectors have a lower embodied energy intensity and a lower embodied energy-labour ratio than other sectors?

Secondly, there have been very few systematic assessments of which economic sectors show the characteristics of labour-intensive services desirable for a post-growth economy, although Jackson (2017, p.220) lists "nutrition, education, care, maintenance and repair, recreation, craft, creativity, culture", as examples. The key characteristics of the labour-intensive services promoted in the post-growth literature are the possibility to provide meaningful jobs, low energy intensity and low rates of labour-productivity growth (Jackson, 2017). For the purpose of our study, we focus on the latter two elements. We therefore identify which demand sectors show the characteristics of labour-intensive services by answering our second research question:

2. Which demand sectors feature low embodied energy intensity combined with low rates of growth in embodied labour productivity?

A full discussion on which demand sectors and activities can be considered as labour-intensive services desirable for a post-growth economy also requires a thorough assessment of the first characteristic, namely whether they can provide meaningful jobs. Such an assessment is beyond the scope of this paper as it requires careful consideration of how to define meaningful work. It is also more usefully conducted from a direct perspective, as the types of work carried out within direct sectors are likely to be more homogeneous than the embodied work in different demand sectors. However, further research conducting such assessments is very important for the development of strategies for a post-growth economy. Druckman and Mair (2019) provide a good example of research assessing the potential of the health care sector to provide meaningful jobs.

Thirdly, it has been proposed that labour-intensive services face an economic disadvantage compared to other sectors due to Baumol's cost disease. The theory of Baumol's cost disease, proposed by William Baumol and co-authors (Baumol and Bowen, 1965; Baumol, 1967; Baumol et al., 1985; Baumol, 2012), suggests that sectors with low labour productivity growth rates face relative cost and price increases compared to sectors with high labour productivity growth rates. While Baumol's theory is highly stylised, there is considerable evidence that the processes it describes play a role in shaping the economy in the US (Nordhaus, 2006), the EU (Hartwig, 2011; Fernandez and Palazuelos, 2012), South Korea (Oh and Kim, 2015) and across the OECD (Hartwig, 2012; Hartwig, 2015). While there is evidence for the existence of Baumol's theories across these countries and regions, the strength of the effect varies in line with different contexts. Baumol (2012) himself suggests that his theory has significant implications for the transition to a sustainable economy, because manufacturing sectors with a high environmental impact are getting continuously cheaper compared to the labour-intensive services with low environmental impacts. We therefore investigate whether we can find evidence for such an effect by answering our third research question:

3. Do demand sectors with low embodied energy intensity and low rates of growth in embodied labour productivity also have higher rates of price inflation compared to other demand sectors?

3.2 Materials and methods

3.2.1 Calculating embodied energy intensity and embodied labour productivity

For our purposes, we define the embodied energy intensity, $t_{E,I}$, in each demand sector i as the ratio of embodied inputs of energy, $g_{E,i}$, and the monetary final demand that is spent in this demand sector, y_i (Equation 3-1). For embodied labour productivity, $p_{L,i}$, we divide the monetary final demand that is spent in this demand sector, y_i, by the embodied inputs of labour, $g_{L,i}$ (Equation 3-2). We define the embodied energy-labour ratio in each demand sector, r_i, as the ratio of the embodied inputs of energy, $g_{E,I}$, and the embodied inputs of labour, $g_{L,i}$ (Equation 3-3).

$$t_{E,i} = \frac{g_{E,i}}{y_i} \tag{3-1}$$

$$p_{L,i} = \frac{y_i}{g_{L,i}} \tag{3-2}$$

$$r_i = \frac{g_{E,i}}{g_{L,i}} \tag{3-3}$$

For convenience, we will refer to $g_{E,i}$ and $g_{L,i}$ as the embodied energy and labour of the relevant demand sectors. The embodied energy and labour capture the inputs that are used in all stages along the supply chain of a certain end-product. For example, the embodied energy of the UK demand for goods from the vehicles sector includes any direct energy that is used around the world in the supply chain, such as any direct energy used to produce the required steel in China or car parts in Eastern Europe.

We obtain the embodied energy and labour for all demand sectors in the UK and Germany using the standard approach based on multi-regional input-output analysis (Miller and Blair, 2009; Owen et al., 2017). Calculating the embodied energy and labour for each demand sector requires three elements of monetary data that we obtain from the multi-regional input-output (MRIO) database EXIOBASE (Stadler et al., 2018). Figure 3-1 shows a graphic representation of an MRIO database and the three elements. The first element is a vector that includes the total economic output for each direct sector in each country ($\mathbf{x}$). This output represents the sum of all sales, including to intermediate and final demand. The second element is the flow matrix $\mathbf{Z}$ that contains the flow of money from each direct sector in each country to all other direct sectors in all countries. These flows represent the intermediate inputs in the production process. In our case, $\mathbf{Z}$ represents a square matrix with i number of rows and j number of columns, where i and j are equal to the number of sectors. The third element is a relevant vector of final demand ($\mathbf{y}$) for which we want to calculate the embodied energy or labour. The vector $\mathbf{y}$ gives the sum of global final consumption expenditure by households, non-profit organisations and the government, as well as gross fixed capital formation, changes in inventories and changes in valuables for each demand sector.

The total output in each sector, x_i, is equal to the sum of final demand in the sector y_i and all the intermediate inputs the sector delivers to other sectors, i.e., the row elements of $\mathbf{Z}$ (Equation 3-4).

$$x_i = z_{i,1} + z_{i,2} + \cdots z_{i,j} + y_i \tag{3-4}$$

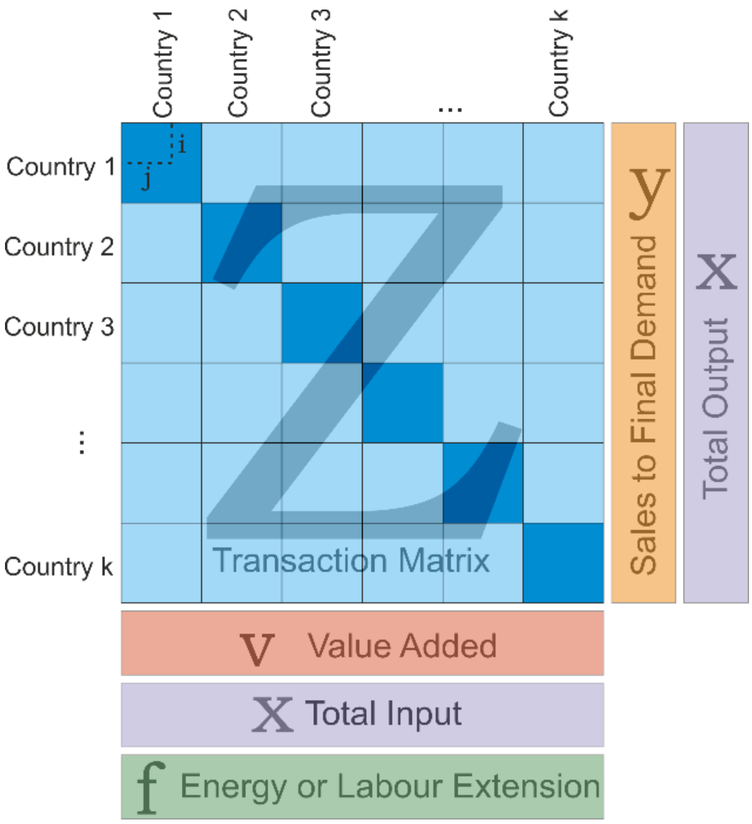

Figure 3-1: Basic MRIO structure. The **Z** matrix contains all inter-sector transactions. Vector **x** represents the total economic input or output and vector **y** represents sales to final demand. **Z**, **x** and **y** are in financial units. Vector **f** is the energy or labour extension, which is in energy or labour units. Adapted from Brockway et al. (2019).

To obtain the embodied inputs, we firstly need to calculate how much of the economic output from each sector in each country is part of the supply chain for the different demand sectors in each country. This means that we need to express **x** as a function of **y**.

To do so we define a matrix **A**, with the same dimensions as **Z**, that expresses the total intermediate inputs in each sector, recorded in **Z**, as a fraction of the total output created in the sector, given in **x**. The elements of **A** are given by Equation 3-5.

$$a_{i,j} = \frac{z_{i,j}}{x_j} \qquad (3\text{-}5)$$

We can use Equation 3-5 to substitute the elements of **Z** in Equation 3-4 and obtain in matrix notation:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \qquad (3\text{-}6)$$

Now Equation 3-6 can be rearranged to express **x** as a function of **y**:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{3-7}$$

where **I** is the identity matrix and **L** is usually referred to as the Leontief inverse.

Equation 3-7 can tell us how much economic output from different sectors around the world is embodied in the supply chain of the final demand in different demand sectors and countries. We can calculate the embodied energy and labour of those final demand sectors by using information on the direct energy and labour intensity of output in different direct sectors and different countries that are part of the supply chain. Such extension vectors constitute the fourth element needed for the calculation. The vector $\mathbf{f_E}$ describes the total inputs of direct energy in each sector in each country. We can divide this by the total output of each sector, **x**, to obtain the direct output intensity of energy in each sector (**e**).

$$\mathbf{e} = \mathbf{f_E}\hat{\mathbf{x}}^{-1} \tag{3-8}$$

A vector with a "hat" ($\widehat{\ }$) represents a diagonal matrix, whose diagonal elements are the elements of the vector. We can multiply both sides of Equation 3-7 with **e** to obtain:

$$\mathbf{f_E} = \mathbf{eLy} \tag{3-9}$$

To calculate the embodied energy, we can obtain a flow matrix $\mathbf{F_E}$ by diagonalising **e** and **y**:

$$\mathbf{F_E} = \hat{\mathbf{e}}\mathbf{L}\hat{\mathbf{y}} \tag{3-10}$$

The flow matrix has the same dimensions as **Z.** Each column of $\mathbf{F_E}$ shows the supply-chain energy inputs associated with the final demand for the corresponding demand sector. Summing the columns of $\mathbf{F_E}$ gives the vector that contains the embodied energy associated with each sector of final demand, $\boldsymbol{g_E}$. To obtain the embodied labour, $\mathbf{g_L}$, the same procedure is employed but using a vector $\mathbf{f_L}$ that describes the total labour inputs and provides a flow matrix $\mathbf{F_L}$.

To calculate rates of change over time in prices and intensities we fit a log-linear regression model to the relevant variable over the whole time period to obtain the compound rate of growth in the variable as suggested by Gujarati (1995).

3.2.2 Data sources

We use the EXIOBASE V3.4 database (Stadler et al., 2018), to obtain the relevant data of $\mathbf{x}$, $\mathbf{Z}$, and $\mathbf{y}$ for our analysis. The database covers the period from 1995 to 2011 and represents the global economy using 44 countries and 5 rest-of-the-world regions. EXIOBASE disaggregates the economy into 163 sectors based on the NACE rev. 1.1 classification. However, for our purposes we aggregate all the data to a level of 70 sectors, largely by removing the very detailed sub-classifications in the sectors of agriculture, food production, metal mining and processing and recycling. Direct labour inputs for each sector and region ($\mathbf{f}_L$) were also obtained from EXIOBASE in the form of total hours worked in each year.

Direct energy inputs for MRIO analysis can be constructed in different ways representing different stages of the energy conversion chain (Owen et al., 2017). In this study we are interested in the relationship between energy and labour productivity. Therefore, we focus on inputs at the final energy stage, because we consider those to be closer to the labour inputs than energy inputs at the primary energy stage. At the time of writing, EXIOBASE V3.4 provides a number of energy extension vectors. However, these cover only primary energy inputs (such as primary energy supply) or final energy inputs in the form of gross energy accounts, which cannot be used to calculate the embodied energy of demand sectors due to double counting (Stadler et al., 2018). The final energy extension vector use in the analysis ($\mathbf{f}_E$) was therefore prepared by the authors (see Section 3.2.4).

While EXIOBASE V3.4 covers the whole global economy, we focus on the two countries of Germany and the UK. The reason is that there is very limited information available on direct final energy consumption in the service sectors in a standardised format covering the global economy over the time period of our analysis (see Section 3.2.4). As the service sectors are a special focus of our study, we require more detailed information on sectoral final energy consumption in the service sectors than is provided in international energy databases. In the absence of standardised information, such detailed information can only be obtained from national data sources. While such information from national sources is available for many countries, it requires considerable work to obtain and process the relevant data to make them compatible with the input-output database. Obtaining and processing such national data for more than two countries was not possible within the constraints of our study. We chose the UK and Germany as case studies, because they represent two developed nations that have maintained different economic models and industrial structures (Peck and Theodore, 2007).

3.2.3 Preparing the final demand vectors

The flow matrices $\mathbf{F_E}$ and $\mathbf{F_L}$ can be used to calculate the embodied energy and labour for different subsets of the final demand vector ($\mathbf{y}$). We use two different kinds of such subsets in our analysis.

Firstly, for comparing demand sector shares in demand and embodied energy and labour, as well as comparing embodied intensities of demand sectors in current prices, we try to capture as much as possible of the embodied energy and labour associated with UK and German final demand. Therefore, we use the final demand from both domestic and imported sources for each demand sector in Germany and the UK respectively. However, the total embodied energy calculated in this study does not include energy use for non-commercial purposes, such as for residential use or private transport. Results of this analysis are presented in Section 3.3.1.

Secondly, to investigate the rates of change in embodied energy and labour intensities in constant prices we only include the domestic final demand. The reason is that we require sectoral price indices to deflate final demand. These were not available for all countries from which parts of final demand are imported. Therefore, we only investigate the embodied intensities of the domestic components of final demand. This includes all final demand for products in the UK and Germany where the end product is produced domestically. It excludes final demand for imported finished products. However, the embodied energy and labour of this domestic demand still include global inputs of intermediate products along the supply chain. The results of this analysis are presented in Sections 3.3.2 and 3.3.3.

To obtain time series of embodied energy and embodied labour productivity for domestic demand in constant prices we first obtain the relevant intensities for each demand sector in current prices and then deflate the final demand (the denominator) using a price index. For price indices we use the sectoral implied GVA deflators for the UK and Germany provided by the Eurostat database (Eurostat, 2018). These were the only price indices that we could obtain in a consistent format covering all demand sectors in both countries and the whole time period. Using the price indices, we produce time series of final demand in constant 2010 prices using chained volume indices (Lequiller and Blades, 2014). We do not convert the input-tables into constant prices, as for example done by Lan et al. (2016), because our analysis is focused on the total embodied energy and labour in each demand sector and does not analyse how structural changes in the global economy change these values over time. We therefore consider that a deflation of the input-output tables would only add unnecessary uncertainty to our results.

All analysis was conducted at the level of the 70 direct and demand sectors; we aggregate the results to 25 demand sectors to reduce the uncertainty related to the embodied energy and labour measures and for increased clarity of presentation (Table 3-1). After the calculation of embodied inputs and intensities some demand sectors were excluded from the presentation because they do not feature any direct final energy consumption themselves. These include the energy-producing sectors and the sector of “Private Households with Employed Persons” (see Section 3.2.4).

A large part of the output and final demand in the Real Estate sector consists of imputed rents for owner-occupied housing. We remove these from the figures for output and demand in the sector to obtain a more realistic value of the embodied labour productivity in the demand sector. For Germany, no information of the share of imputed rents in the Real Estate sector was available before 2011.

Table 3-1: Sector classification used for presenting results

Demand sector	NACE Codes (Rev. 1.1)
Agriculture, Forestry, Fishing	01, 02, 05
Mineral Products	13, 14, 26
Food, Beverages and Tobacco	15, 16
Textiles, Clothes, Leather	17, 18, 19
Paper, Printing, Publishing	21, 22
Chemicals	24
Metals and Fabricated Metal Products	27, 28
Machinery, Electrical Equipment, Computers	29, 30, 31, 32, 33
Transport Equipment	34, 35
Other Manufacturing	20, 25, 36, 37
Construction	45
Wholesale and Retail Trade	50, 51, 52
Hotels and Restaurants	55
Transport	60, 61, 62, 63
Finance and Insurance	65, 66, 67
Real Estate Activities	70
IT and Communication	64, 72
Business Services	71, 73, 74
Public Administration	75
Health	85
Education	80
Other Services	41, 90, 91, 92, 93
Sectors not Presented in Results	
Fuel Producers	10, 11, 23
Production and Distribution of Electricity, Gas, Steam, Hot Water	40
Private Households with Employed Persons	95

Therefore, we only include the demand sector in the first part of the analysis, which estimates embodied energy intensities and embodied labour productivities in 2011. We exclude the Real Estate demand sector from the second part of the analysis covering the rates of change in embodied labour productivity. Any aggregate totals of demand, embodied energy and embodied labour that are presented in the following analysis exclude the embodied energy and labour associated with the demand for the energy-producing sectors, private households and imputed rents. They also exclude any energy use for non-commercial purposes, such as residential use and private transport.

3.2.4 Preparing the energy extension vector

This section provides a summary of the methods and data sources used to construct the energy extension vector. A more detailed description can be found in the supplementary information (Appendix C).

As outlined above, we focus on the embodied final energy in this study. Final energy use represents any final energy carriers (e.g., petrol, natural gas, electricity) that are consumed by end users, such as firms, households or the government. It excludes any energy that is used in the extraction of primary energy carriers (e.g., oil and gas extraction) or in the transformation of such primary energy into final energy (e.g., oil refineries). Final energy consumption also excludes any losses that occur in the transformation and distribution of energy (e.g., losses in thermal power stations). For brevity we will use the term “energy” to describe final energy inputs in the reminder of this article.

As outlined above, calculating the embodied energy for the different demand sectors requires information on the direct final energy inputs into each of the EXIOBASE sectors in each region, captured in the vector $\mathbf{f_E}$. We use a two-stage process to prepare the vector of direct energy inputs. In the first step we use data on direct final energy consumption provided by the International Energy Agency (IEA, Paris, France) to construct a complete vector $\mathbf{f_E}$ for all countries and regions. In a second step we use national data sources to construct more detailed vectors of direct energy inputs for Germany and the UK which then replace the relevant entries for the UK and Germany in the vector produced in the first step.

For the first step, we draw on data from the IEA World Energy Balances (IEA, 2018), which provide details on the total final consumption (TFC) of energy in more than 140 countries. The IEA World Energy Statistics and Balances can be downloaded with institutional or other user licence. From TFC, we exclude non-energy use and the energy consumption by private households for residential and transport purposes, because our study focuses on energy inputs into economic production. This leaves us with the relevant direct final energy consumption in each country disaggregated into 23 IEA flows.

To produce $\mathbf{f_E}$ the IEA countries are firstly aggregated into the 49 EXIOBASE countries and regions. Secondly, the 23 flows of direct final energy consumption in the IEA data are split and allocated to the 70 EXIOBASE sectors in our analysis. This allocation process requires additional information and assumptions. For most sectors, we split the relevant IEA flows proportionate to monetary output or energy expenditure obtained from EXIOBASE. This approach has the advantage that it can be implemented easily and consistently across all countries. However, the assumption of proportionate energy and monetary flows also introduces an amount of uncertainty into the analysis. This is especially the case for the service sectors, as the direct energy consumption in all service sectors (excluding transport) is represented in a single flow in the IEA energy balances. To address this limitation, we focus our analysis on the UK and Germany and construct more detailed energy inputs for these countries in the second step, paying particular attention to the service sectors. This limits the uncertainty because service sector outputs are traded less than manufactured goods.

A second limitation of the IEA energy balances for our purposes is presented by the fact that they are assembled based on a territorial principle, while national economic accounts and EXIOBASE follow a residency principle (Stadler et al., 2018). This is particularly problematic for the transport sector. As a detailed modelling of the different transport flows is beyond the resources and time available for this study, we resolve these issues using a number of simplifying assumptions (see Supplementary Information in Appendix C).

In the second step we construct direct energy input vectors for the UK and Germany using national data sources that offer more detail than the IEA data. For the UK these data sources include the “Energy consumption in the UK” dataset (Department for Business Energy & Industrial Strategy, 2018) and for Germany the sources include the German energy balances (AG Energiebilanzen, 2019) as well as reports on energy use in the service (Geiger et al., 1999; Schlomann et al., 2004; Schlomann et al., 2009; Schlomann et al., 2013) and transport sectors (Adler, 2005; Statistisches Bundesamt (Destatis), 2018).

3.2.5 Limitations

Constructing the input-output tables, as well as the labour and energy extension vectors covering the global economy presents a challenging task that relies on many assumptions and interpolations to correct for gaps and inconsistencies in the data. Uncertainties in input-output results are difficult to quantify and are not commonly reported (Owen et al., 2014). Uncertainties arise from the methods used in constructing the input-output tables as well as from the construction and use of extension vectors. Peters et al. (2012) compare the aggregate carbon footprints for different countries calculated by different studies. They conclude that the results are broadly consistent and that differences in the footprint results are largely due to differences in extension vectors and differences in definitions for allocating emissions to international trade, rather than differences in the footprinting methods and MRIO databases. Lenzen et al. (2010) conduct a Monte Carlo analyses to estimate the uncertainty associated with carbon emissions embodied in imports and exports from the UK. They report standard deviations for total embodied emissions in the range of 3–8%. However, they also highlight that, firstly, uncertainty at the level of individual demand sectors can be considerably higher and secondly, that their method cannot capture systematic errors associated with the calculation of embodied inputs.

While our results therefore need to be considered with caution, we utilise the best data and methods available and consider the results a useful addition to the post-growth economics literature. More detailed information on underlying assumptions and uncertainties associated with the construction of the EXIOBASE 3 database and the labour extension vector is provided in Stadler et al. (2018), while more information on the construction of the energy extension is available in the supplementary information to this article (Appendix C).

3.3 Results

3.3.1 Comparing embodied energy intensities across demand sectors

Even though we are using embodied energy intensity measures, our results show that service demand sectors, with the exception of transport, have a lower embodied energy intensity than other demand sectors (Figure 3-2, Table 3-2). In both countries, the embodied energy intensity of the service demand sectors is in the range of 0.9–1.9 MJ/EUR, while the production demand sectors, which include the manufacturing and mining demand sectors, show values between 3.5 to 7.6 MJ/EUR. An outlier is the Other Manufacturing demand sector in the UK with 11.0 MJ/EUR. However, this is likely to be an overestimate as it includes all the unclassified industrial energy use in the UK (see Appendix C). The

Agriculture, Forestry, Fishing demand sector shows values in the same range as the production demand sectors (4.3 MJ/EUR and 5.6 MJ/EUR). In both countries the Transport demand sector has the highest embodied energy intensity with values of 13.2 and 11.0 MJ/EUR. The position of the Construction demand sector is somewhat different in the two countries. While embodied energy intensity in the Construction demand sector is in the range of the service demand sectors in the UK, it sits between the service and manufacturing demand sectors in Germany (Table 3-2).

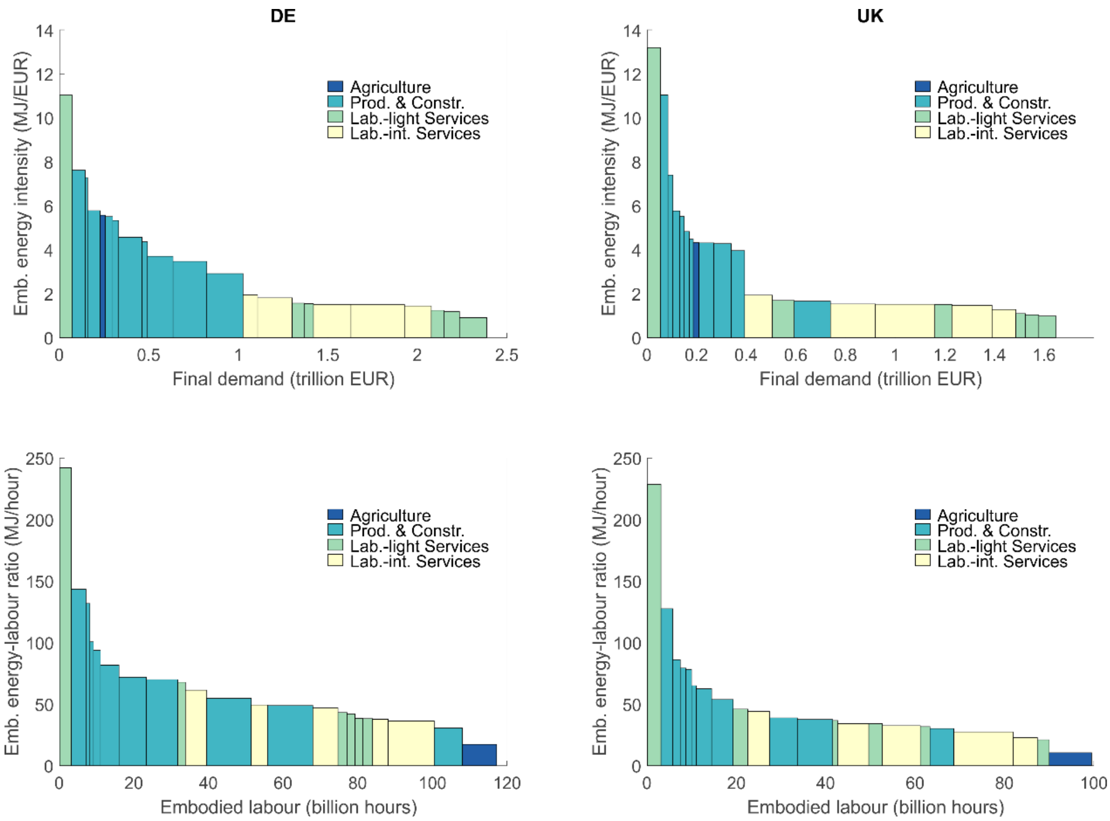

Figure 3-2: Sectoral embodied energy intensity plotted against sectoral final demand (top row) and sectoral embodied energy-labour ratio plotted against sectoral embodied labour (bottom row). The areas covered by the rectangles represent the total embodied energy associated with the final demand in the respective countries (excluding the embodied final energy of energy-producing sectors and final energy use for non-commercial purposes).

Table 3-2: Embodied energy intensities, embodied energy-labour ratios and final demand share in 2011 for the 22 energy-using demand sectors in the UK and Germany.

	2011					
	UK			DE		
Demand Sector	**Energy Intensity (MJ/EUR)**	**Energy/ Labour (MJ/h)**	**Demand Share (%)**	**Energy Intensity (MJ/EUR)**	**Energy/ Labour (MJ/h)**	**Demand Share (%)**
Agriculture						
Agriculture, Forestry, Fishing	4.3	10	1.4	5.6	17	1.2
Production & Construction						
Mineral Products	4.5	65	0.9	7.3	101	0.6
Food, Beverages and Tobacco	4.3	38	4.2	4.6	49	5.4
Textiles, Clothes, Leather	5.8	30	1.7	5.5	31	1.8
Paper, printing, Publishing	4.8	79	1.3	4.4	132	1.3
Chemicals	7.4	86	1.2	7.6	143	3.1
Metals and Fabricated Metal Products	5.5	78	1.1	5.3	94	1.4
Machinery, Electrical, Equipment, Computers	4.3	54	3.7	3.5	55	7.9
Transport Equipment	4.0	62	3.3	3.7	72	6.0
Other Manufacturing	11.0	128	1.8	5.8	82	2.9
Construction	1.7	39	8.8	2.9	70	8.5
Labour-light Services						
Wholesale and Retail Trade	1.7	46	5.4	1.5	38	2.2
Transport	13.2	229	3.2	11.0	242	2.9
Finance and Insurance	1.0	32	4.2	1.2	38	3.6
Real Estate Activities	1.5	34	4.2	0.9	68	6.4
IT and Communication	1.0	21	3.3	1.2	42	3.0
Business Services	1.1	36	2.3	1.6	43	2.8
Labour-intensive Services						
Hotels and Restaurants	1.3	23	5.9	1.9	38	3.4
Public Administration	1.5	34	9.8	1.5	47	8.8
Health	1.5	33	11.0	1.4	49	6.3
Education	1.5	27	14.6	1.5	36	12.5
Other Services	1.9	44	6.8	1.8	61	8.1
Total *	2.6	44	100	2.9	59	100

*Totals exclude demand and embodied energy and labour inputs for the energy-producing sectors, private households and imputed rents.

When considering the embodied energy-labour ratios the results are somewhat different from the results for embodied energy intensities. Firstly, the clear distinction between the service demand sectors and other demand sectors becomes more blurred. The Textiles, Clothes and Leather demand sector, the Food, Beverages and Tobacco demand sector and the Agriculture, Forestry, Fishing demand sector all have values of the embodied energy-labour ratio that are similar or lower than many service demand sectors (Table 3-2). For all of these three demand sectors, a large proportion of the supply-chain labour inputs are performed abroad in low-wage countries (Tables A2 and A3 in Appendix B). The common perception that the production and agriculture demand sectors are “high-energy” is therefore partially the result of ignoring the dependence of some of these demand sectors on low-wage labour in other parts of the world.

3.3.2 Identifying labour-intensive services

To investigate the rates of change in embodied labour productivities, we only consider the final demand for domestic sectors in the UK and Germany (see Section 3.2.3).

Based on our results, we identify five demand sectors as labour-intensive services. These include the demand sectors Hotels and Restaurants, Public Administration, Health, Education and Other Services. These five demand sectors show embodied energy intensities smaller than 2 MJ/EUR (Table 3-2) and rates of change in embodied labour productivity smaller than 1% per year in both countries (Table 3-3, Figure 3-3). The remaining service demand sectors with low embodied energy intensity show either higher rates of growth in embodied labour productivity in at least one of the two countries. We will be referring to this group of demand sectors as labour-light services.

The Wholesale and Retail Trade demand sector and the IT and Communications demand sector show consistently higher rates of growth in embodied labour productivity in both countries, well exceeding 2% and 3% per year respectively (Table 3-3, Figure 3-3). In contrast the results for the Finance and Insurance demand sector and the Business Services demand sector diverge between the two

Table 3-3: Rates of change in embodied energy intensity and embodied labour productivity as well as in the embodied energy-labour ratio for domestic demand sectors. Intensities represent embodied energy and labour inputs per unit real demand (const. 2010 EUR).

	Cumulative Annual Growth Rate between 1995 and 2011 (%)					
	UK			DE		
Demand sector	**Energy Intensity**	**Labour Prod.**	**Price Index**	**Energy Intensity**	**Labour Prod.**	**Price Index**
Agriculture						
Agriculture, Forestry, Fishing	−4.7	3.3	−2.2	−3.3	2.4	−1.4
Production & Construction						
Mineral Products	1.6	−2.7	2.2	−0.7	0.3	0.6
Food, Beverages and Tobacco	−2.4	1.7	−0.2	−0.1	−2.0	1.3
Textiles, Clothes, Leather	0.0	3.0	−0.9	−1.8	−0.2	−0.2
Paper, printing, Publishing	−1.8	2.3	−0.3	−1.9	3.0	−1.6
Chemicals	−4.8	3.3	−0.9	−0.4	0.1	−0.1
Metals and Fabricated Metal Products	−3.6	1.9	−0.6	−2.4	0.5	1.0
Machinery, Electrical, Equipment, Computers	−4.3	3.3	−1.8	−2.5	0.6	−1.2
Transport Equipment	−4.6	3.4	−1.0	−1.5	−0.6	0.9
Other Manufacturing	0.7	1.6	1.2	0.6	0.1	1.1
Construction	−0.3	−1.0	2.9	0.3	−0.7	1.2
Labour-light Services						
Wholesale and Retail Trade	−2.0	2.6	1.4	−3.8	2.8	−0.4
Transport	−2.4	1.6	0.3	0.1	0.4	0.9
Finance and Insurance	−4.5	3.5	2.0	6.0	−5.2	9.1
Real Estate Activities	-	-	-	-	-	-
IT and Communication	−6.5	6.9	−3.8	−2.6	3.8	−3.8
Business Services	−3.8	2.6	0.5	−0.2	−1.3	0.8
Labour-intensive Services						
Hotels and Restaurants	−1.4	0.0	1.6	−0.9	0.9	2.2
Public Administration	−1.6	−0.5	2.6	−2.1	0.8	0.9
Health	−0.8	−2.5	4.9	−0.9	−1.3	2.2
Education	−0.7	0.6	1.8	−1.0	0.1	0.3
Other Services	−0.7	0.0	3.6	−1.0	−0.3	1.6
Total domestic demand	−2.3	0.8	1.5	−1.1	−0.1	0.7

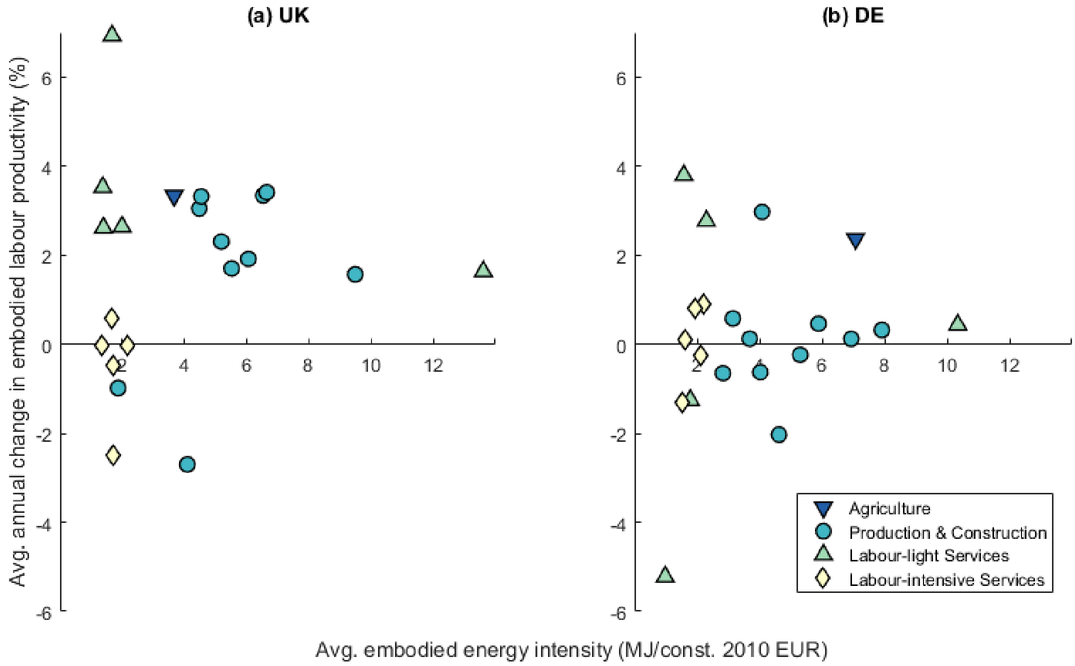

Figure 3-3: Relationship between change in embodied labour productivity and the average embodied energy intensity for domestic demand sectors between 1995 and 2011 in (a) the UK and (b) Germany.

countries. Both these demand sectors show relatively high rates of growth in embodied labour productivity in the UK but negative rates of change Germany.

The Finance and Insurance demand sector in Germany presents a strong outlier with rates of change in embodied labour productivity of –5.2% driven by an increase in the price index by 9.1%. This is not a result of the financial crisis as the rates of change in embodied labour productivity and prices between 1995 and 2006 are similar (Table A4, Appendix B). However, the rate of change in direct labour productivity of GVA is much less extreme showing –0.6% per year (Table A5, Appendix B). This could indicate that, for this demand sector, the use of the implied GVA deflator is not well suited to deflate final demand. This is likely to be related to the challenges associated with measuring real output in the sector in general (Inklaar et al., 2008; Christophers, 2011).

The low rates of direct labour productivity growth in the labour-intensive service sectors is often contrasted with high rates of direct labour productivity growth in the manufacturing, transport and agriculture sectors (Mulder and de Groot, 2004; Maroto and Rubalcaba, 2008). However, our results using an embodied perspective only fit this pattern in the UK but not in Germany.

In the UK, the production demand sectors, the Transport demand sector, as well as the Agriculture, Forestry, Fishing demand sector show rates of growth in embodied labour productivity that are considerably higher than in the labour-intensive services, ranging from 1.6% to 3.4% per year (Table 3-3, Figure 3-3a). The only exception is the Mineral Products demand sector, which records a considerable reduction in embodied labour productivity over the time period studied.

The results for Germany differ considerably from the UK. Most strikingly the production demand sectors as well as the Transport demand sector show only very low growth rates or even reductions in embodied labour productivity over the time period studied (Table 3-3). The only exception is the demand sector Paper, Printing and Publishing which shows a rate of change in the embodied labour productivity of 3% per year. Similar to the UK, the Agriculture, Forestry, Fishing demand sector also shows relatively high rates of growth in embodied labour productivity of 2.4% per year.

The low rates of growth in embodied labour productivity in the German production demand sectors are not a result of low growth in the direct labour productivity of the German direct production sectors. Calculating the growth of direct labour productivity, in the form of GVA in constant 2010 prices per hour of work, shows relatively high and positive rates of growth in the German manufacturing sectors over the same time period (Table A5, Appendix B). The low rates of embodied labour productivity growth are therefore the result of low direct labour productivity growth in other parts of the supply chain offsetting the direct labour productivity growth in German production sectors. A similar effect can also be observed for the UK, with direct labour productivity growth rates in the production sectors being higher than the growth in embodied labour productivity in the corresponding demand sectors (Table A5, Appendix B). However, the effect is weaker so that the embodied rates of growth are still relatively large and positive for the UK.The time period covered by our results includes the financial crisis starting in 2008, which could have a distorting impact on our results. We therefore conducted the same analysis covering only the time period from 1995 to 2006. While restricting the time period changes the results for some demand sectors, especially some UK manufacturing demand sectors, the overall patterns are very similar to the ones described for the full time period (Figures A1 and A2 and Table A4, Appendix B).

We can now compare the importance of the different demand sector groups in the total final demand, total embodied energy and total embodied labour considered in this study. These totals exclude the final demand and associated embodied inputs for the energy-producing sectors, for the demand sector Private Households with Employed Persons and the demand for imputed rents. The total embodied energy also does not include any energy used for non-commercial purposes in each country, for example for residential use or private transport. The comparison reveals some common features across both countries (Figure 3-4). The share of the two service demand sector groups makes up the majority of final demand, but their combined share in the total embodied energy and labour is much smaller. Of the two service demand sector groups, the labour-intensive services take up a considerably bigger share than the labour-light services in final demand and in embodied labour. The difference between the embodied energy shares of the labour-intensive services and the labour-light services is much

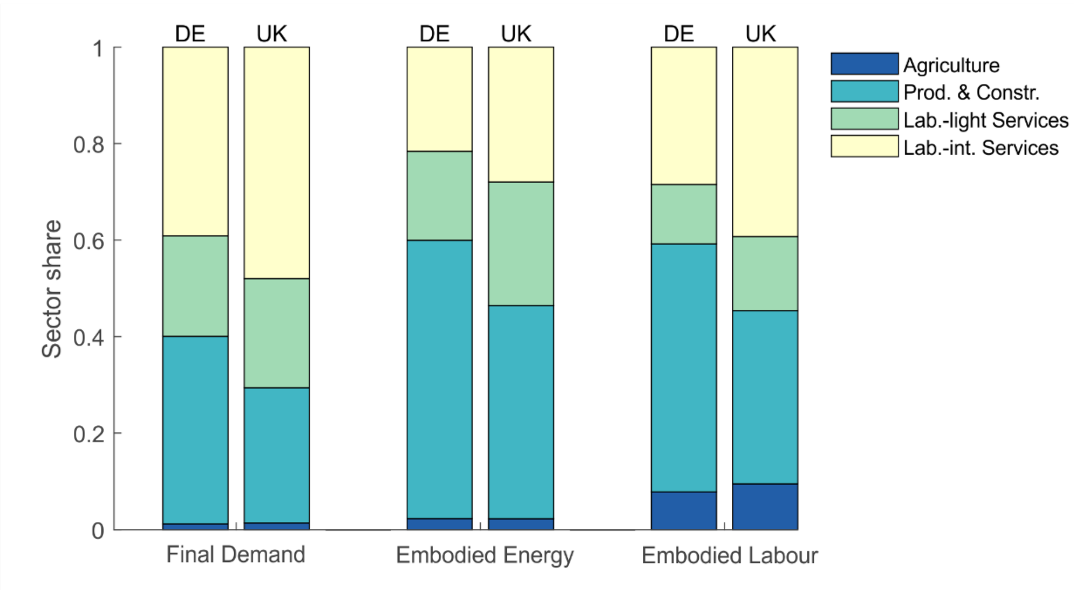

Figure 3-4: The shares in total final demand, embodied energy and embodied labour in the UK and Germany associated with different demand sectors for the year 2011. Totals exclude demand and embodied energy/labour inputs for the energy-producing sectors, private households and imputed rents.

smaller, because the labour-light service sectors include the embodied energy of the transport demand sector. The main difference between the two countries is related to the demand sector group Production & Construction, which has a considerably bigger share in Germany across all three categories.

3.3.3 Evidence of Baumol's cost disease in low-energy demand sectors

Baumol (2012) highlights that the cost disease might have negative environmental consequences if the environmentally damaging products from sectors of high environmental impact and high labour productivity growth get continuously cheaper compared to the services provided by low-energy service sectors with low labour productivity growth. This has important implications for the labour-intensive services proposed for a post-growth economy, as these would fall into the latter category.

To test Baumol's suggestion, we investigate the relationship between the embodied energy-labour ratio and the rate of change in the price index. We use the embodied energy-labour ratio instead of the embodied energy intensity because the former can be calculated independent of the price index.

We find that the results for the UK largely support Baumol's suggestion. The labour-intensive service demand sectors, as well as the Construction demand sector, show low embodied energy-labour ratios combined with relatively high rates of price inflation, ranging from 1.6% to 4.9% per year. In contrast, the production demand sectors as well as the Transport sector and the Agriculture, Forestry, Fishing demand sector show higher energy-labour ratios combined with falling prices (Figure 3-5a, Table 3-3). Exceptions to this pattern are the demand sectors Mineral Products and Other Manufacturing, which show increases in prices despite high embodied energy-labour ratios. For the labour-light service demand sectors the results are mixed. They show a wide range of price inflation rates ranging from –3.8% per year in IT and Communications to low rates of increase in Business Services (0.5%) and higher rates in Wholesale and Retail Trade (1.4%) and Finance and Insurance (2.0%).

For Germany, the results are less clear cut. Overall the rates of price inflation in the labour-intensive services are much lower than in the UK, ranging from 0.3%

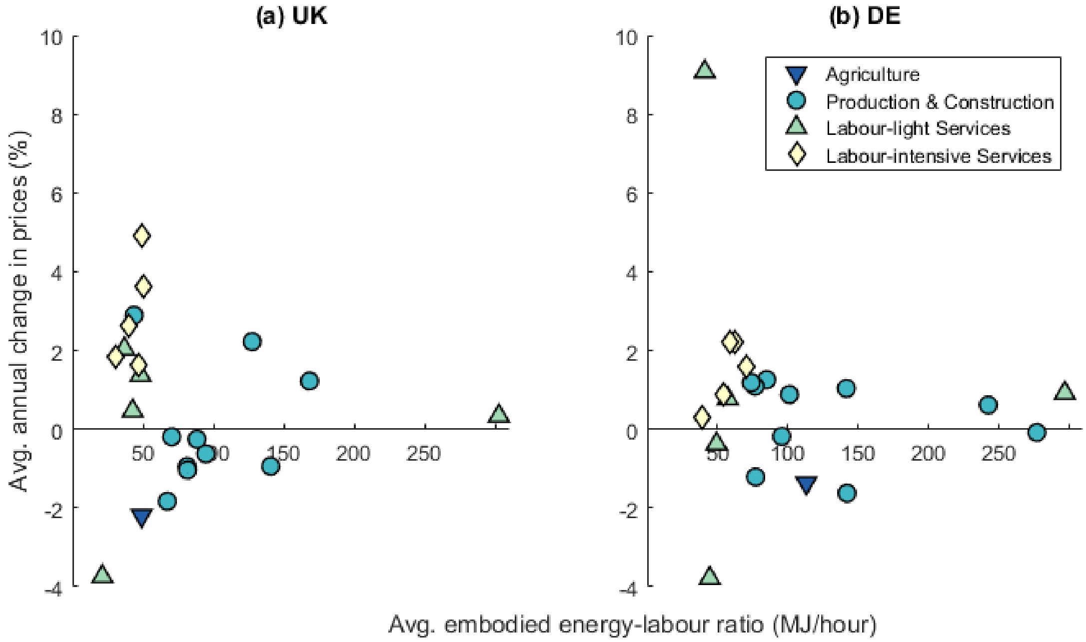

Figure 3-5: Relationship between change in sector price indices and the average embodied energy-labour ratio in (a) the UK and (b) Germany.

to 2.2% per year. The rates of price inflation in the labour-intensive service sectors are also not distinctly higher than the rates in many of the production demand sectors, with the latter exhibiting a wide range of values from –1.6% to 1.3% (Figure 3-5b). The lack of a clear distinction in price inflation rates between labour-intensive service demand sectors and production demand sectors is not surprising given that there is also less of a distinction in the rates of change in embodied labour productivity, discussed in Section 3.3.2.

Similar to the UK the labour-light services show a wide range of price inflation rates ranging from falling prices in IT and Communications (–3.8%) and Wholesale and Retail Trade (–0.4%), over low rates of increase in Business Services (0.8%) to extremely high rates in Finance and Insurance (9.1%).

3.4 Discussion

3.4.1 Comparing our results to the literature

To our knowledge, there are no other studies that compare embodied energy intensity to growth rates of embodied labour productivity across demand sectors. Gazheli et al. (2016) compare embodied carbon intensity with direct labour productivity growth across sectors in Germany, Spain and Denmark. They do not find evidence for a correlation between embodied carbon intensity and direct labour productivity growth in any of the countries. Our results would suggest that this lack of a correlation could be due to the fact that some of the labour-light services show relatively low levels of embodied energy intensity with relatively high rates of growth in embodied or direct labour productivity. Jackson et al. (2014) briefly compare the levels (but not growth rates) of embodied GHG intensities and embodied labour intensity across demand sectors in the UK or Canada. They highlight that the personal and social services demand sector provides a very high level of embodied labour intensity with a low level of embodied GHG intensity.

We can also compare our results to the literature on Baumol's cost disease, which includes a discussion on which service sectors can be considered to be part of the "stagnant" group of sectors with low potential labour productivity growth. Our results are similar to other empirical assessments, even though the other studies use a direct rather than an embodied perspective. Using an analysis of different direct labour productivity measures, Baumol et al. (1985) identify the following service sectors in the US to be stagnant according to the majority of measures: finance and insurance; hotels, personal and repair; auto repair and service; movies and amusement; medical, educational and non-profit; government enterprises; government industry. In a more recent study, Maroto and Rubalcaba (2008) determine different rates of direct labour productivity growth in different EU service sectors and estimate low or negative rates of direct labour productivity growth (< 1% per year) in the sectors hotels and restaurants, real estate activities, business services and social & personal services. They estimate a slightly higher rate of direct labour productivity growth in the public sector (1.67% per year), but this is still considerably lower than the direct labour productivity growth they estimate for the manufacturing sectors (5.93% per year).

Jackson (2017, p.220) lists the activities of "nutrition, education, care, maintenance and repair, recreation, craft, creativity, culture" as examples of labour-intensive services desirable for a post-growth economy. The five broad service demand sectors that we identify as being labour-intensive encompass all of these activities. Our results therefore support the assumptions in the post-growth literature that these activities could potentially be demand sectors able to support job creation in a post-growth economy.

The Construction demand sector presents an interesting case. In both countries it is showing relatively low values of embodied energy intensity. In addition, it is showing negative rates of change in embodied labour productivity, which means that it largely fulfils the two criteria we applied to identify labour-intensive services. However, while our estimated values of embodied energy intensity in the demand sector are quite low, the construction sector is generally considered to have high environmental intensities with regard to other environmental impacts, especially with regard to overall material use and GHG emissions from cement production (Giesekam et al., 2014). We have therefore not included it in the category of labour-intensive services. Nevertheless, our results highlight that construction activities are labour-intensive and that the demand sector could therefore provide an important source of jobs in a post-growth economy, as long as it can be made less environmentally intensive, for example in the area of retrofitting houses or in the construction of low-impact housing.

3.4.2 Potential energy savings from structural change

Our results confirm that most service sectors are less energy intensive than manufacturing and transport sectors, even from an embodied perspective. The picture still holds when the embodied energy-labour ratio is considered, although the distinction is not quite as clear, with some manufacturing demand sectors showing values similar to service demand sectors. Overall, a shift in final demand away from sectors with high embodied energy intensity towards labour-intensive service sectors would therefore reduce the embodied energy of final demand in Germany and the UK.

To estimate the potential magnitude of reductions in embodied energy we can imagine a radical scenario in which the share in final demand of all demand sectors with high embodied energy intensity (>3 MJ/EUR) in 2011 is reduced by half, this includes the production demand sectors as well as the Transport demand sector and the Agriculture, Forestry Fishing demand sector. The value of demand reduced in the energy-intensive demand sectors is redistributed to the five labour-intensive service demand sectors, according to their shares in demand in 2011, so that overall demand is unchanged. We can then calculate new, hypothetical, values for the embodied energy and labour using the embodied energy and labour intensities for 2011. Such a hypothetical scenario would reduce the total embodied energy of the demand sectors covered in this study by about 22% in both Germany and the UK. As our study excludes energy consumption for residential purposes and private transport, the reductions in the total final energy footprint in the UK and Germany would be smaller.

Such reductions in embodied energy would constitute an important step towards reducing environmental impacts. However, they are relatively small, given that the scenario describes structural changes that are very large by historical standards. In addition, the scenario is very simple and might not be achievable in practice as some categories of energy-intensive demand might not be easily reduced because they constitute important human needs, such as food or clothing.

For a post-growth economy, it is not only the overall embodied energy that needs to be reduced by structural change, but also the overall energy-labour ratio. In our scenario the overall embodied energy-labour ratio would be reduced by 8% and 11% in Germany and the UK respectively. The potential contribution that structural change towards labour-intensive services can make to lower the embodied energy-labour ratio is therefore even smaller than the one for embodied energy. However, a large part of the embodied labour for both countries is employed abroad. The ratio of domestic and foreign labour inputs in the supply chain varies significantly between demand sectors, with the production demand sectors and the Agriculture, Forestry, Fishing demand sector generally being associated with larger proportions of labour employed abroad (Tables A2 and A3, Appendix B). Any shifts towards labour intensive services imagined in the post-growth literature would therefore reduce the energy-labour ratio within the UK and Germany and increase employment domestically, even if it does not lead to big changes in the aggregate embodied energy-labour ratio.

The sustainability challenge requires us to find ways to provide for human needs within planetary boundaries. Overall, our results indicate that structural change towards labour-intensive services can make a contribution to the goals of a post-growth economy and to addressing the sustainability challenge, by reducing energy consumption and creating employment. It is difficult to define how much final energy consumption has to be reduced in developed countries to ensure environmental sustainability. However, we would suggest that the magnitudes of energy savings discussed in this section on their own are unlikely to be sufficient for avoiding environmental crises from climate change and other environmental impacts.

Therefore, it is important to focus on other strategies that can reduce energy use across sectors. One way to achieve this is to increase policy efforts to reduce their energy intensity. This is especially relevant for the service sectors which have generally lagged behind other sectors with regard to energy intensity reductions (Mulder et al., 2014; Hardt et al., 2018). An important question for the post-growth literature is then how such efforts to innovate and reduce energy intensity interact with labour productivity, as there is evidence that increased efforts for environmental innovation increase productivity (Aldieri et al., 2019). Another possibility to reduce energy consumption would be through policies for targeted reductions in unnecessary economic demand. This is likely to be most effective in production demand sectors that have a high energy intensity and already have exhausted many options for easy energy intensity improvements. In those sectors related to land-use change, such as agriculture or forestry, another important objective for the post-growth economy would be to restore the capacity of the land to provide important ecosystem services (Pechanec et al., 2019).

Nevertheless, even if the energy savings of high-level shifts in demand towards labour-intensive that we examine here are limited, there might still be other reasons why such shifts towards labour-intensive services have to form an important part of the post-growth transition. Such reasons can include the ability of these demand sectors to provide meaningful and socially useful work.

3.4.3 Baumol's cost disease as a barrier to the post-growth transition

The theory of Baumol's cost disease rests on a stylised division of the economy in sectors with high labour productivity growth and sectors with low labour productivity growth. Our results for the UK largely fit with Baumol's theory. There are high rates of growth in embodied labour productivity in the production demand sectors and the labour-light service demand sectors compared to low rates of growth in the labour-intensive service demand sectors. We find relative price increase in labour-intensive service demand sectors relative to high-energy production demand sectors. In contrast the results for Germany show stagnating value in embodied labour productivity in many of the production and labour-light service demand sectors that are similar to those in the labour-intensive services.

The diverging results with regard to embodied labour productivity in the production demand sectors in Germany and the UK highlight that it is important to go beyond the stylised division and take into account local context and complexity. This complexity has also been highlighted in other research on the topic (Hartwig, 2011; Fernandez and Palazuelos, 2012). The adoption of an embodied perspective demonstrates one aspect of this complexity, namely the interconnectedness of the different direct sectors. Most demand sectors rely on a mix of inputs from direct labour-intensive and non-labour-intensive activities, which shapes the rates of embodied labour productivity improvements. As our results demonstrate, this can lead to considerable differences in the rates of change of labour productivity between direct and embodied measures.

Nevertheless, drawing on our results for the UK and the wider evidence in the literature, we consider that Baumol's cost disease should be taken seriously when developing strategies for a transition to a post-growth economy. At first glance it might appear that Baumol's cost disease already supports a post-growth transition, as it leads to a shift of labour and demand in current prices towards labour-intensive services and might even act to reduce economic growth. However, as a general tendency we would suggest that Baumol's cost disease would act as a barrier to the post-growth transition for two reasons. Firstly, the shift in demand towards labour-intensive service demand sectors is largely a result of price changes and not mirrored in real production. The share of energy-intensive production demand sectors in demand does not decline strongly in real terms and hence energy demand is not strongly reduced by these changes (Henriques and Kander, 2010).

Secondly, as Baumol (2012) himself argues, some of the fundamental features of the cost disease are working against sustainability concerns. Manufactured goods, which have a high direct energy intensity, are becoming ever cheaper compared to labour intensive services with low direct energy intensity. In addition, the rising relative costs of repair foster a throw-away society. The only reason that Baumol's cost disease produces a shift in labour and output in current prices towards some labour-intensive services is the fact that these services are so important that demand for them is kept up despite increasing relative prices and costs (e.g., health care, education). Other labour-intensive services, which are not essential, such as theatre, become luxury products or are completely priced out of the market (Baumol, 2012). Even those labour-intensive services that are seen as essential and are often publicly provided (e.g., health care) face a continuous uphill battle from rising costs which need to be constantly justified.

Post-growth economics proposes that a sustainable economy will require a much larger share of activities to be concentrated in labour-intensive services. Baumol's cost disease suggests that a shift of demand towards such sectors would provide considerable challenges as these demand sectors will constantly struggle with rising relative costs and prices. An important question for the post-growth economics literature is therefore how to change the economic system to reduce the disadvantage that labour-intensive service demand sectors face from Baumol's cost disease. This presents a difficult challenge as Baumol's cost disease relates to some fundamental features of our market economy, such as competition and the important role of labour costs. Our analysis shows that many of the demand sectors showing low or negative price inflation also have a higher embodied energy-labour ratio. A reform of the tax system that moves taxes away from labour and onto energy use or GHG emissions could therefore make a start in addressing the disadvantage faced by labour-intensive services. Such tax reforms are a common suggestion in the post-growth literature (Cosme et al., 2017). Other policies could be targeted at specific labour-intensive services, for example obligations for companies to offer repair services together with their products. Another possible way to increase labour-intensive services would be to increase the non-market provision of such services through communities or the state, especially where such services are already provided in a non-market environment.

3.4.4 Structural change and economic growth are intertwined

Our results for Germany and the UK do not only show differences with regard to rates of change and embodied labour productivity in production demand sectors, but also the economy as a whole. The embodied labour productivity of all demand sectors covered in this study is essentially stagnant in Germany, while it shows a positive rate of growth in the UK. Similarly, the overall rate of price inflation is well below 1% in Germany but considerably higher in the UK. Our results reflect different rates of aggregate GDP growth in the two countries. Between 1995 and 2011, real GDP in the UK grew considerably more than in Germany, and the difference is even more pronounced for nominal GDP (Table 3-4).

Table 3-4: GDP growth in the UK and Germany between 1995 and 2011

	Growth in nominal GDP between 1995 and 2011 (%)	**Growth in real GDP between 1995 and 2011 (%)**
Germany	36.2	24.2
UK	86.5	41.6

Data source: Eurostat (2020)

The diverging results between the two countries therefore highlight another key feature of the wider literature on structural change. This is the fact that structural change is closely linked to the process of economic growth, as stressed by Kuznets (1973). Two of the main causes of structural change that have been identified in the literature are differential rates of labour productivity growth in different sectors (Baumol, 1967) and changes in demand composition associated with rising incomes (Pasinetti, 1993). Both of these mechanisms can be expected to operate only weakly in an economy that is not showing growth in aggregate labour productivity, income and demand. Without high productivity growth in at least some sectors, we also would not expect the manifestation of Baumol's cost disease.

This raises important questions for post-growth economists as they generally envision structural change towards labour-intensive services in a non-growing economy or even as a strategy to lower economic growth. However, the literature on structural change so far has very little insights to offer on how structural changes can be achieved in a non-growing economy.

3.5 Conclusions

Our current economic system is not sustainable as it is increasingly destroying the ecological life support systems of our planet. To address the sustainability challenge, we need to find ways to rapidly reverse environmental destruction while simultaneously meeting human needs and improving living conditions. Post-growth economists propose that structural changes in our economy away from material production and towards labour-intensive services, such as health care, education, arts and crafts or repair services, can make an important contribution to addressing the sustainability challenge by reducing the environmental impact of the economy and provide meaningful jobs.

Our study produces some empirical evidence regarding the realisation of this proposal by investigating the relationship between embodied energy intensity and embodied labour productivity of final demand sectors in the UK and Germany between 1995 and 2011. Specifically, we investigate three questions, namely whether service demand sectors feature lower levels of embodied energy intensity than other demand sectors, which service demand sectors can be considered labour-intensive and whether these labour-intensive service demand sectors might be affected by Baumol's cost disease. Our results confirm some of the assumptions in the post-growth economics literature but also raise some important challenges.

Firstly, we confirm that service demand sectors show lower values of embodied final energy intensity than other demand sectors and we identify five demand sectors as labour-intensive, combing low levels of embodied energy intensity with low rates of growth in embodied labour productivity. These include Hotels and

Restaurants, Public Administration, Education, Health Care and Other Services. Given the lower embodied energy intensity of these demand sectors, structural change in final demand towards these labour-intensive service sectors would likely reduce the embodied energy associated with the final demand in Germany and the UK.

Secondly, however, our results also suggest that the magnitude of reductions in embodied energy that can be achieved from structural change in final demand towards labour-intensive services are relatively small and, on their own, are unlikely to be sufficient for reducing the environmental impacts of the respective economies to sustainable levels. This is the case because large fractions of demand as well as the embodied labour are already concentrated in demand sectors with low embodied energy intensity. While labour-intensive service demand sectors provide very important services for human flourishing, increasing their share in demand is no panacea for reducing environmental impact. To achieve rapid reductions in energy footprints it is therefore important to achieve improvements in energy intensity within sectors as well as reductions in overall economic demand and production.

Lastly, our results highlight some potential challenges to achieving such structural changes towards labour-intensive services for a post-growth transition. For the UK we find some support for the theory of Baumol's cost disease with rates of price inflation in labour-intensive services being higher than in other sectors, especially compared to production sectors with high embodied energy-labour ratio. Baumol's cost disease suggests that the tendency of our economic system to chase labour productivity improvements poses a considerable challenge to labour-intensive demand sectors. As it is undesirable and/or difficult to improve embodied labour productivity in these demand sectors, they face continuously rising costs and prices relative to other demand sectors that are able to increase labour productivity. Such rising costs threaten their existence in the market place or their political justification, if they are provided publicly, and therefore provide a potential barrier to the expansion of labour-intensive services envisioned in the post-growth literature.

For Germany we do not find evidence supporting Baumol's cost disease as rates of growth in embodied labour productivity and price inflation are low across the whole economy, including the manufacturing demand sectors. These results highlight another challenge to the post-growth proposals, namely the fact that structural change is closely intertwined with the process of economic growth. There are currently no theories to explain how structural change might happen in an economy that is not growing.

Our research improves our understanding of the implications and challenges of structural changes towards labour-intensive services. However, it also highlights some important unanswered questions for the post-growth transition: How can we reduce the environmental impacts of labour-intensive services even further? How can structural change towards labour-intensive services be achieved without further economic growth? How can we create an economic environment that allows such labour-intensive services to flourish in the face of increasing labour productivity in other sectors? If we are serious about fostering labour-intensive, community-based services as part of a post-growth transition we need further research to answer these questions.

3.6 Author contributions

Conceptualization; L.H., J.B., P.G.T. and T.J.F.; Methodology: L.H., J.B., P.G.T. and T.J.F.; Formal Analysis: L.H.; Data Curation: L.H.; Writing—Original Draft Preparation: L.H.; Writing—Review & Editing: L.H., J.B., P.G.T. and T.J.F.; Visualization: L.H.; Supervision: J.B., P.G.T. and T.J.F.; Funding Acquisition: J.B. and P.G.T.

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Chapter 4

What structural change is needed for a post-growth economy: A framework of analysis and empirical evidence

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Abstract

In order to avoid environmental catastrophe we need to move to a post-growth economy that can deliver rapid reductions in environmental impacts and improve well-being, independent of GDP growth. Such a move will entail considerable structural change in the economy, implying different goals and strategies for different economic sectors. So far there are no systematic approaches for identifying the desired shape of structural change and sectoral goals in terms of output, demand and employment. We present a novel analysis that addresses this gap by classifying economic sectors into groups with similar structural change goals. Our framework for the classification considers sectoral characteristics along three dimensions, which are (a) the final energy intensity, (b) the potential for labour productivity growth and (c) the relationship between labour productivity and the energy-labour ratio. We present empirical evidence on the three framework dimensions for economic sectors in the UK and Germany and derive structural change goals for four sector groups sharing particular combinations of the sector characteristics. Our analysis allows us to discuss the specific role of different economic sectors in the structural change envisioned in the post-growth transition and the most important challenges they might be facing.

Keywords: Post-growth Economics; Degrowth; Structural Change; Energy Footprint; Labour Footprint;

4.1 Introduction

To avoid serious environmental crises, global society needs to drastically reduce resource use and eliminate global greenhouse gas (GHG) emissions in a few decades (UNEP, 2016; IPCC, 2018). Up to now, growing GHG emissions and resource use have been closely coupled to growing economic activity, as measured by GDP (Wiedmann et al., 2015; Csereklyei et al., 2016). As long as global GDP continues to grow, achieving the necessary reductions in GHG emissions and resource would require rates of decoupling that are much higher than any rates achieved in the past (Hickel and Kallis, 2019; Parrique et al., 2019; Wiedenhofer et al., 2020; Haberl et al., 2020). Achieving the necessary reductions in GHG emissions and resource use will therefore likely (but not certainly) lead to reductions in GDP growth rates and even in GDP levels in high-income countries (Kallis, 2018, p.112). Without a radical economic transformation, such reductions in GDP growth rates or levels will have detrimental social impacts (Jackson, 2017, pp.82–83).

High-income countries therefore face the challenge of transforming their economies to simultaneously increase human well-being and deliver the necessary reductions in GHG emissions and resource use, independent of whether GDP grows or contracts. Fortunately, GDP is not a good measure of human well-being, so the challenge is difficult but not impossible (Stiglitz et al., 2010; Costanza et al., 2014). We refer to an economy that meets this challenge as a “post-growth economy” following Jackson and Victor (2011) and Jackson (2017, p.160). The literature features other, similar approaches under the terms of degrowth (D’Alisa et al., 2015; Kallis, 2018) or steady-state economics (Daly, 2008; Dietz and O’Neill, 2013). For the purpose of our article the commonalities of these approaches are more important than their differences and we will refer to them collectively as the “post-growth literature”.

The transformation to a post-growth economy will not affect all sectors of the economy equally. Production and consumption will have to be reduced in some sectors but expanded in others, leading to changes in the sectoral composition of output, demand and employment (Kallis, 2011). For the purpose of our study we refer to such changes in the sectoral composition of demand, output and employment as “structural change”, although structural change in a wider sense can also refer to other aspects, such as institutions, industrial organisation or technology (Ciarli and Savona, 2019).

Even though structural change is recognised as an important feature of the post-growth transition, the post-growth literature does not yet provide a systematic discussion of the structural change that is desired and of how it can be achieved. Scattered references identify sectors considered harmful to the post-growth transition, such as marketing (Dietz and O’Neill, 2013, p.96), speculative finance (Daly, 2008) or resource extraction (Sekulova et al., 2013). A somewhat more comprehensive discussion is provided of the sectors that are desired. This discussion focuses especially on the provision of labour-intensive services to create meaningful employment (Jackson and Victor, 2011; Jackson, 2017, pp.147–149).

Such discussions of specific sectors are a useful starting point for a post-growth structural change analysis, but they have not been integrated into a comprehensive framework that systematically identifies sector goals and strategies. Without such a framework the post-growth literature leaves many open questions on structural change, for example: Which sectors specifically need to expand or shrink in terms of their output, demand or employment share? And what does that mean for sector-specific goals, for example with regard to labour productivity or energy intensity?

Developing a framework that can answer such questions would advance the post-growth agenda in three ways. Firstly, given that structural change will inevitably be part of the post-growth transition, the development of effective strategies to achieve the transition will require a clear picture of the structural change needed, including sector-specific goals and strategies. Secondly, such a framework helps to make the often abstract vision of the post-growth economy more concrete, because it describes a vision for specific sectors, while still maintaining a comprehensive view of the whole economy. Thirdly, having such a concrete vision can help with the communication of post-growth ideas to policy-makers and businesses. Policy makers and businesses are familiar with using sectoral approaches, even if the goals they pursue are different from the objectives of a post-growth economy. For example the UK government has developed sector roadmaps for energy efficiency (e.g. DECC, 2015) and includes “sector deals” in its industrial strategy (HM Government, 2017). Similarly, the German Council of Economic Experts (2019) suggests that “there could be justification for a vertical policy intervention that is tailored to individual sectors or technologies”.

To address this gap in the post-growth literature we present a novel framework to systematically define the structural change required for a post-growth economy. We use the framework to classify economic sectors in the UK and Germany into groups and define the sectoral goals for each group with regard to the sectoral share in output, final demand and employment as well as with regard to sectoral labour productivity growth. Sectors are allocated into groups based on their characteristics along three dimensions, derived from the overarching structural change objectives for a post-growth economy. The three dimensions are (a) the sectoral final energy intensity, (b) the potential for labour productivity growth and (c) the relationship between the growth in labour productivity and the growth in the energy-labour ratio. For each sector in the UK and Germany we present empirical evidence on each of the three dimensions from both a direct and an embodied perspective.

We build on the analysis presented in Hardt et al. (2020) and Chapter 3 of my thesis, but go beyond its results to present a new and complementary analysis as well as new results. Firstly, Hardt et al. (2020) focus specifically on labour-intensive services. The analysis we present here covers the whole economy outlining sector goals and discussing challenges for all parts of the economy. Secondly, Hardt et al. (2020) only investigate the embodied energy intensity and embodied labour productivity growth rates. The analysis we present here adds new results regarding an important third dimension, namely the relationship between labour productivity and the energy-labour ratio. Thirdly, Hardt et al. (2020) consider only sectoral characteristics from an embodied perspective. The analysis we present here compares the sectoral characteristics from a direct and embodied perspective.

Based on the analysis and discussion we highlight important gaps in current research on the post-growth transition and identify where more research and democratic discussion is needed to determine sector goals and policies to achieve them. Our analysis is intended as a first demonstration of our framework as applied to the economy as a whole. It therefore faces limitations in terms of the level of sectoral detail and depth of discussion in each sector. We envision our framework to be further developed and applied across different scales in the future, for example to guide the development of more fine-grained strategies for different sectors in different countries.

4.2 Analytical approach

4.2.1 Definition of economic sectors

We are concerned with structural change in terms of the sectoral composition of the economy, which requires a classification of economic sectors. We use the sectoral classification from the system of national accounts, because it allows us to use the available data on sectoral gross value added (GVA), final demand and employment.

Within the framework of national accounts, economic sectors can be represented from two perspectives. We refer to the first as the direct perspective, because it defines economic sectors by similar activities. From a direct perspective the Transport Equipment sector includes all businesses producing transport equipment. Sectoral data are conventionally presented from a direct perspective in the national accounts.

We refer to the second perspective as the embodied perspective, because it defines economic sectors based on the supply chain inputs of a product or unit of final demand. We therefore use the term of “demand sector” to refer to sectors conceptualised from this perspective. From an embodied perspective the Transport Equipment demand sector includes not only the assembly of the equipment itself but also all the intermediate inputs used in the production process, such as steel, computer software or electricity. The embodied inputs for different demand sectors can be derived from the input-output tables published as part the national accounts. An embodied perspective has been employed for structural change analysis (Pasinetti, 1981; Pasinetti, 1993) as well as for the analysis of emissions or energy use embodied in trade (e.g. Barrett et al., 2013; Lan et al., 2016).

We use the same set of sectors for each perspective. That means that for each direct sector there exists a corresponding demand sector whose embodied inputs are coming from the corresponding direct sector, but also other direct sectors along the supply chain. The characteristics of the corresponding sectors and demand sectors are therefore related and give complementary insights. In this study we therefore do not classify sectors and demand sectors separately. Instead, we use the term “sector” to refer to the two together and assign the corresponding sectors and demand sectors to the same sector group. We use the information given by the different perspectives to inform different aspects of the classification process and of the identification of structural change goals. For example the information provided by the embodied perspective is useful to determine goals with regard to structural change in final demand and can be used to ensure that structural change goals and policies are consistent with overarching, global objectives of the post-growth economy. In turn, the direct perspective can be more easily related to real businesses and features more homogenous production processes. It is therefore more useful for informing goals and policies targeting production-related aspects, such as energy intensity and labour productivity.

4.2.2 A framework for structural change

The post-growth literature does not feature a systematic discussion of structural change. But we can identify the goals post-growth economists want to achieve from structural change by analysing the references to sectors that are desired or not. Two overarching objectives stand out (Figure 4-1). Firstly, increasing the share of sectors with lower environmental impact in output and demand will reduce the overall environmental impact of economic production (Cosme et al., 2017). Here we focus mostly on final energy use as one important element of environmental impact. Secondly, increasing the share of labour-intensive sectors and demand sectors in GVA and demand can provide meaningful employment and offset job losses from reduced production and demand or increased labour productivity in other sectors (Jackson, 2015).

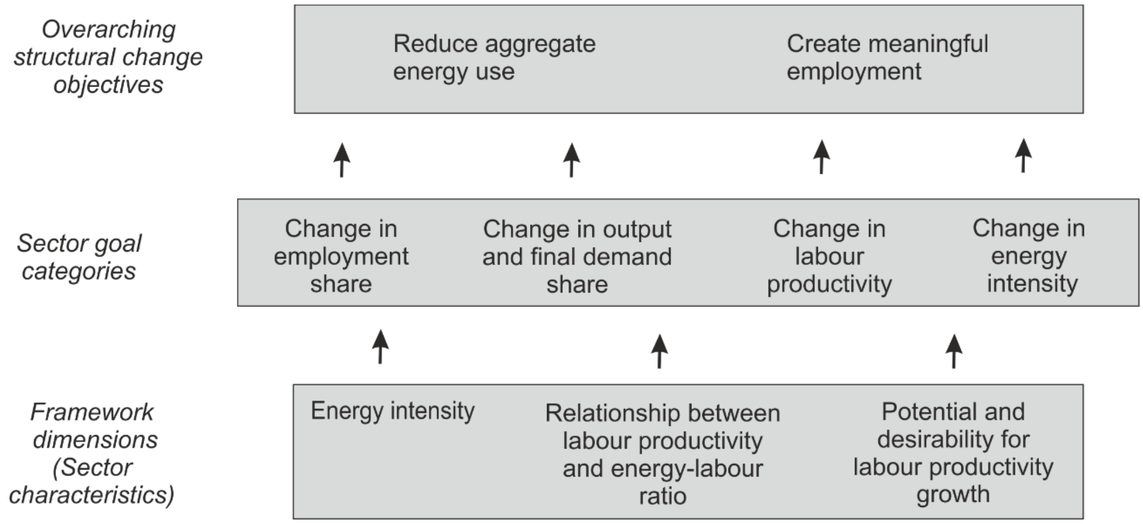

Figure 4-1: Framework for determining individual sector goals

The purpose of our framework is to translate the two overarching objectives into goals for specific sectors. We specifically identify sector goals in four categories (Figure 4-1). The first category is the change in the sector share in output and final demand, where the goal could be an increase or a decrease in the sector share. The second category is the change in the sectoral employment share. The two categories effectively break down the structural change in the economy into its sector-specific components. But it is difficult to determine the goals in the first two categories without knowing the desired changes to sectoral labour productivity and energy intensity. We therefore add a third category, which is the change in labour productivity, and a fourth category, which is the change in energy intensity. The framework produces for each economic sector a set of goals, describing whether the sector share in output, final demand, and employment is expected to increase or decrease and whether labour productivity and energy intensity are expected to increase or decrease.

How the two overarching objectives are translated into sector-specific goals is determined by the inherent characteristics of different sectors. For example the GVA share of energy-intensive steel production needs to be reduced to achieve the overarching objective of reducing aggregate energy use. While the sectoral goals might seem obvious for some sectors, difficulties arise where there are trade-offs between the different goals. For example, taken on their own, energy intensity reductions are desirable in all sectors. But in some sectors reductions in energy intensity might clash with the goal of labour productivity growth. To strike a balance between comprehensiveness and ease of application we determine sector goals based on sector characteristics in three dimensions, which we assess both from a direct and an embodied perspective. The three dimensions are the energy intensity, the potential for future labour productivity growth and the relationship between labour productivity and the energy-labour ratio (Figure 4-1). Another important dimension that can inform structural change goals is the desirability of labour productivity growth. For the transition to a post-growth economy, labour productivity growth might not be desirable in all sectors where it is possible. We do not empirically assess this dimension or use it in this study to classify sectors and demand sectors, but we discuss some of its implications.

The three dimensions omit any assessment of the ability of a sector to contribute to the provision of basic human needs and well-being. Arguably, such an ability is a key determinant for the sector goals in the transition to a post-growth economy. We omit such a dimension in our framework because it cannot be assessed based on economic statistics alone and requires democratic discussion. Our framework can therefore give indications about the directions of the sector goals but not necessarily the desired magnitude of change. For example we identify sectors in which final demand should be reduced. But in order to determine by how much it should be reduced, further assessment of the contribution of such sectors to human well-being is necessary.

4.2.2.1 Dimension 1: Final energy intensity

The first dimension describes the final energy intensity of a sector. We include final energy intensity in the framework because it determines how much a change in the sector share in output or final demand can contribute to the overarching objective of reducing aggregate energy use and therefore the wider overarching objective of reducing environmental impacts. It also determines the importance of further energy intensity reductions in the sector in comparison with other goals.

The first overarching structural change objective for a post-growth economy is the reduction of overall environmental impact. For the purpose of our analysis we focus on the empirical assessment of final energy intensity at the expense of other measures of environmental impact, such as GHG emissions or resource use. We do so for two reasons. Firstly, final energy use is closely related to other environmental impacts, such as carbon emissions and nitrogen pollution (Owen et al., 2018). Secondly, final energy use features a prominent role in the post-growth literature because it is related to labour productivity growth (see Section 4.2.2.3). However, in cases where we consider that the energy-intensity alone is not a good proxy for the environmental impact of a sector, we also take into account information on other environmental impacts from the literature. Most importantly this applies to the Construction sector. Further research that extends our framework to systematically include other measures of environmental impact would be a useful addition to the post-growth literature.

We define the direct energy intensity of a sector as the direct final energy consumption per Euro of GVA in constant prices, as is commonly done in the literature (Hammond and Norman, 2012). We define the embodied energy intensity for each sector as the embodied final energy consumption per Euro of final demand in constant prices. We restrict the analysis to the domestic components of final demand, as price deflators for non-domestic components are not readily available.

For the purpose of allocating economic sectors into groups we distinguish two types of sectors, namely sectors of high energy intensity and those of low energy intensity. We will refer to sectors of high energy intensity as energy-intensive sectors and to sectors with low energy intensity as energy-light sectors.

Defining an exact threshold above which a sector or demand sector counts as energy-intensive is always arbitrary to some degree. For the purpose of this study we generally consider sectors as energy intensive if their direct and embodied energy intensity exceeds 3 MJ/EUR. We derive this threshold from the results on embodied energy intensity presented in Chapter 3. In the UK the embodied energy intensity divides the demand sectors into two distinct groups, one with embodied energy intensities below 2 MJ/EUR and one with embodied energy intensities above 4 MJ/EUR (Figure 3-2). In Germany a similar, but somewhat less distinct, jump is visible around 3 MJ/EUR. We therefore consider this a suitable threshold for our analysis.

4.2.2.2 Dimension 2: Potential for labour productivity growth

The second dimension describes the potential for labour productivity growth in a sector. We include the dimension in the framework because it determines how changes in the employment and output share of a sector can contribute to the overarching objectives of creating meaningful employment. Sectors and demand sectors with low potential for labour productivity growth are generally those that comprise large shares of activities in which the reductions of labour inputs would directly reduce the quality of the output, such as care services or education. Such sectors and demand sectors are often considered desirable in the post-growth literature because they can slow down aggregate labour productivity growth, or even reduce the level of aggregate labour productivity, and therefore mitigate the threat of unemployment in a non-growing economy (Jackson and Victor, 2011). In addition it is often considered that such activities are likely to provide meaningful work because they deliver a high social value (Jackson, 2015). However, while such sectors might have the potential for meaningful work, they do not necessarily feature good working conditions in the current system, as explored by Druckman and Mair (2019).

In order to assess the potential of future sectoral labour productivity growth we use the historical rates of labour productivity growth as an indicator. Using historical rates has the advantage that they can be calculated easily and consistently across economic sectors from existing data. But there are also large uncertainties in how far historical rates of labour productivity growth will be similar to future rates. For example, past labour productivity growth might have exhausted the potential for further growth in some sectors, or the development of new technologies might redistribute the potential for labour productivity growth between sectors (Frey and Osborne, 2017).

Based on historical values of labour productivity growth we distinguish two potential values for the dimension in our analysis, which are based on different rates of historical direct and embodied labour productivity growth. We refer to labour-light sectors as those sectors that have a high potential for labour productivity growth. We refer to labour-intensive sectors as those sectors that have a low potential for labour productivity growth. We use rates of labour productivity growth rather than levels of direct and embodied labour intensity for the reasons outlined in Section 4.2.2.4. In order to distinguish between labour-light and labour-intensive sectors we use the threshold of a 1% annual rate of direct and embodied labour productivity growth. Baumol et al. (1985) use a similar threshold to define "stagnant" sectors in their analysis based on a distinct gap in direct labour productivity growth rates observed in their data. A similar gap can be observed in our own results, with direct and embodied labour productivity growth rates being either lower than 1% per year or higher than 1.5% per year, with only a single exception (see Section 4.3).

We define the direct sectoral labour productivity as the sectoral GVA in constant prices divided by the hours of direct labour inputs. We define the embodied labour productivity as the amount of final demand in constant prices per embodied hour worked. We obtain the annual compound rate of growth in direct and embodied labour productivity in each sector by fitting a log-linear regression model over the whole time period (Gujarati, 1995, pp.169–171).

In general policy discourse it is usually assumed that labour productivity growth should be pursued in all sectors that have the potential for it. However, from a post-growth perspective labour productivity growth is not necessarily desirable and there might be sectors in which it is possible to increase labour productivity but where it might be undesirable. The post-growth literature offers several potential reasons. Labour productivity growth can eliminate meaningful jobs, for example if highly skilled craft work is replaced by repetitive factory work (Nørgård, 2013; Mair et al., 2020). Labour productivity growth can harm the well-being of workers if it increases job demands or job insecurity (Isham et al., 2020). Labour productivity growth can also come at the cost of worsening environmental impacts. Factory workers might be replaced by energy-intensive machines or farm workers by bee-harming pesticides. Indirectly, labour productivity growth may increase environmental impacts if it makes environmentally-damaging products cheaper than environmentally-friendly ones (Baumol, 2012, pp.71–73).

We do not include the desirability of labour productivity growth in our framework here because it is difficult to assess empirically which sectors and demand sectors could provide meaningful work. While such an analysis is possible, it lies beyond the time and resource constraints of our research project. The lack of such an analysis is an important limitation of our framework and of the wider post-growth literature and should be addressed in future research. More empirical research into the desirability of labour productivity growth in different sectors is vital for the development of a post-growth strategy.

4.2.2.3 Dimension 3: Relationship between labour productivity and the energy-labour ratio

The third dimension in our framework describes the relationship between the growth in labour productivity and the growth in the energy-labour ratio in different sectors. We include the dimension in the framework because it is important for assessing the potential trade-offs between sector goals. The previous two dimensions treat energy intensity and labour productivity separately and do not consider potential trade-offs between them, for example whether increasing or reducing labour productivity might come at the cost of increased energy use. Simply examining the relationship between labour productivity and energy intensity, however, does not yield useful information about how changes in labour productivity might influence energy intensity, because energy intensity is influenced by a range of factors. It is therefore difficult to tell whether energy intensity is changing because of or despite labour productivity growth, and how further changes in labour productivity would influence energy intensity.

The literature considers that energy use and labour productivity are linked, because an increased availability of energy has allowed for the increasing replacement of labour with machines and for more efficient ways of organising labour (Elkomy et al. 2020). Empirical evidence indicates that historical growth in aggregate labour productivity has been associated with a growing energy-labour ratio (Kander et al., 2013; Semieniuk, 2016). On a sectoral level the evidence on the relationship between labour productivity and the energy-labour ratio is limited. Two studies by Mulder and de Groot (2004) and Witt and Gross (2019) suggest that there might be a correlation between growth in direct labour productivity and in the direct energy-labour ratio in the manufacturing and transport sectors, but not in the service sectors.

To explore the link between energy intensity and labour productivity it is therefore useful to decompose the growth in energy intensity into the growth of the energy-labour ratio and the growth of labour productivity (Semieniuk, 2016). Examining the relationship between the two growth rates can provide insights into the potential trade-offs between the goals in our framework. The first important question is whether the two ratios are generally moving in the same or opposite directions. For example sectors which are expected to increase labour productivity and reduce energy intensity face a trade-off between the two goals, if increases in labour productivity are associated with increases in the energy-labour ratio, but not if they move in opposite directions. Whereas sectors in which reductions in labour productivity are considered useful to increase employment would face a trade-off with reductions in energy intensity if labour productivity and the energy-labour ratio move in opposite directions, but less so if they move in the same direction. Of course, if labour productivity and the energy-labour ratio are not related at all, there are no trade-offs. In addition to the general direction of change of the two ratios, the relative rates of change also provide information on the magnitude of the potential trade-offs. For example even if they move in the same direction, the trade-off between labour productivity growth and energy intensity can be quite small if labour productivity grows faster than the energy-labour ratio, as this would still allow for reductions in energy intensity.

Ideally, the dimension should be empirically assessed by examining the statistical correlation between labour productivity and the energy-labour ratio in each sector. However, doing so would require the implementation of several statistical tests for each sector, the description and discussion of which is beyond the scope of this article. Instead, to obtain a first indication for this dimension, we calculate the rates of change in the direct and embodied energy-labour ratio and compare them to the rates of change in the direct and embodied labour productivity. The direct energy-labour ratio is the direct final energy consumption divided by the hours of direct labour inputs in each sector. The embodied energy-labour ratio is the embodied final energy consumption of each demand sector divided by the embodied amount of hours worked.

To classify economic sectors in our framework we divide sectors into two groups, depending on whether the changes in the energy-labour ratio and labour productivity are in the same or opposite direction, and consider the relative magnitude of the rates of change in the discussion. In the future, however, it would be useful to explore the relationship between the energy-labour ratio and labour productivity at a sectoral level using more sophisticated econometric methods.

4.2.2.4 Levels or rates of change

As outlined in the previous section, we use the level of energy intensity to classify economic sectors. But for our dimensions of labour productivity and the energy-labour ratio we use the rate of change rather than the level.

For energy intensity we consider the level more useful than the rate of change for translating the overarching structural change objective to reduce energy use into sectoral goals. Firstly, the use of energy intensity, measured as direct or embodied energy use per GVA or final demand, is a meaningful and commonly used measure for comparing the level of direct and embodied energy intensity across sectors (Hammond and Norman, 2012; Lan et al., 2016). Shifting GVA and final demand towards sectors with lower embodied energy intensity therefore contributes directly to the overarching goal of reductions in aggregate direct and embodied energy use. Secondly, the direct and embodied energy intensity of energy-intensive sectors is often considerably higher than for energy-light sectors (see empirical results in Section 4.3). Energy-intensive sectors and demand sectors are therefore likely to remain relatively more energy intensive, even if they feature higher rates of reductions in direct or embodied energy intensity. Therefore we consider it more useful for structural change to shift GVA and demand towards sectors with low levels of direct and embodied energy intensity, rather than to sectors with high rates of reduction in direct and embodied energy intensity. For our classification we therefore use the calculated levels of direct and embodied energy intensity presented in Section 4.3. However, the rates of change of direct and embodied energy intensity are presented in Table A10 in Appendix D.

For labour productivity growth, the situation is somewhat different and we consider it more useful to focus on the rates of growth in direct and embodied labour productivity. Firstly, the overarching structural change objective to create meaningful employment is motivated equally by the need to create jobs now and by the need to prevent future unemployment resulting from aggregate productivity growth in a non-growing economy (Jackson and Victor, 2011). In order to achieve the objective, it is therefore useful to not only focus on reducing the static level of labour productivity but also its growth rate.

Secondly, and more importantly, we consider that it is difficult to meaningfully compare the level of labour productivity or its inverse, labour intensity, across sectors. For example, based on a low level of embodied energy intensity and a low rate of embodied labour productivity growth, we identified five labour-intensive service demand sectors in Chapter 3. These sectors align well with the activities that have been identified intuitively as labour-intensive in the post-growth literature. However, when comparing the average level of embodied labour intensity of those demand sectors between 1995 and 2011 (in constant prices), they do not show a higher level of embodied labour intensity than other demand sectors (Figure 4-2, Table A11). If anything, their embodied labour intensity is often lower than the one of other demand sectors with higher embodied energy intensity. When comparing the direct sectors the picture is very similar. The direct sectors corresponding to the five labour-intensive demand sectors identified in Chapter 3 feature a low level of energy intensity, but their level of labour intensity is in the same range as that of other sectors (Figure 4-2, Table A11). Our findings are therefore at odds with the results of Jackson et al. (2014), who find a higher level of embodied labour intensity for their demand sector of “Personal and social services” compared to other demand sectors.

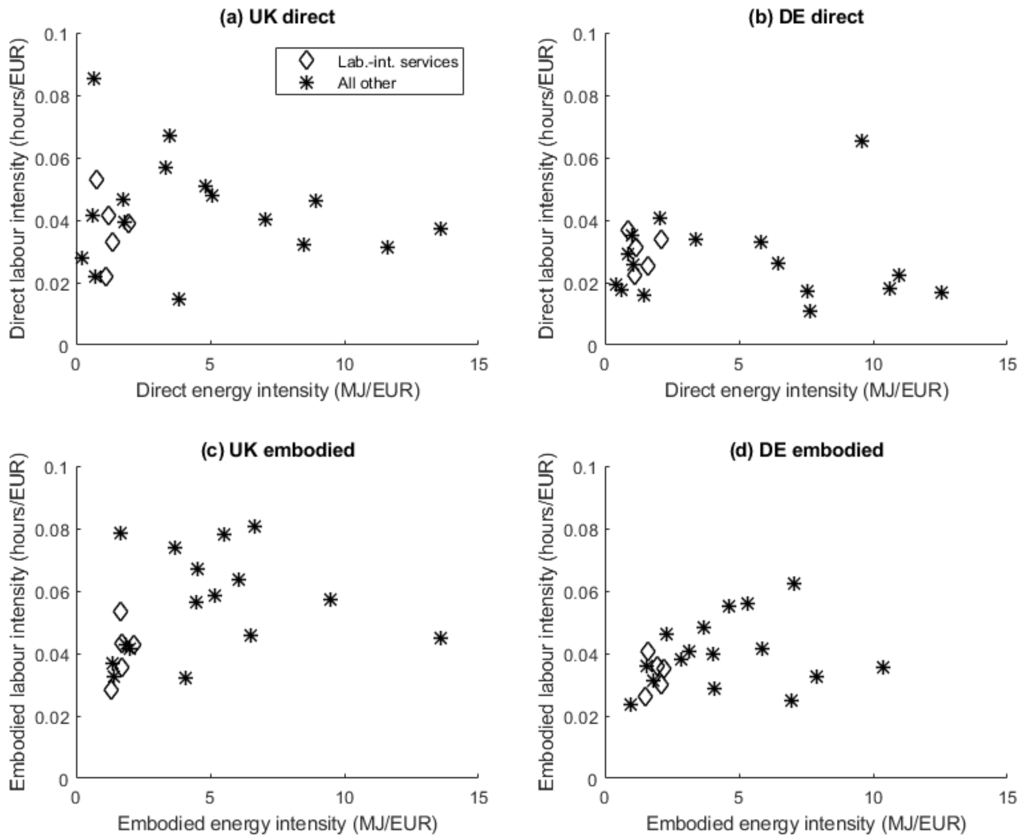

Figure 4-2: Relationship between sectoral energy and labour intensity in the UK and Germany for both direct and embodied perspective. Ratios are calculated with GVA and final demand values in constant 2010 EUR and averaged across 1995-2011. Labour-intensive services refer to the labour-intensive service sectors identified in Chapter 3.

We would suggest that the five sectors fail to measure a higher level of direct or embodied labour intensity, because the nominator (direct or embodied labour input) and the denominator (GVA or final demand) of the ratio are not independent. In the theory of Baumol's cost disease (Baumol, 1967; Nordhaus, 2006), Pasinetti's theory of structural change (Pasinetti, 1981; Pasinetti, 1993) as well as in post-Keynesian economic theory (Herr, 2009) it is assumed that labour costs are an important determinant of prices. If this is true, then any reductions in the labour input needed for a specific product would reduce its price and therefore the value of the monetary denominator (output, demand) in the labour intensity ratio. The overall value of the ratio would remain largely unchanged as long as the wage rate remains constant. For example if technological improvements in the vehicles demand sector would allow for the production of the same car using less hours of embodied work, arguably indicating a real reduction in embodied labour-intensity, the price of the car and therefore the value of monetary final demand would also be reduced, showing a much lower reduction in measured embodied labour intensity in current prices, or no reduction at all.

This issue of the interdependency between labour inputs and monetary GVA or demand is less of a problem when investigating the rate of change of labour intensity. The rate of change compares the direct or embodied labour intensity of the same sector and therefore the monetary measures of GVA or final demand can be corrected for price inflation over time. But such a correction is not possible when comparing the level of labour intensity across sectors, because the physical output of the different sectors cannot be meaningfully compared. Price effects from the interdependency of labour inputs and GVA or final demand cannot be corrected for. The relative levels of direct and embodied labour intensity across sectors, as measured using monetary GVA and demand values, might therefore not reflect the labour intensity as measured in physical terms very well, if at all. Instead the relative monetary direct and embodied labour intensities are likely determined more strongly by the wage rate and other factors, such as the wage-profit distribution in the sector (Shaikh, 2016a).

For example, for energy-intensive sectors, the embodied labour-intensity is generally higher than the direct labour intensity in our results (Figure 4-2). The same is not the case for energy-light sectors. One factor explaining the difference could be that embodied wage rates in the energy-intensive demand sectors are lower than the direct wages in the corresponding direct sector. The energy-intensive demand sectors are largely made up of the manufacturing demand sectors which feature a high proportion of embodied labour performed abroad (Tables A2 and A3, Appendix B), which is likely to be paid wages that are lower than the ones in the corresponding direct sectors in the UK and Germany. However, any definite conclusions on this matter would require a more detailed analysis of the wages embodied in the different demand sectors.

For the reasons outlined above we consider it more meaningful for our study to identify labour-intensive sectors based on lower rates of growth in direct and embodied labour productivity rather than based on higher levels of direct and embodied labour intensity.

4.2.3 Sector goals

Based on the sector characteristics in the three framework dimensions, we identify the sector goals in each sector. For the purpose of our study, sectors can only be assigned one of two possible values in each of the three dimensions, for example they are either energy-intensive or energy-light. Two values in three dimensions gives eight possible combinations of sector characteristics. Each of the eight combinations represents a group of sectors with its own set of goals, derived from their specific characteristics. Table 4-1 provides an overview of those sector goals for the different groups. To increase the clarity of presentation and discussion, we group the eight possible combinations into four overarching groups based on the first two dimensions. Each of these four groups has then 2 sub-groups according to the characteristic in the third dimension.

The goals outlined in Table 4-1 are derived purely from theoretical considerations. In summary, the need to reduce the overall energy use in the economy suggests that output and energy use associated with sectors of high energy intensity should be reduced relative to other sectors. In addition labour productivity growth in the labour-light sectors should be supported. Such support assumes that growth in direct and embodied labour productivity is desired where it is possible. From a post-growth perspective such growth might not always be desired and we briefly discuss the potential implications of this in Section 4.4. The share of the labour-intensive sectors in output, demand and employment should be increased in order to reduce aggregate labour productivity growth and create meaningful employment. Energy intensity should also be reduced throughout the economy, but there might be trade-offs with labour productivity goals, depending on the relationship between labour productivity and the energy-labour ratio. The resolution of these trade-offs depends on the other characteristics in each sector.

Table 4-1: Overview of proposed framework dimensions and sector-specific policy goals for a post-growth economy

Sector group	**Dimension 1: Energy intensity**	**Dimension 2: Labour productivity growth**	**Dimension 3: Change in energy-labour ratio relative to change in labour productivity**	**Sector goals**
Group 1a	High	High	Same direction	1. Reduce sector share in final demand and output 2. Reduce energy intensity 3. Increase labour productivity if compatible with energy intensity reductions (labour productivity growth > energy-labour ratio growth) 4. As a result of reductions in demand and output, combined with increases in labour productivity, sector share in employment is likely to fall
Group 1b	High	High	Opposite direction	1. Reduce sector share in final demand output 2. Reduce energy intensity 3. Increase labour productivity as there is no trade-off with energy intensity 4. As a result of reductions in demand and output, combined with increases in labour productivity, sector share in employment is likely to fall
Group 2a	High	Low or negative	Same direction	1. Reduce sector share in final demand and output 2. Reduce energy intensity 3. Consider reductions in labour productivity if it can help achieve point 2 (fall in labour productivity < fall in energy-labour ratio). 4. Impact on employment share depends on balance between reductions in output/demand and relative labour productivity growth in other sectors
Group 2b	High	Low or negative	Opposite direction	1. Reduce sector share in final demand and output 2. Reduce energy intensity 3. Maintain labour productivity as reductions would increase the energy-labour ratio and energy intensity 4. Impact on employment share depends on balance between fall in output/demand share and relative labour productivity growth in other sectors

Sector group	Dimension 1: Energy intensity	Dimension 2: Labour productivity growth	Dimension 3: Change in energy-labour ratio relative to change in labour productivity	Sector goals
Group 3a	Low	Low or negative	Same direction	1. Expand output and demand share in order to increase employment share 2. Reduce energy intensity 3. Potentially reduce labour productivity to create employment, but only if compatible with energy intensity reductions (fall in labour productivity < fall in energy-labour ratio)
Group 3b	Low	Low or negative	Opposite direction	1. Expand output and demand share in order to increase employment share 2. Reduce energy intensity 3. Maintain labour productivity as reductions would increase energy-labour ratio and energy intensity
Group 4a	Low	High	Same direction	1. Reduce sector share in final demand output 2. Reduce energy intensity 3. Increase labour productivity if compatible with energy intensity reductions (labour productivity growth > energy-labour ratio growth) 4. As a result of reductions in demand and output, combined with increases in labour productivity, sector share in employment is likely to fall
Group 4b	Low	High	Opposite direction	1. Reduce sector share in final demand and output 2. Reduce energy intensity 3. Increase labour productivity as there is no trade-off with energy intensity reductions 4. As a result of reductions in demand and output, combined with increases in labour productivity, sector share in employment is likely to fall

In practice, some combination of sector characteristics are likely to be more prevalent than others and some might not exist at all. We therefore discuss the sector goals in more detail in Section 4.4 in the context of our empirical results.

4.2.4 Empirical data

We demonstrate the application of our framework by providing empirical estimates for the three framework dimensions and for different economic sectors. We calculate sectoral values for final energy intensity, the rate of change in labour productivity and the rate of change in the energy-labour ratio, both from a direct and embodied perspective. Our empirical evidence covers sectors in the UK and Germany between 1995 to 2011.

Our empirical results build on the work of Hardt et al. (2020), presented in Chapter 3, and we utilise their estimates of embodied final energy intensity and the rate of change in embodied labour productivity. We extend the analysis by calculating the rate of change in the embodied energy-labour ratio as well as presenting direct measures for all three dimensions.

Our analysis draws on the EXIOBASE V3.4 database, which provides data on the global economy from 1995 to 2011 (Stadler et al., 2018). EXIOBASE disaggregates the economy into 163 sectors based on the NACE rev. 1.1 classification. For our analysis we aggregate all the data to a level of 70 sectors. For presentation, the results are further aggregated into 21 sectors (Table A12, Appendix D). By definition, direct energy-producing sectors, such as coal mining, oil refining or electricity production, do not feature any direct final energy consumption. Energy-producing sectors are therefore not included in the 21 sectors for which results are presented. In addition we exclude the Real Estate sector from the empirical analysis, because the large fraction of real and imputed rents in the sector makes it difficult to calculate meaningful values of labour productivity.

From EXIOBASE we obtain (a) symmetrical input-output tables indicating the flows of intermediate demands between all sectors in all countries, (b) the final demand for products from different sectors in the UK and Germany, (c) the sectoral gross value added (GVA) for sectors in the UK and Germany and (d) the labour inputs for each sector in the global economy in terms of total hours worked. EXIOBASE provides all monetary data in current prices only. We convert the data on GVA and final demand to constant 2010 prices using GVA deflators obtained from the Eurostat database (Eurostat, 2018).

To calculate the direct and embodied final energy use for each economic sector we use the energy extension vector calculated by Hardt et al. (2020). The extension vector is based on data from the IEA World Energy Balances (IEA, 2018), with additional detail for the UK and Germany obtained from country-specific sources. For brevity we will use the term “energy” to describe final energy inputs in the reminder of this article. More details on the method for calculating the direct and embodied energy measures can be found in Hardt et al. (2020).

4.3 Empirical sector classification

4.3.1 Group 1: Energy-intensive and labour-light sectors

Group 1 includes sectors that are energy intensive and have a high potential for labour productivity growth. In the empirical classification we present here, we consider a high rate of historical labour productivity growth as a proxy for the potential of future labour productivity growth. We allocate the manufacturing sectors (with the exception of Mineral Products) as well as the Agriculture, Forestry, Fishing sector and the Transport sector to Group 1.

All of the Group 1 sectors have an embodied energy intensity of more than 3 MJ/EUR, which compares to embodied energy intensities between 1.0 and 2.3 MJ/EUR for the sectors in Group 3 and Group 4 (Tables 4-2 and 4-3). Similarly most of the sectors in Group 1 feature levels of direct energy intensity of more than 3 MJ/EUR. The only exceptions are the Machinery, Electrical, Equipment, Computers sector in both countries and the Transport Equipment sector Germany, which feature values of direct energy intensity that are lower than 3 MJ/EUR and are in the same range as the service sectors. We still assign these sectors to Group 1, because we consider that the embodied energy intensity is more important for our classification, given that the overarching structural change objective of reducing energy use needs to be considered from a global perspective.

Table 4-2: Energy intensity and annual rates of change in labour productivity and energy-labour ratio for sectors in the UK.

UK	Direct measures			Embodied measures		
Sector	Energy intensity (MJ/EUR)	Labour prod. change (%)	Energy-labour ratio change (%)	Energy intensity (MJ/EUR)	Labour prod. change (%)	Energy-labour ratio change (%)
Group 1						
Agriculture, Forestry, Fishing	3.5	4.1	-0.5	3.7	3.3	-1.5
Food, Beverages and Tobacco	7.1	3.7	0.9	5.5	1.7	-0.8
Textiles, Clothes, Leather	4.8	4.8	6.6	4.5	3.0	3.0
Paper, Printing, Publishing	5.1	3.0	2.0	5.2	2.3	0.4
Chemicals	8.5	6.4	0.2	6.5	3.3	-1.7
Metals and Fabricated Metal Products	8.9	3.1	-3.5	6.1	1.9	-1.7
Machinery, Electrical Equipment, Computers	1.8	5.6	2.2	4.5	3.3	-1.1
Transport Equipment	3.3	5.4	0.8	6.6	3.4	-1.4
Other manufacturing	11.6	3.2	4.8	9.5	1.6	2.3
Transport	13.6	3.0	0.8	13.6	1.6	-0.8
Group 2						
Mineral Products	3.8	-1.2	3.1	4.1	-2.7	-1.2
Construction	0.6	-0.2	-3.1	1.9	-1.0	-1.2
Group 3						
Hotels and Restaurants	1.1	1.0	-1.1	1.3	0.0	-1.4
Public Administration	1.2	-0.6	-4.4	1.7	-0.5	-2.0
Health	1.4	-2.8	-5.0	1.7	-2.5	-3.3
Education	0.8	1.1	-2.9	1.7	0.6	-0.1
Other Services	2.0	0.8	-0.1	2.2	0.0	-0.7
Group 4						
Wholesale and Retail Trade	1.8	2.6	0.6	2.0	2.6	0.5
Finance and Insurance	0.2	6.6	2.4	1.4	3.5	-1.2
IT and Communication	0.7	7.9	1.4	1.7	6.9	0.0
Business Services	0.7	3.7	0.8	1.4	2.6	-1.3
Real Estate	-	-	-	-	-	-

Table 4-3: Sectoral energy intensity and rates of change in labour productivity and energy-labour ratio for sectors in Germany

Germany (DE)	**Direct measures**			**Embodied measures**		
Sector	Energy intensity (MJ/EUR)	Labour prod. change (%)	Energy-labour ratio change (%)	Energy intensity (MJ/EUR)	Labour prod. change (%)	Energy-labour ratio change (%)
Group 1						
Agriculture, Forestry, Fishing	9.6	4.3	1.7	7.1	2.4	-1.0
Food, Beverages and Tobacco	5.8	-1.3	-0.4	4.6	-2.0	-2.1
Textiles, Clothes, Leather	6.5	3.7	1.9	5.3	-0.2	-2.1
Paper, Printing, Publishing	7.6	6.4	5.1	4.1	3.0	1.0
Chemicals	7.7	2.1	2.5	6.9	0.1	-0.3
Metals and Fabricated Metal Products	11.0	2.0	0.1	5.9	0.5	-1.9
Machinery, Electrical Equipment, Computers	0.6	4.2	0.5	3.1	0.6	-2.0
Transport Equipment	1.5	3.3	0.9	4.0	-0.6	-2.1
Other manufacturing	3.4	2.5	2.6	3.7	0.1	0.7
Transport	12.6	4.6	2.6	10.3	0.4	0.5
Group 2						
Mineral Products	10.6	3.3	2.0	7.9	0.3	-0.4
Construction	1.0	0.1	0.8	2.8	-0.7	-0.4
Group 3						
Hotels and Restaurants	2.1	1.9	0.7	2.2	0.9	0.0
Public Administration	1.1	1.7	-1.8	1.9	0.8	-1.3
Health	1.1	-1.7	-2.7	1.5	-1.3	-2.2
Education	0.9	1.0	-2.1	1.6	0.1	-0.9
Other Services	1.6	0.2	-1.6	2.1	-0.3	-1.3
Group 4						
Wholesale and Retail Trade	2.1	2.0	-0.9	2.3	2.8	-1.1
Finance and Insurance	0.4	-0.6	-0.5	1.0	-5.2	0.5
IT and Communication	0.9	4.1	-0.5	1.6	3.8	1.1
Business Services	1.1	-2.2	-1.7	1.8	-1.3	-1.5
Real Estate	-	-	-	-	-	-

Group 1 sectors also well exceed 1% annual growth in direct labour productivity in both countries. The exception is the Food, Beverages and Tobacco sector which only achieves such rates in the UK (Tables 4-2 and 4-3). Our estimates are in line with results in the literature that have estimated high rates of direct labour productivity growth for the manufacturing, agriculture and transport sectors across different high-income countries and time periods (Baumol et al., 1985; Mulder and de Groot, 2004; Maroto and Rubalcaba, 2008).

Growth in embodied labour productivity, however, is generally lower than growth in direct labour productivity in Group 1 sectors (Tables 4-2 and 4-3). In the UK, embodied labour productivity growth in all Group 1 sectors still exceeds 1% per year. In contrast, embodied labour productivity growth in most of Germany's Group 1 sectors is well below 1% or even negative. It seems that the growth in direct labour productivity in Germany's Group 1 sectors has been offset by lower labour productivity growth in other parts of the supply chain. Given the short time frame of our analysis we cannot say whether the pattern of low embodied labour-productivity growth in Germany's Group 1 sectors presents a long-term trend. On balance, we decided to assign these sectors to Group 1, given the consistency in high direct labour productivity growth rates in both countries and the inconsistent embodied labour productivity growth rates between the two countries. In addition we consider the direct perspective somewhat more relevant for defining sector goals with regard to labour productivity, as direct labour productivity growth can be more easily conceptualised and targeted by policies than embodied labour productivity growth.

The third dimension of the framework asks whether labour productivity growth in Group 1 sectors has been associated with growth in the energy-labour ratio. Only very few of the sectors in Group 1 give results for this dimension that are consistent across the direct and embodied perspective and the two countries. When presenting the results in Tables 4-2 and 4-3, we therefore do not allocate the sectors into the two subgroups identified in Table 4-1. But we discuss the findings below.

For Group 1 sectors, the results for the third dimension are relatively consistent within the direct and within the embodied perspective, but not between them.

For the direct perspective, most Group 1 sectors show the two ratios moving in the same direction, with a positive growth rate in the direct energy-labour ratio in combination with growth in direct labour productivity (Figure 4-3). The exceptions are the Agriculture, Forestry, Fishing sector and the Metals and Fabricated Metals sector in the UK, which show falling rates of the direct energy-labour ratio, despite a growth in direct labour productivity (Table 4-2). Group 1 therefore generally fall into the subgroup 1a from a direct perspective. In most sectors the growth rate of the direct energy-labour ratio is below the growth rate of direct labour productivity, leading to a decline in direct energy intensity (Figure 4-3).

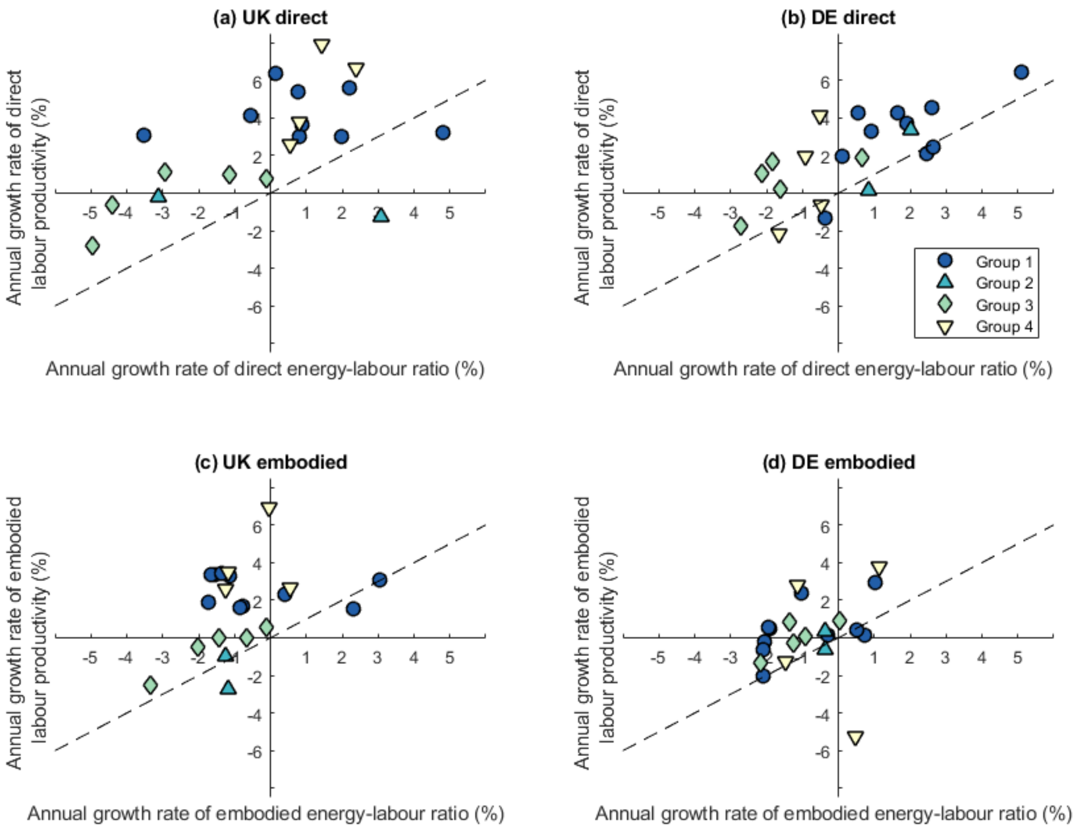

Figure 4-3: Relationship between the average growth rates in embodied labour productivity and the embodied energy-labour ratio between 1995 and 2011 for different economic sectors.

The growth rate of embodied labour productivity in Group 1 sectors is generally lower than the growth rate of direct labour productivity. Such lower rates are due to the fact that the supply chains of Group 1 demand sectors contain inputs from the direct sectors of other groups, which generally have lower rates of growth in the direct energy-labour ratio. For many sectors in Group 1 the embodied growth in the energy-labour ratio is reduced to negative values. As a result, from an embodied perspective, the results for the third dimension are still consistent between the two countries. But, compared to the direct perspective, several sectors show the embodied labour-productivity and embodied energy-labour ratio moving in opposite directions, combing positive growth rates of the former with negative growth rates of the latter (Figure 4-3). For the majority of sectors in which the two ratios move in the same direction, growth rates in embodied labour productivity are still higher than those in the embodied energy-labour ratio, indicating reductions in the embodied energy intensity.

4.3.2 Group 2: Energy-intensive and labour-intensive sectors

In our empirical classification Group 2 includes sectors with high energy intensity but low rates of labour productivity growth. We allocate the Mineral Products and Construction sectors to Group 2.

The Mineral Products sector is the only sector that mostly fits these characteristics. Its direct and embodied energy intensity exceeds 3 MJ/EUR in both countries (Tables 4-2 and 4-3). It also features a declining direct and embodied labour productivity in the UK and a low growth of 0.3% in embodied labour productivity in Germany. Only the direct labour productivity growth in Germany defies the pattern with a 3.3% annual rate of growth. However, the values for the third dimension show an inconsistent pattern, which makes it difficult to allocate it to one of the subgroups. The two ratios both grow in Germany from a direct perspective and both decline in the UK from an embodied perspective. But they move in opposite directions in Germany from an embodied perspective and in the UK from a direct perspective.

We also allocate the Construction sector to Group 2, because it shows low rates of direct and embodied labour productivity growth. The Construction sector does not strictly fit the characteristics of Group 2 because its energy intensity is low, with values below 3 MJ/EUR for direct and embodied energy intensity. We still consider it useful to allocate the sector to Group 2 because it shows large environmental impacts in other aspects, particularly a high material intensity (Giesekam et al., 2014). For the third dimension the results show that the direct labour productivity and direct energy-labour ratio and the embodied labour productivity and embodied energy-labour ratio are consistently moving in the same direction, placing the sector and demand sector in subgroup 2a.

4.3.3 Group 3: Energy-light and labour-intensive sectors

In our empirical classification Group 3 includes sectors that show low energy intensity and low rates of labour productivity growth. We allocate five sectors to this group, namely the sectors Hotels & Restaurants, Public Administration, Health, Education and Other Services (Tables 4-2 and 4-3). These are the same as the labour-intensive services identified in Hardt et al. (2020), Chapter 3 of my thesis, who only draw on embodied measures. Here we add results from a direct perspective which confirm the allocation of the five sectors to Group 3.

The direct energy intensities of all five Group 3 sectors range from 0.8 MJ/EUR to 2.1 MJ/EUR, while the embodied energy intensities range from 1.3 MJ/EUR to 2.2 MJ/EUR (Tables 4-2 and 4-3). Such values are all well below the 3 MJ/EUR threshold and considerably lower than the ones recorded for Group 1 sectors.

The five sectors also show growth rates in embodied labour productivity at or below 1% per year (Tables 4-2 and 4-3). From a direct perspective, the picture is less consistent. In the UK the Education sector lies slightly above the threshold with a growth rate of direct labour productivity at 1.1 % per year. In Germany, the growth rates in direct labour productivity in the Hotels & Restaurants and Public Administration sectors measure 1.9% and 1.7% respectively. Such rates are well above our threshold but still below the growth rates of direct labour productivity growth in Group 1 sectors. On balance we decided to allocate the sectors to Group 3, as they show consistently low rates of embodied labour productivity growth, whereas none of the sectors show high rates of direct labour productivity growth in both countries.

Again the results for the third dimension are very inconsistent between countries and between the embodied and direct perspective so that it is difficult to assign the sectors to sub-groups. The only sectors with consistent results are the Health sector, where the two ratios always move in the same (declining) direction and the Education sector, which combines a growing direct and embodied labour productivity with a growing direct and embodied energy-labour ratio in both countries.

For the other sectors and demand sectors the pattern is much less consistent. However, some important tendencies can be observed. Firstly, in those cases where the two ratios move in the opposite direction, there are no sectors that combine reductions in the direct or embodied labour productivity with increases in the direct or embodied energy-labour ratio (Figure 4-3). Such combination would be the most problematic from a post-growth perspective because it indicates strong growth in the direct or embodied energy intensity. Secondly, in those cases where the ratios move in the same direction, the growth rate of direct or embodied labour productivity is always higher than the growth rate of the direct or embodied energy-labour ratio, indicating reductions in energy intensity and only limited trade-offs (Figure 4-3).

4.3.4 Group 4: Energy-light and labour-light sectors

In our empirical classification, Group 4 contains sectors of low energy intensity but high rates of labour productivity growth. We allocate the sectors of Wholesale and Retail Trade, Finance and Insurance, IT and Communications and Business Services to this group.

For the first dimension, the direct energy intensities of Group 4 sectors range from 0.2 MJ/EUR to 2.1 MJ/EUR, while the embodied energy intensities range from 1 MJ/EUR to 2.3 MJ/EUR (Table 4-2 and 4-3). Such values are well below the threshold of 3 MJ/EUR and very similar to the ones in Group 3.

For the second dimension only the IT and Communications sector and the Wholesale and Retail Trade sector show consistently high rates of direct and embodied labour productivity growth in both countries, well exceeding our 1% threshold (Tables 4-2 and 4-3). For the Finance and Insurance and Business

Services sector, the growth rates of labour productivity show very different values in the two countries. In the UK direct and embodied labour productivity grew by more than 2.6% per year in both sectors (Table 4-2). In Germany direct and embodied labour productivity fell in both sectors (Table 4-3). Such divergent results can also be found in the literature where different studies come to different conclusions on direct labour productivity growth in the two sectors for different countries and time periods (Baumol et al., 1985; Maroto and Rubalcaba, 2008). We decided to allocate the two sectors to Group 4 because the high rates of labour productivity growth in the UK seem to indicate that the two sectors have a potential for labour productivity growth, even if it was not realised in Germany.

For the third dimension the relationship between the energy-labour ratio and labour productivity for Group 4 sectors varies between countries and between the direct and embodied perspective, so that it is difficult to assign the sectors and demand-sectors into the relevant sub-groups.

In the UK the picture is very similar to the one in Group 1. The direct energy-labour ratio is growing in combination with growing direct labour productivity in all Group 4 sectors (Figure 4-3a). But growth rates in the embodied energy-labour ratios are generally lower, so that two sectors feature a combination of a growing embodied labour productivity but falling embodied energy-labour ratio (Figure 4-3c). In those sectors where the ratios are moving in the same direction, the growth in direct or embodied labour productivity is higher than the growth in direct or embodied energy-labour ratio, indicating reductions in the direct or embodied energy intensity (Figure 4-3).

In Germany the combinations are even less consistent. From a direct perspective, the sectors split evenly into two sectors which combine growth in direct labour productivity with declines in the direct energy-labour ratio and two sectors which combine declines in direct labour productivity with declines in the direct energy-labour ratio (Figure 4-3b). From an embodied perspective the four German sectors in this group show all four possible combinations of growing or declining embodied energy-labour ratio and embodied labour productivity (Figure 4-3d).

4.3.5 Group comparison

After allocating economic sectors into the four groups, we can compare the structure of total GVA, final demand, direct and embodied energy use and employment covered in this study with regard to the four groups (Figure 4-4). These totals exclude the GVA, final demand, direct energy and labour and embodied energy and labour associated with the energy-producing sectors and the sector "Private Households with Employed Persons". The total direct and embodied energy also excludes the energy use for non-commercial purposes in the two countries, such as for residential use and private transport.

A key feature that is consistent across countries is the high share of Group 1 in direct and embodied energy use. The share of Group 1 in direct and embodied energy use is much higher than the group's share in GVA and final demand, which follows from the higher direct and embodied energy intensity of Group 1 sectors. The main difference between the two countries is a larger share for Group 1 sectors in Germany across all direct and embodied measures.

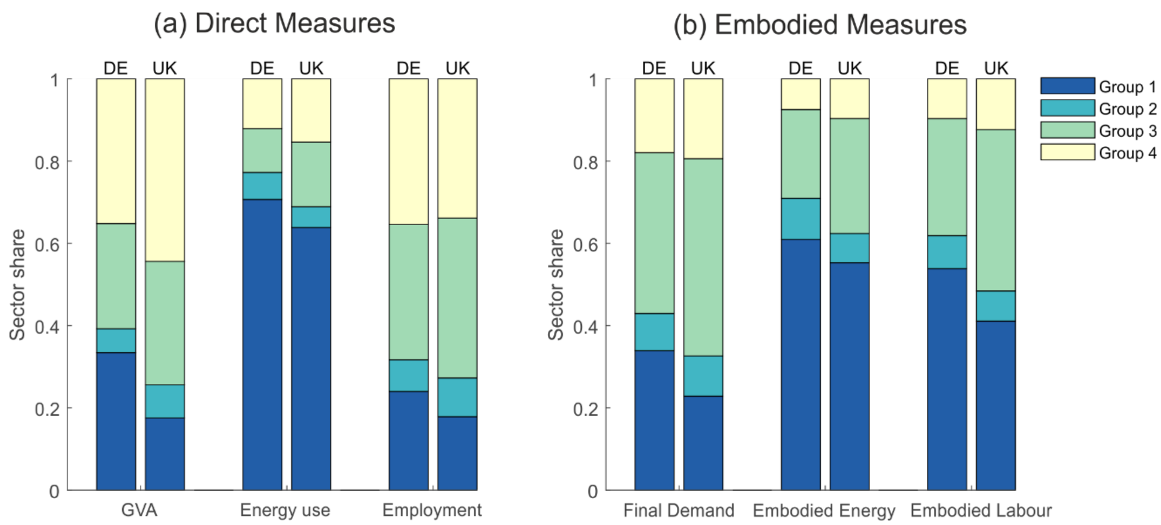

Figure 4-4: Sector shares in 2011 in (a) GVA, direct energy use and direct employment and (b) final demand, embodied energy and embodied labour. GVA and final demand are in current prices and exclude the energy-producing sectors, the sector "private households with employed persons" and imputed rents. Direct and embodied energy use also excludes energy use for private transport and residential purposes.

Two differences stand out between the direct and embodied perspectives. Firstly, the share of Group 1 sectors in direct employment is much smaller than the share of Group 1 sectors in embodied employment. The difference highlights that the demand for industrial and agricultural products in high-income countries is now strongly dependent on labour abroad (Simas et al., 2015; Sakai et al., 2017). Secondly, the share of Group 4 is of similar size as the share of Group 3 for the direct measures, but the share of Group 4 is much smaller for the embodied measures. The difference highlights that the output of Group 4 sectors is mostly used as intermediate input into other sectors rather than directly bought as final demand.

4.4 Sector goals and challenges

In Section 4.2 we identify theoretical structural change goals for different sector groups based on different combinations of characteristics in our three framework dimensions (Table 4-1). In Section 4.3 we allocate real sectors from the UK and Germany to the sector groups based on empirical data (Table 4-2 and Table 4-3). Combining the insights presented in Section 4.2 and Section 4.3, we can now provide a first discussion of what structural change for a post-growth economy might look like.

4.4.1 Group 1: Energy-intensive and labour-light sectors

We allocate to Group 1 the sectors producing agricultural goods, transport services, and manufactured goods (with the exception of mineral products).

An important structural change goal for the post-growth transition is to reduce the share of Group 1 sectors in output and final demand. Such a reduction is important to reduce aggregate energy intensity and energy use, given that Group 1 sectors are responsible for the majority of direct and embodied energy use covered in this study in both Germany and the UK (Figure 4-4). But there are limits to the magnitude of reductions in energy intensity and energy use that can be achieved from relative shifts in output and final demand alone (Hardt et al., 2020; Chapter 3 of my thesis).

A second important goal for the post-growth transition is therefore the reduction of direct and embodied energy intensity within Group 1 sectors (Table 4-1). But the magnitude of energy savings that can be achieved from intensity reductions also faces limits from thermodynamic laws and rebound effects (van den Bergh, 2011; Brockway et al., 2017). In light of such limitations, the transition to a post-growth economy might not only need relative, but also absolute, reductions in the output and final demand of Group 1 sectors.

The post-growth and climate change mitigation literature offers a range of policy proposals to achieve the goal of reducing the share of energy-intensive sectors in output and final demand. Some policies aim to reduce demand for energy-intensive goods and services by increasing their relative prices, for example through taxes or cap-and-trade schemes (Cosme et al., 2017; Hardt and O'Neill, 2017). It is assumed that an increase in the relative price of Group 1 sectors would entice consumers to shift their demand towards sectors with lower embodied energy intensity. Such a shift in final demand would also lead to a reduction in the share of the direct output of Group 1 sectors. In addition, higher relative prices might induce producers to reduce their need for high-energy inputs in the supply chain, for example by increasing resource efficiency (Barrett and Scott, 2012). Such changes in supply chains could lead to further reductions in the direct output share of Group 1 sectors, as well as reductions in the embodied energy-intensity of sectors across the board. Other proposals promote a shift to business models that sell the services derived from energy-intensive products rather than the products themselves, for example selling washing services rather washing machines (Jackson, 2017, p.142; Moran et al., 2018). Such a shift in business models would lead to a shift in final demand from Group 1 sectors to service sectors (e.g. machinery rental). At the same time the products would be used more efficiently, so less production would be needed, reducing the direct output of Group 1 sectors.

Equity considerations pose a key challenge to the implementation of any policies that aim to achieve reductions in the final demand and output of Group 1 sectors. Many Group 1 sectors provide essential goods which often make blanket policies, such as energy or carbon taxes, regressive (Owen and Barrett, 2020). To ensure that reductions in the final demand for Group 1 sectors are perceived as fair, a democratic discussion is needed to determine who should reduce demand, for what kind of products, and by how much. Baumol's cost disease might provide another challenge to the effectiveness of price-based policies aimed at reducing demand for Group 1 sectors. If the embodied labour productivity in Group 1 sectors continues to grow relative to other groups, the relative prices Group 1 sectors might fall, counteracting the effect of price-based policies (Baumol, 2012, pp.71–73).

Increasing labour productivity in Group 1 sectors constitutes another goal for the post-growth transition, where it is desirable (Table 4-1). Given the high direct and embodied energy intensity of Group 1 sectors we suggest that the goal to reduce energy intensity should receive priority over the goal to increase labour productivity (Table 4-1). But our empirical results suggest that trade-offs are limited. Group 1 sectors have often achieved reductions in energy intensity and growth in labour productivity at the same time, both from a direct and an embodied perspective. Still, direct labour productivity growth in Group 1 sectors might come at the cost of a higher direct energy-labour ratio. We do not consider such a cost to be problematic because the share of the labour force employed in Group 1 sectors will likely become quite small, given the combination of growing labour productivity and shrinking output.

Strategies to achieve the goals of reducing energy intensity and increasing labour productivity are more easily developed from a direct perspective, because direct sectors feature more homogenous production processes and because direct sectors fall under the jurisdiction of individual countries. The policy goals of reducing direct energy intensity and increasing direct labour productivity are not unique to the post-growth transition and are discussed extensively in the wider economics literature. We do not discuss the literature here but we want to point out an important challenge that is unique to the post-growth transition. In the post-growth transition labour productivity growth in Group 1 sectors is aimed to be achieved while simultaneously reducing output and final demand in the sectors. In the mainstream economics literature, labour productivity growth in a sector is considered to be a pre-condition or even a driver of output growth (Nordhaus, 2005). Kaldor's growth laws suggest that labour productivity growth in the manufacturing sectors is not only an important driver of output growth in the manufacturing sectors themselves but also in the wider economy (Thirlwall, 1983; Marconi et al., 2016). Achieving labour productivity growth in Group 1 sectors under the conditions of contracting output might therefore pose difficulties. Or, in reverse, the achievement of labour productivity growth in Group 1 sectors might jeopardise the goal of reducing demand and output in such sectors.

In addition, labour productivity growth might not be desired in all Group 1 sectors from a post-growth perspective. In some Group 1 sectors it might be desirable to adopt more labour-intensive production methods to create meaningful jobs, for example by moving to small-scale, artisanal methods (Nørgård, 2013; Mair et al., 2020). In Australia, the rise of artisan bakeries has already been recognised to lower labour productivity growth (Ferguson, 2015). The existence of different labour productivity goals in different Group 1 sectors would rise a special challenge for the post-growth economy, because policies will have to be tailored to achieve opposite outcomes in different parts of the economy.

While the transformation towards labour-intensive production methods in Group 1 sectors is a common theme in the post-growth literature, the literature does not offer a detailed discussion of its implications. No systematic analysis is provided that identifies in which sectors the adoption of more labour-intensive methods would be feasible and desirable. There might be many sectors, such as steel production, in which small-scale, labour-intensive production is not possible or desirable. In the few sectors for which the literature identifies labour-intensive production methods as desirable, there is little analysis of the consequences of a large-scale uptake of such methods. For example, post-growth economists propose small-scale, labour-intensive farming techniques, such as organic and permaculture approaches, on the ground that they are efficient in terms of energy and land use. But the literature offers hardly any scientific assessments of how a large-scale shift towards labour-intensive farming would impact yields, food availability and labour requirements (Infante Amate and González De Molina, 2013). Kostakis et al. (2018) suggest that an approach of “design global, manufacture local” could be useful for many aspects of a degrowth economy.

Their approach features local, decentralised production using simple technologies or 3D printing, based on designs developed in a global digital commons. It is not clear whether such an approach would be more or less labour-intensive or energy-intensive than current industrial production.

Once it is clearer in which sectors more labour-intensive production methods are desired for a post-growth economy, achieving the adoption of such methods will require the removal of important barriers. In our current market system, businesses are continuously under pressure to reduce production costs, a key driver of labour productivity growth (Jackson and Victor, 2011; Shaikh, 2016b). Except in niche areas, labour-intensive, small-scale manufacturing businesses cannot compete against the low prices of goods mass-produced in energy-intensive factories and by cheap labour abroad. Ecological tax reform that shifts tax burdens from labour to environmental impacts have been proposed to reduce the energy intensity relative to labour intensity (Daly, 2008). But in a system where competition is based on costs and prices, labour-intensive production methods will always struggle, even if price incentives are somewhat shifted in their favour. The adoption of labour-intensive methods in Group 1 sectors requires a system that puts greater value on quality, durability and fair working conditions. Johanisova et al. (2013) propose that an increase in the use of social enterprises, not-for-profit organisations and other “non-market capitals” can play an important part in creating such a system. In order for such organisations to flourish, however, consumers would also need to be willing to shift away from mass consumption to buy fewer, more expensive and high-quality products.

4.4.2 Group 2: Energy-intensive and labour-intensive sectors

In our empirical analysis we only allocate the Construction sector and the Mineral Products sector to Group 2 based on potential direct and embodied labour productivity growth.

As Group 2 sectors are labour-intensive, expansion of production and consumption in Group 2 sectors would contribute to the overarching objective to create meaningful employment by reducing aggregate labour productivity growth. Given the environmental emergencies that society is facing, however, we would suggest that the overarching objective to reduce energy intensity and energy demand should take priority. In that case, the most important goal for Group 2 sectors is to reduce their share in output and final demand, similar to Group 1 sectors (Table 4-1).

The sector goals for the remaining production in Group 2 sectors are not clear cut, because there are potential trade-offs between different goals. On the one hand, it might be desirable to reduce labour productivity in order to create meaningful jobs and reduce aggregate labour productivity growth. On the other hand, such reductions in labour productivity could increase the energy intensity of production. If labour productivity and the energy labour-ratio move in opposite directions, reductions in labour productivity increase the energy-labour ratio and energy intensity. Even in the case of increasing energy intensity, Kallis (2018, p.134) suggests that the adoption of more labour-intensive production methods could be worthwhile because lower aggregate labour productivity restricts the overall scale of production and environmental impact. Still, there might be better ways to provide meaningful employment and lower aggregate labour productivity without increasing the energy intensity in already energy-intensive sectors. If the labour productivity and the energy-labour ratio are moving in the same direction, the trade-offs are much smaller, especially if the latter falls faster than the former.

The Mineral Products sector shows very inconsistent results in our study, more research is therefore needed to identify the relevant sector goals and trade-offs with regard to energy intensity and labour productivity in specific contexts, both from a direct and an embodied perspective. In the Construction sector the direct and embodied labour productivity consistently move in the same, declining, direction as the direct and embodied energy-labour ratio. However, the balance between the two differs between the two countries. While the former falls faster than the latter in Germany, indicating increases in the direct and embodied energy intensity, the pattern is reversed in the UK, indicating reductions in direct and embodied energy intensity. The Construction sector is therefore a potential candidate for considering reductions in labour productivity to create employment, although it depends on the specific circumstances.

4.4.3 Group 3: Energy-light and labour-intensive sectors

In our empirical analysis we allocate five sectors to Group 3, namely Hotels & Restaurants, Public Administration, Health Care and Other Services. The five sectors are the same as the labour-intensive services already identified in Hardt et al. (2020), Chapter 3 of my thesis.

The sectors in Group 3 have a low direct and embodied energy intensity, so that employment-related goals can take priority over energy-related goals. The most important goal for Group 3 sectors is therefore to increase their share in direct and embodied employment (Table 4-1). Such shifts would serve to offset employment losses in other sectors, and to reduce the growth in aggregate direct and embodied labour productivity to prevent potential unemployment in the future.

Many of the Group 3 sectors are largely publicly provided, such as Health, Education and Public Administration. A straightforward policy option for expanding output, demand and employment in Group 3 sectors is therefore to increase public expenditure in such areas. However, such expansions in public expenditure could indirectly lead to expansions in demand and output of Group 1 sectors, through the increased income and expenditure of workers employed in Group 3 sectors (Horen Greenford et al., 2020). Increases in public expenditure therefore need to be combined with measures to reduce demand and output in Group 1 and Group 2, as discussed in Section 4.4.1. Increasing output, demand and employment in Group 3 sectors that are not publicly provided, such as Hotels & Restaurants and Other Services, is more difficult. Potential policy options to support such sectors would be the creation of affordable spaces for such businesses by local authorities, and public information campaigns to emphasise the positive value that such labour-intensive services can bring to the community in comparison to material consumption.

While Group 3 sectors and demand sectors have a low direct or embodied energy intensity relative to Group 1 and Group 2 sectors, Group 3 sectors still account for a non-negligible fraction of the direct and embodied energy use in the UK and Germany covered in this study (Figure 4-4). Any expansion in the employment, output and final demand share of Group 3 sectors therefore needs to be combined with reductions in energy intensity (Table 4-1).

In addition to shifting output and final demand towards Group 3 sectors, reducing the direct and embodied labour productivity in the group could help to create meaningful employment in the transition to a post-growth economy (Table 4-1). However, reducing labour productivity could clash with the goal to reduce energy intensity, if labour productivity moves in the opposite direction as the energy-labour ratio (Table 4-1). Our evidence does not find any examples for such a relationship in Group 3 sectors, neither from a direct nor from an embodied perspective. There are some sectors where the ratios for dimension 3 move in opposite directions, but in all of these cases they combine positive growth in the direct or embodied labour productivity with negative growth in the direct or embodied energy-labour ratio. More research is needed to identify whether the two ratios would continue to move in the same direction if the growth in direct or embodied labour productivity is reversed. Our results show that in those sectors and demand sectors where the two ratios move in the same direction, the growth in direct or embodied labour productivity is always bigger than the growth in the direct or embodied energy-labour ratio, so that there are only limited trade-offs with reductions in the direct or embodied energy intensity.

As a caveat it is worth noting that many of the Group 3 sectors constitute non-market services, for which economic output and final demand is difficult to define and measure (Eurostat, 2016, pp.34–38). It is therefore not completely clear how the pursuit of increased employment in Group 3 sectors will impact the sector shares in output and final demand. Increases in employment can manifest either as increases in output or as reductions in labour productivity, depending on how output is measured. For example, adding an additional teacher into each school class could lead to increased output if output is measured as teacher-hours, or to reduced labour productivity if output is measured as number of students taught. Overall it is likely that the share of Group 3 in output and final demand will increase if the employment share increases, at least in current prices.

We already discuss the challenges for achieving an expansion of Group 3 sectors in Hardt et al. (2020), Chapter 3 of my thesis, and will only provide a brief summary here. Firstly, Group 3 sectors feature low direct and embodied labour productivity growth and therefore face increasing relative costs compared to sectors with high direct and embodied labour productivity growth (Baumol, 1967; Baumol et al., 1985; Baumol, 2012). Such a cost disadvantage has already pushed several market services that are important for a post-growth economy, such as repair services, into the margins of our economy. Non-market services, such as health care and education, face continuous political discussions about the justification of increasing public expenditure. Secondly, new and existing jobs in Group 3 sectors need to be made high quality. At the moment, many jobs in these sectors are low-paid and associated with difficult working conditions, for example for nurses (Currie and Carr Hill, 2012; Druckman and Mair, 2019) or hospitality workers (Kotera et al., 2018). Lastly, any expansion of Group 3 sectors needs to consider the boundary between paid and unpaid work. Even though our framework focuses only on the formal economy, the development of strategies for the post-growth transition needs to take into account all work performed in society, whether it is paid or not (Sekulova et al., 2013). In the context of a post-growth economy it might be useful to assess where it makes sense that products and services are delivered by the formal economy, especially if other policies reduce the need for monetary income from work (D'Alisa and Cattaneo, 2013; Nørgård, 2013). Such a question is particularly relevant for Group 3 sectors, because many of them already straddle the boundary between paid and unpaid work, for example in the areas of health care, education or art.

4.4.4 Group 4: Energy-light and labour-light sectors

In our empirical analysis we allocate four sectors to Group 4. The four sectors are Wholesale and Retail Trade, Finance and Insurance, IT and Communications and Business Services. Here, we also discuss the Real Estate sector as part of Group 4, even though we do not present empirical results for it.

It is difficult to determine structural change goals for Group 4 sectors, because they cannot contribute strongly to any of the overarching objectives. Direct and embodied labour productivity growth is possible and likely, indicating that these sectors are not a potential source of meaningful employment. Direct and embodied energy intensity is low, so there is no strong rationale for reducing output and final demand from an environmental perspective either. While the direct and embodied energy intensity is low, Group 4 sectors still account for a non-negligible fraction of the direct and embodied energy use covered in this study in the UK and Germany (Figure 4-4). A post-growth perspective would therefore suggest that output and final demand in Group 4 sectors should be reduced, unless such output and final demand is necessary for meeting basic needs or increasing wellbeing. In effect the structural change goals for Group 4 sectors are therefore similar to those for Group 1: reduce final demand and output where possible, reduce the energy intensity of the remaining production and increase labour productivity (Table 4-1).

Another reason why it is difficult to define structural change goals for Group 4 sectors, is the fact that Group 4 direct sectors largely provide intermediate inputs into other sectors rather than final demand. As Figure 4-4 shows, the share of Group 4 sectors in value added is much larger than the share of Group 4 sectors in final demand. The group's share in final demand is also dominated by the Real Estate sector, which largely consists of real and imputed rent payments (Table 4-4). Defining and achieving structural change goals for Group 4 sectors therefore requires an analysis of how production is interconnected with other sector groups.

Table 4-4: Sector shares of labour-light services in final demand

	Demand share in 2011 (%)	
Sector	**UK**	**DE**
Share of Group 4 sectors in total final demand	25.7	20.4
Sector shares within Group 4		
Wholesale and Retail Trade	18.3	10.0
Finance and Insurance	14.4	16.4
Real Estate	47.4	43.7
IT and Communications	11.2	13.8
Business Services	8.8	16.2

More than other groups in our framework, Group 4 sectors highlight the limitations of the national accounts and of our framework that relies on national accounts data. For many sectors in Group 4 it is difficult to measure final demand and value added in constant prices. As the services delivered are intangible and heterogeneous, it is difficult to separate any price increases into quality improvements or inflation (Eurostat, 2016, p.112). Such difficulties are more serious for financial services and business services than for communication services and wholesale and retail trade (Schettkat and Yocarini, 2006; Inklaar et al., 2008). Similar difficulties apply for the non-market services in Group 3. But because the structural change goals for Group 3 sectors are clearly focused on employment, it is less of an issue. Group 4 sectors not only highlight measurement difficulties, but also problems with the underlying conventions in the national accounts, defining what counts as a productive activity and what does not. It is a social and political decision which forms of income count as a productive activities and contribute to GDP and which ones are classified as transfer payments distributing the production from other parts of the economy. For some Group 4 sectors it is not clear cut in how far they contribute to the creation of new value. For example, the income of the finance sectors has only recently been included as a productive activity contributing to GDP (Christophers, 2011). It is likely that a considerable part of the income obtained in the sectors of this group, especially in the Finance & Insurance, Real Estate and Communication & IT sectors can be considered as economic rent payments. Such rent payments have important implications for inequality in the post-growth transition (Stratford, 2020). A full review of this issue is beyond the scope of this paper, but it serves to highlight the difficulties of defining output, demand and value added in many sectors in this group.

The difficulties of defining structural change goals for Group 4 sectors do not mean that the sectors are not important for the post-growth transition. On the contrary, the sectors in this group are very much at the heart of many important challenges that our society is facing. Such challenges include unaffordable land and housing (Kenny, 2019), the impacts of financial speculation (Jackson, 2018), the gig economy facilitated by technological platforms (De Stefano, 2016) or the power of communication companies to exploit personal data and influence democratic processes (Hind, 2019). Group 4 sectors present a very diverse set of challenges that will require specific strategies for reform. Such strategies will undoubtedly affect the output, demand and employment of Group 4 sectors, but it might be less useful to define sector goals in such terms.

4.5 Conclusion

In order to avoid environmental catastrophe, the environmental impacts from economic production and consumption in high-income countries have to be reduced rapidly. Given the close coupling of GDP and environmental impacts, achieving the necessary reductions in high-income countries will likely lead to lower GDP growth, or even reductions in GDP. In high-income countries, we therefore need to create a post-growth economy that can simultaneously increase human well-being and deliver rapid reductions in environmental impacts, independent of whether GDP is growing or declining.

The transformation to a post-growth economy will require structural change in the sectoral composition of output, final demand and employment as well as strategies tailored to specific sectors. There will be winners and losers, sectors that will expand, and sectors that will contract. Politicians are often not explicit about the necessity of such structural change. They are especially not willing to identify sectors that will lose out in the transition to a sustainable economy. Sometimes not even in obvious cases, such as the oil and gas industry. As post-growth economists, we need to start defining the necessary structural change in order to stimulate a discussion about which sectors need to expand and which sectors need to contract. Providing such a definition is crucial for moving discussions beyond the abstract question of whether reductions in aggregate GDP are desirable and feasible.

Our analysis starts to systematically define the structural change necessary for the transition to a post-growth economy. The framework and evidence presented allows for a consistent vision of structural change to take shape. The production and consumption of energy-intensive goods will be reduced as much as possible. Small-scale, labour-intensive production should be encouraged where feasible, while industrial, efficiency-focused production will only be pursued where it makes sense from a social and environmental perspective. Potential losses of employment will be offset by increasing employment in labour-intensive services with high social value, while making sure that the new and existing jobs in these sectors are of high quality. Finally, the remaining services will have to be scrutinised in how far they can contribute real value to a post-growth economy.

More research is needed to fully utilise the framework and develop sectoral strategies at a more detailed level. Especially information on the potential and desirability of labour productivity growth in different sectors, and its implications for energy use, is currently lacking in the post-growth literature. More information on such sector characteristics is needed to inform discussions on important normative questions: What production is necessary and desirable? Where could production and demand be reduced? Where exactly would reductions in labour productivity be desirable and where is further pursuit of labour productivity sensible? These questions tie into current debates about the future of automation. Research from a post-growth perspective can offer something to such debates by investigating the desirability of automation and by putting automation into the context of environmental challenges.

Even if we cannot determine all sector characteristics and structural change goals with certainty yet, the preliminary outline we present already highlights some important challenges for achieving the necessary structural change. The production, employment and consumption of different sectors is not distributed equally across countries and across income groups. Strategies for achieving structural change need to be just and equitable. Some of the sector goals we identify also go against the grain of our current economic system. Business is currently dominated by pressures to reduce costs and grow markets and output. Many of our sector goals would require resistance to such pressures. Achieving the goals might entail increasing costs, reductions in output and the shrinking of markets and supply chains. Can markets be reformed so that they support achieving such objectives? If yes, how? Do we need to find alternative ways of providing some goods and services? The answer to the last question is almost certainly yes. The post-growth literature has already started to develop alternative approaches but more needs to be done. For example Raworth (2017) distinguishes between four domains of provisioning, the market, government, commons and the household. Such a perspective could be linked with our framework to determine which sectors might be best suited to which of the four domains.

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Chapter 5
Discussion and conclusion

I started my thesis by posing the research question: How can structural change contribute to the creation of a post-growth economy? I can decompose the question into three components. Firstly, we, as societies in high-income countries, need to know where we want to go, what kind of structural change would help us achieve the overarching goals of the post-growth economy. Secondly, once we know where we want to go, we need to assess whether current structural change is taking us in the right direction. Thirdly, we need to know what is driving structural change in order to develop effective strategies for steering it in the desired direction.

The articles presented in Chapters 2-4 provide important new insights for all three components because they address my three research objectives:

A. To provide evidence on the role of international trade in shaping structural change and energy use in high-income countries.
B. To provide empirical evidence on sectoral characteristics for the identification of labour-intensive services, focusing on an embodied perspective.
C. To develop a systematic approach for determining desirable structural change and sector-specific strategies for a post-growth economy.

In the following I combine the insights from the three articles with the results of the wider literature to outline an answer to the research question, taking each of the three components in turn.

5.1 Where do we want to go?

The transition to a post-growth economy will require structural change in the composition of output, final demand and employment. Such structural change entails the need for different trajectories and strategies for different sectors, for example we might want to reduce output in the cement sector but increase it in the health care sector. While the need for structural change is commonly acknowledged in the post-growth literature, the analysis of structural change has remained at the beginning. There are some references to sectors that are desirable or not, but the literature does not offer a systematic analysis. The need to shift to labour-intensive services, proposed by Jackson and co-authors (Jackson and Victor, 2011; Jackson, 2015; Jackson, 2017, p.148), has received the most comprehensive treatment in the literature. Still, there is little empirical analysis identifying labour-intensive services, both from a direct and embodied perspective, and little discussion of how shifts to such services can be achieved. In my research I have built on the beginnings provided in the literature to provide a more systematic vision of the structural change required for a post-growth economy.

In Chapter 1 I identify two overarching structural change goals for the post-growth transition, drawing on the references to desired sectors and the discussion of labour-intensive services. The first goal is the reduction of environmental impacts by shifting output and demand to less environmentally-damaging sectors. For the purpose of my research I focus on final energy use, because we need to reduce both direct and embodied energy demand to achieve rapid reductions in emissions. The second goal is the creation of meaningful employment in sectors of high social value by shifting output, demand and employment towards labour-intensive sectors. A shift towards such labour-intensive sectors would not only directly create jobs, it would also slow the rate of aggregate labour productivity growth in the economy and prevent unemployment in a non-growing economy.

Labour-intensive services play a crucial role for the transition to a post-growth economy because expanding the share of such sectors in output, demand and employment contributes to both overarching structural change goals. In Chapter 3 I provide an empirical analysis to identify labour-intensive service demand sectors in the UK and Germany. I define labour-intensive services as those demand sectors with a low embodied energy intensity and low rates of growth in embodied labour productivity.

Based on my analysis, five demand sectors show the two characteristics of labour-intensive services, namely the demand sectors Hotels & Restaurants, Public

Administration, Health, Education and Other Services. The group of five demand sectors captures most of the activities that are mentioned as desirable in the post-growth literature, such as education, care or culture (Dietz and O'Neill, 2013, p.137; Jackson, 2017, p.220) or "relational" goods and services (Kallis, 2017, p.8). My research confirms the intuitive notion in the post-growth literature that a shift in final demand towards the five demand sectors would reduce aggregate embodied energy intensity and aggregate embodied labour productivity growth. But, at the same time, the reductions in embodied energy that can be achieved solely from shifts in final demand have limits. My modelling in Chapter 3 suggests that shifting 50% of demand in energy-intensive demand sectors to energy-light demand sectors would reduce the total embodied energy covered in the study, which excludes energy use for residential and private transportation purposes, by only 22% in both Germany and the UK.

Chapter 4 goes beyond the focus on labour-intensive services to provide a systematic analysis of structural change goals for the economy as a whole. I introduce a novel framework that translates the two overarching structural change goals into sector-specific goals. I identify sector-specific goals regarding the sector's share in GVA, final demand and employment as well as regarding sectoral energy intensity and labour productivity. My analysis provides a first comprehensive vision of structural change for a post-growth economy founded on empirical data. The vision is built around four sector groups with similar characteristics and similar structural change goals.

Group 1 includes energy-intensive sectors with high potential for direct and embodied labour productivity growth. My analysis suggests that the group includes the manufacturing sectors as the well as the transport and agricultural sectors (Table 5-1). The high energy intensity of Group 1 sectors demands that we reduce the sectors' shares in final demand and GVA. In the remaining production we should strive to increase labour productivity where this can eliminate undesirable jobs. My results in Chapter 4 show that such increases in direct and embodied labour productivity are compatible with reductions in direct and embodied energy intensity. Increases in direct labour productivity might increase the direct energy-labour ratio, but that might be acceptable, given a shrinking

Table 5-1: Sector groups identified in Chapter 4

Sectors	NACE Codes (Rev. 1.1)
Group 1	
Agriculture, Forestry, Fishing	01, 02, 05
Food, Beverages and Tobacco	15, 16
Textiles, Clothes, Leather	17, 18, 19
Paper, Printing, Publishing	21, 22
Chemicals	24
Metals and Fabricated Metal Products	27, 28
Machinery, Electrical Equipment, Computers	29, 30, 31, 32, 33
Transport Equipment	34, 35
Other Manufacturing	20, 25, 36, 37
Transport	60, 61, 62, 63
Group 2	
Mineral Products	13, 14, 26
Construction	45
Group 3	
Hotels and Restaurants	55
Public Administration	75
Health	85
Education	80
Other Services	41, 90, 91, 92, 93
Group 4	
Wholesale and Retail Trade	50, 51, 52
Finance and Insurance	65, 66, 67
Real Estate Activities	70
IT and Communication	64, 72
Business Services	71, 73, 74
Other (not analysed)	
Fuel Producers	10, 11, 23
Production and Distribution of Electricity, Gas, Steam, Hot Water	40
Private Households with Employed Persons	95

labour force. However, the post-growth literature suggests that there might be energy-intensive sectors in Group 1 where it is desirable to adopt more labour-intensive production methods in order to create meaningful work, even if further increases in labour productivity would be possible (Nørgård, 2013; Mair et al., 2020). I do not specifically identify such sectors in my thesis. But in such cases the reductions in labour productivity in order to create more meaningful work might have to be balanced against energy concerns, if such reductions lead to increases in the energy-labour ratio or energy intensity.

Group 2 includes energy-intensive sectors with a low potential for labour productivity growth. The group appears to be a relatively small part of the economy. I identify only the Mineral Products sector and the Construction sector, and the latter could potentially also be allocated to Group 3 (Table 5-1). Given the high energy intensity of Group 2 sectors, the highest priority should be the reduction of the sectors' share in final demand and GVA. Whether, where and how labour productivity should be reduced in the remaining production is an open question. The answer will depend on the context of different sectors, because the creation of meaningful jobs needs to be balanced with the potential energy requirements of more labour-intensive production methods.

Group 3 includes energy-light sectors with a low potential for labour productivity growth. The group includes the five labour-intensive service demand sectors identified in Chapter 3 and their corresponding direct sectors (Table 5-1). In order to create meaningful employment and reduce aggregate labour productivity growth we should increase the employment share of Group 3. Increases in the group's share in employment will likely be associated with increases in the group's share of final demand and GVA. It could also be associated with reductions in direct and embodied labour productivity depending on how final demand and GVA are measured. My analysis suggests that there are few trade-offs between the goal to increase employment and the goal to reduce energy intensity. Sectors in Group 3 have shown reductions in the direct and embodied energy intensity and the direct and embodied energy-labour ratio independent of whether GVA, final demand or labour productivity have been growing or declining.

Finally, Group 4 includes energy-light sectors with high potential for labour productivity growth. The group is the most difficult for identifying structural change goals, because the sectors cannot contribute strongly to any of the three overarching structural change goals. The group is also very heterogeneous, including sectors such as Wholesale and Retail Trade, IT and Communication, Finance and Insurance, as well as a wide range of Business Services, such as marketing, research and legal services. Identifying structural change goals for the groups' sectors therefore requires a more specific assessment of how the sectors can add value to a post-growth economy.

5.2 Are we moving in the right direction?

Based on the vision of structural change, we can assess how far historical structural change has taken us in the direction of a post-growth economy. My research suggests that structural change over the past decades has been partially in the right direction, but not consistently so. Where desired structural change has occurred, its magnitude has been small.

5.2.1 Energy use

Reducing the share of energy-intensive sectors in both GVA and final demand is a key overarching structural change goal I identify in Chapter 4. Such a structural change would reduce the energy intensity of the economy and, in the absence of further growth, also direct and embodied energy use.

As I have discussed in Section 1.3.3, the literature suggests that structural change from industry to service sectors has not been a strong driver of direct energy intensity reductions when looking across high-income countries and time periods (Henriques and Kander, 2010; Mulder and de Groot, 2013; Marrero and Ramos-Real, 2013; Fernández González et al., 2013). While structural change in GVA has reduced the direct energy intensity of many high-income countries, it has also increased direct energy intensity in some. In those countries where structural change has contributed to direct energy intensity reductions, the contributions were small. For example Henriques and Kander (2010) estimate that structural change did not reduce the direct energy intensity by more than 9% between 1971 and 2005 in any of the high-income countries they studied.

The decomposition analysis in Chapter 2 adds some important insights to this literature by presenting a detailed analysis of how structural change has impacted direct final energy use in the UK between 1997 and 2013. The results confirm the patterns observed in the literature. Structural change did make an important contribution to reducing direct energy use in the in the UK. But the reductions in direct energy use from structural change were much smaller than the reductions from direct energy intensity improvements within sectors. I find that the energy savings from structural change are largely associated with structural change within the industry sectors, rather than with structural change in output from industry to service sectors. The importance of within-industry structural change might explain why my analysis suggests a larger contribution from structural change than many studies in the literature, which focus on structural change from industry to services only.

In the framework presented in Chapter 4, energy-intensive sectors are allocated to sector Groups 1 and 2. The data produced in Chapter 3 and Chapter 4 allow for an assessment of whether the UK and Germany have achieved any structural change in GVA and final demand away from the sectors in Group 1 and Group 2 between 1995 and 2011.

Germany does not show any noteworthy structural change in GVA and final demand away from the sectors in Group 1 and Group 2 (Figure 5-1). As a result the share of the two groups in direct energy use is increasing and the share in embodied energy use is stable. The UK shows a somewhat stronger reduction in the share of Group 1 and 2 in GVA (Figure 5-2). The reduction in Group 1 and 2 shares reduces direct energy use in absolute terms. But it does not translate into a falling share of Group 1 and Group 2 sectors in direct energy use, because the direct energy intensity in Group 3 and 4 is falling faster than in Group 1 and Group 2 sectors. The shares of Group 1 and Group 2 in final demand and embodied energy use are stable until the financial crisis, after which both fall.

My results mirror the inconsistent results in the literature, which largely adopts a direct perspective. Structural change in GVA away from energy-intensive sectors has reduced direct energy intensity and direct energy use in the UK, but not in Germany. From an embodied perspective, the move in final demand away from energy-intensive sectors has been negligible in both countries, except during the financial crisis in the UK. If we want to achieve meaningful reductions in energy intensity through structural change, we need to achieve faster structural change in both GVA and final demand away from Group 1 and Group 2 sectors.

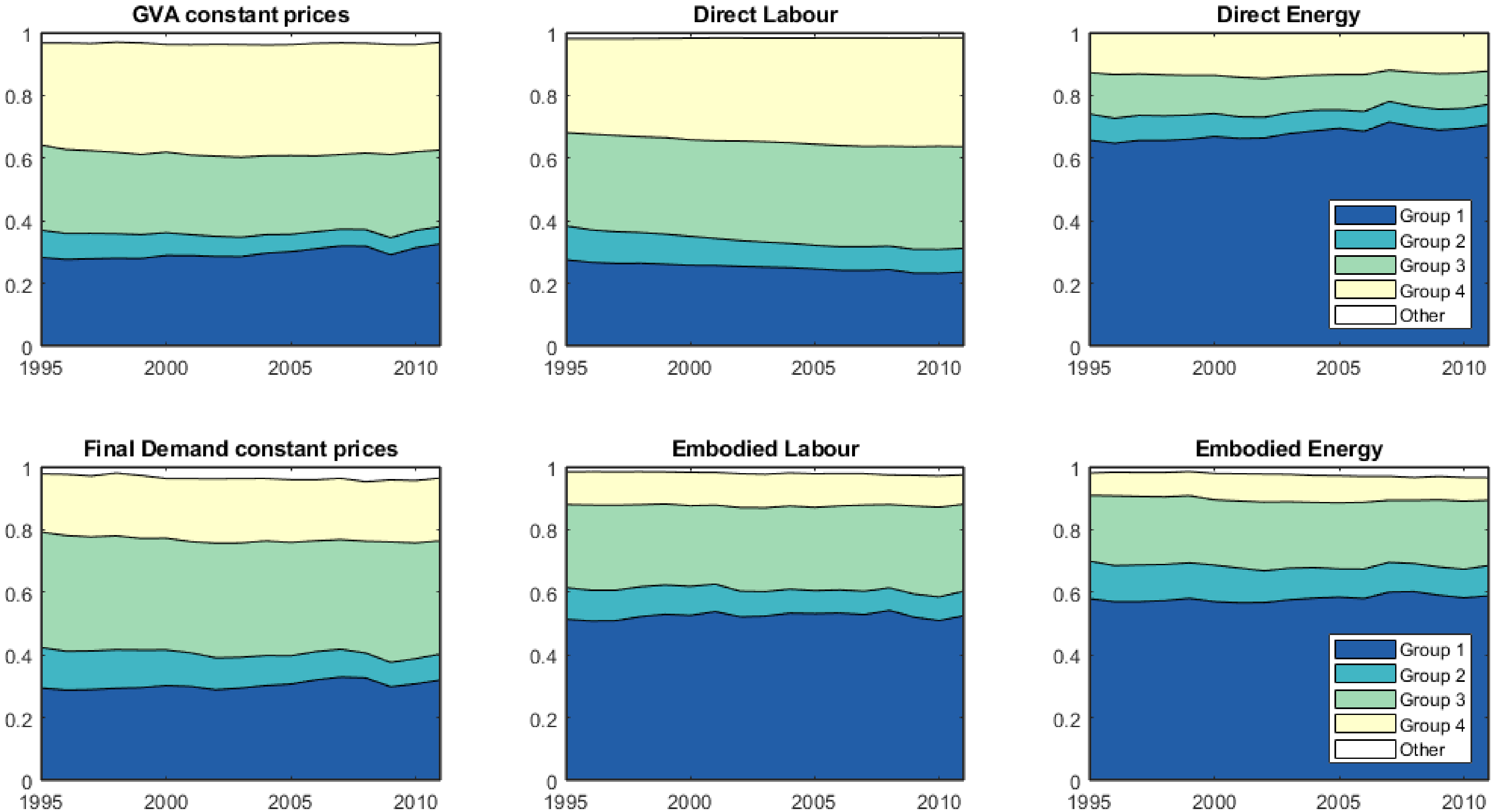

Figure 5-1: Structural Change in Germany between 1995 and 2011. Total direct and embodied energy use excludes energy use for residential purposes and private transport.

Figure 5-2: Structural Change in the UK between 1995 and 2011. Total direct and embodied energy use excludes energy use for residential purposes and private transport.

5.2.2 Employment

The second overarching structural change goal for a post-growth economy is to create meaningful jobs, by shifting employment towards labour-intensive sectors with low rates of labour productivity growth. In Chapter 3 I identify five labour-intensive service sectors. The five sectors constitute Group 3 in the framework presented in Chapter 4. The literature on structural change identifies the stylised fact that the share of service sectors in direct employment has been rising consistently with rising income over the past century in high-income countries (Fuchs, 1980; Kongsamut et al., 1997; Schettkat and Yocarini, 2006). But the rising share of direct service sector employment includes all service sectors and not only labour-intensive ones. It is therefore not clear in how far the rising share of service sector employment is in line with the goals of the post-growth economy.

The literature on Baumol's cost disease provides more useful insights because it is specifically concerned with the employment share of labour-intensive sectors. The literature confirms Baumol's hypothesis that the employment share of labour-intensive sectors grows with respect to labour-light sectors, which can slow down aggregate labour productivity growth in the economy (Nordhaus, 2006; Hartwig, 2011; Fernandez and Palazuelos, 2012). The strength of this effect can be mediated by other factors. For example, increases in exports of labour-light sectors can counteract reductions in their employment share and mitigate the reductions in aggregate labour productivity growth (Oh and Kim, 2015).

I can use the data produced in Chapter 3 and Chapter 4 to assess whether structural change in the UK and Germany has been in line with the goals of a post-growth economy. In both countries, the share of Group 3 sectors in direct employment increased between 1995 and 2011, although the increase in Germany is small (Figure 5-1 and Figure 5-2). Despite the increased employment share, the group's share in real GVA is falling or stagnating, reflecting the relatively lower rate of direct labour productivity growth. The pattern for embodied labour shares is less consistent. In Germany the share of Group 3 sectors in embodied labour is stagnant, whereas it shows a U-shaped development in the UK.

From a direct perspective, structural change in employment has therefore been in line with the predictions of Baumol's cost disease and the post-growth goal of increasing the employment share of labour-intensive services. But from an embodied perspective, the picture is less consistent. The discrepancy raises questions about how far changes in the employment structure within the UK and Germany have been driven by the offshoring of jobs in Group 1 and Group 2 sectors (see Section 5.3.2).

5.3 What are the drivers of structural change and how could we change them?

Historical trends in structural change in high-income countries, specifically the UK and Germany, have partially been in line with the post-growth goals identified in Chapter 4. I examine whether the drivers that have produced desirable structural change in the past are in line with post-growth principles and can be scaled up for the transition to a post-growth economy. As I discuss in Section 1.3.2, there are three important drivers of structural change, namely differential rates of labour productivity growth, international trade and changes in the composition of final demand.

I will argue that we cannot rely on historical drivers of structural change to move towards a post-growth economy. The drivers are not in line with post-growth principles, because they are tightly linked to growth in labour productivity, income and offshoring. In the following I discuss how the different drivers have shaped structural change and contemplate how they could be changed to achieve the structural change desired for a post-growth economy.

5.3.1 Differential labour productivity growth

5.3.1.1 Historical drivers

A key driver of structural change is different rates of labour productivity growth in different sectors. According to Baumol's Cost disease, those sectors with low labour productivity growth continuously increase their share in employment which can slow down aggregate GDP growth (Baumol, 1967; Baumol et al., 1985; Baumol, 2012). Both outcomes seem welcome for the transition to a post-growth economy. But despite such outcomes, the structural change produced by differential rates of labour productivity growth will be of limited use.

Firstly, differential rates of labour productivity growth do not improve the environmental performance of the economy. They increase the relative prices and employment share of labour-intensive sectors, but have only a limited effect on the composition of real output and final demand. As real output is more closely aligned with environmental impacts than employment, the effect on environmental impacts is limited. Such an effect is illustrated by the small impact of structural change on energy use in my results and the wider literature.

Secondly, in order to have differential growth rates in labour productivity, some sectors need to have high rates of labour productivity growth. Without high rates of labour productivity growth in the labour-light sectors, there would be no cost disease. But the high labour productivity growth in the labour-light sectors is also a key driver of economic growth in aggregate. Baumol's cost disease should therefore be considered as a side effect of economic growth rather than an obstacle to it. Baumol (2012, pp.50–51) himself describes the future relationship between labour-intensive and labour-light goods as the following: "In that future world, we can have much more of *all* of these goods. (…) The only thing that will change, in terms of the cost to us, is how we will have to divide our money between these items" (emphasis original). Such a future world with more of all goods would be environmentally disastrous.

The high rates of labour productivity growth in the labour-light sectors are not only a key driver of aggregate economic growth, they have also come at an environmental cost. The results I present in Chapter 4 show that such labour productivity growth in the labour-light sectors has been associated with increases in the energy-labour ratio, at least from a direct perspective. My results support evidence from the literature that direct labour productivity growth in the manufacturing and transport sectors is reliant on harnessing increasing amounts of energy per worker (Mulder and de Groot, 2004; Witt and Gross, 2019). In Chapter 4 I suggest that such increases in the energy-labour ratio in labour-light sectors might be acceptable, but only if it is combined with falling production and consumption in those sectors. If labour productivity growth in the labour-light sectors stimulates economic growth while simultaneously increasing the energy-labour ratio, it would seriously jeopardise climate change mitigation (Semieniuk, 2016).

Lastly, the relative price changes that result from differential rates in labour productivity growth might induce changes in the composition of demand that are contrary to the goals of the post-growth economy. Baumol (2012, pp.70–71) suggests that those sectors with high labour productivity growth are also more environmentally harmful. As the products of such sectors are becoming relatively cheaper, he is worried that the falling relative prices might stimulate demand for such sectors and increase environmental impacts. In Chapter 3 I present some novel empirical evidence to test Baumol's suggestion. For the UK I find some evidence that sectors with a higher embodied energy-labour ratio are becoming relatively cheaper. Although there exist both energy-intensive sectors with high price inflation, such as the Mineral Products sectors, as well as energy-light sectors with strongly falling prices, such as the IT & Communications sector. For Germany, no relationship between the embodied energy-labour ratio and price inflation is apparent. I can therefore not find unambiguous evidence for Baumol's suggestion that labour-light sectors are more environmentally harmful. Gazheli et al. (2016) reach a similar conclusion when studying the relationship between carbon intensity and labour productivity across sectors.

The flipside of falling relative prices in labour-light sectors are increasing relative prices in labour-intensive sectors. Such increasing relative prices are potentially problematic from a post-growth perspective, if they reduce the demand for the labour-intensive services in Group 3. My analysis in Chapter 3 provides some indication that labour-intensive service sectors face increasing relative prices compared to other sectors. Such relative price changes are only problematic if they actually influence the composition of final demand in real terms. I discuss the evidence for such impacts in Section 5.3.3.

5.3.1.2 Implications for the post-growth transition

Structural change produced by different rates of labour productivity growth has been closely intertwined with growth in GDP. Such structural change is therefore not helpful for the post-growth transition. But, as I have argued in Chapter 4, the post-growth vision also features different labour productivity growth rates in different sectors, albeit for different reasons. In the current economic system, labour productivity growth is driven by competition pressures on businesses and other organisations to reduce costs and increase profits (Jackson and Victor, 2011; Shaikh, 2016). The different rates of labour productivity growth arise from the fact that it is much easier to increase labour productivity in some sectors than in others.

In contrast, the goal of the post-growth economy is to manage labour productivity in different sectors to reduce unfulfilling jobs, create meaningful ones and ensure the wellbeing of workers. Achieving such goals will require breaking with current sectoral patterns of labour productivity growth and presents different challenges in different sectors. The sector group classification I develop in Chapter 4 is useful for characterising such challenges.

In Group 1 and Group 4 sectors continued labour productivity growth is possible and, in the past, labour productivity growth has successfully been achieved in many of the sectors in the group. In many of those sectors continued labour productivity growth will be desirable to eliminate unwanted jobs. But such labour productivity growth in the past has happened in an environment of growing output. Growing labour productivity might even have been a key driver of output growth in such sectors (Nordhaus, 2005; Tregenna, 2009). The challenge for the post-growth transition will be to continue labour productivity growth in those sectors of Group 1 and Group 4 where it is desirable, while simultaneously reducing production and demand. Examples of such sectors are the industrial production of steel, chemicals or machines that will still be needed in a post-growth economy, but also necessary office-based services that offer unfulfilling jobs.

While labour productivity growth is possible in Group 1 and Group 4 sectors, it might not be desirable. Post-growth economists suggest that there might be sectors in which more labour-intensive, artisan and local production are desirable. It has been argued that the adoption of such methods allows for greater control of the production process, greater work satisfaction and a higher quality products (Nørgård, 2013; Mair et al., 2020). Examples could be clothes and furniture made and repaired by local craftsmen or high quality organic food produced on local farms. The challenge for those sectors is to foster the uptake of labour-intensive production methods and ensure good working conditions against the cost pressures currently faced by many organisations.

Group 2 and Group 3 include sectors in which labour productivity growth is not possible, at least not at high rates. Such low rates of labour productivity growth pose a particular challenge for the labour-intensive services in Group 3, for which an expansion in employment, output and demand is desired. As long as labour productivity is growing in Group 1 and Group 4 sectors, Baumol's cost disease suggests that Group 3 sectors will continue to become relatively more expensive. The challenge for Group 3 sectors is therefore to expand demand and employment despite such relative price changes (see Section 5.3.3).

While the need for such a differentiated treatment of labour productivity is often implied in the post-growth literature, there is no in-depth discussion in which sectors further labour productivity growth is possible and desired. The framework I develop in Chapter 4 makes a start in defining labour productivity goals in different sectors in a systematic manner. But there remain many important questions.

We are so far lacking a detailed assessment of which sectors we want to increase, maintain or reduce labour productivity. In my analysis in Chapter 3 and Chapter 4 I investigate the potential for labour productivity growth but not its desirability. More research is needed to increase our understanding of where labour productivity growth might be desirable from the perspective of workers, identifying jobs we want to eliminate because they are not meaningful. Similarly, we need to identify those areas of production which could benefit from the adoption of more labour-intensive production methods to provide a better work experience.

But, for the post-growth transition, the desirability of labour productivity growth is not only determined by the quality of the work. The system-wide environmental impacts also need to be taken into account. In the context of my thesis I have raised in particular the question about implications for energy use.

What would be the impacts if the desired changes to labour productivity would be implemented at scale? Would they be consistent with the overarching necessity to reduce energy use? Would we have enough workers to produce all our essential needs if we move to more labour-intensive production? Any attempts at answering such questions also have to consider the emerging technologies that will be involved in future labour productivity growth, such as digital and robotic technologies (Frey and Osborne, 2017; Spencer, 2018). Will such technologies replace jobs that are desired or undesired in a post-growth economy and what are the energy and wider environmental implications of such replacements?

Once we have a better idea of how we want to transform production processes in different sectors, whether that means increasing or reducing labour productivity, the next big challenge is to devise ways to achieve such transformations. The post-growth transition will be characterised by strong restrictions on energy and resource use, for example through high taxes or rationing. Such restrictions might incentivise some businesses to focus more strongly on increasing energy and resource efficiency and less strongly on reducing labour costs. Proposals for ecological tax reform combine tax rises on energy and resources with tax reductions on labour income to explicitly foster such a change in focus (Daly, 2008; Cosme et al., 2017; Kallis, 2018, p.128).

While such measures might be helpful to reduce energy and resource use, on their own they are unlikely to achieve the differentiated changes in labour productivity desired for a post-growth economy. Those sectors with high energy intensity, which have the strongest incentives to switch to more labour-intensive production under ecological tax reforms, are not necessarily the same as the sectors in which we want to increase labour-intensive production. For example there might some energy-intensive sectors in which it is desirable to increase labour productivity. Even where ecological tax reforms achieve the uptake of more labour-intensive methods, they are not likely to create the high-quality, artisan jobs envisaged in the post-growth literature. Ecological tax reforms achieve relative shifts in the costs faced by businesses but they do not address the systemic pressures to reduce labour costs. In such an environment, labour-intensive production methods are more likely to take the shape of sweatshops rather than artisan craftsmen.

The challenge of the post-growth transition is to create a system that simultaneously fosters labour productivity growth where it is desirable and more labour-intensive production methods where they can create good jobs. The key to achieving such outcomes is a system that, within environmental constraints, puts the well-being of workers first. Organisations need to be put in a position where they can and want to make the quality of employment a key priority, whether that means increasing or decreasing labour productivity. Labour-intensive production methods of the kind envisioned in the post-growth literature are currently only viable in niche markets, often serving affluent consumers, and unable to compete with goods mass-produced in factories and by cheap labour abroad. In the public sector, organisations should not be pressured into increasing “efficiency” if this comes at the cost of deteriorating working condition.

How can we create such a system? The post-growth literature suggests that a proliferation of alternative business models is a key ingredient. Such alternative business models feature two important characteristics. They are not-for-profit and they have greater democratic control by their employees, for example through employee ownership (Johanisova and Wolf, 2012; Johanisova et al., 2013; Hinton, 2020). Such businesses can prioritise environmental and social objectives over profits. They would be more able to put in place measures to reduce labour productivity if it improves working conditions, because they can keep prices low by reducing profits and dividend payments to shareholders (Trebeck and Williams, 2019, p.127). But alternative business models alone will not be enough to achieve the differentiated labour productivity goals for a post-growth economy, especially the vision of more labour-intensive, artisan production. In order to thrive, such business models will still require wider changes in the economy, including support from government regulation and a reformed financial system. The proliferation of alternative business models will also need to be accompanied by a shift in demand towards fewer, more expensive, and higher quality products. Such a shift is difficult to imagine in the current market environment of price-based competition and consumption.

5.3.2 International trade

5.3.2.1 Historical drivers

My research shows that structural change within high-income countries is closely linked to global trade. International trade has not been the most important driver of structural change in output, employment and energy use, but it has still played an important role (Saeger, 1997; Alderson, 1999; Rowthorn and Coutts, 2004; Kollmeyer, 2009).

While the literature provides indirect evidence on the role of offshoring in reducing energy use in high-income countries, there is little analysis that explicitly links the two. In Chapter 2 I use a novel decomposition analysis that explicitly links the structural change and related energy savings within the UK to international trade. I find that most of the energy savings from structural change within the UK are the result of offshoring rather than of changes in the composition of demand or international trade structures. As a result of such offshoring, the UK, Germany and most other high-income countries are now net-importers of energy use, with their energy footprints being larger than their domestic energy use (Simas et al., 2015; Sakai et al., 2017; Owen et al., 2017).

The literature on deindustrialisation describes a similar effect for structural change in employment over the past decades. Production of labour-intensive industry sectors moved from high-income to low-income countries leading to losses in employment in the former (Rowthorn and Coutts, 2004). Similar to the case of energy use, the demand in most high-income countries is now strongly dependent on labour performed abroad, especially in industrial sectors (Simas et al., 2015; Sakai et al., 2017). The results of my analysis support the results in the literature. In Chapter 3 I show that the fraction of the embodied labour employed domestically is less than 35% for all Group 1 sectors, whether in the UK or Germany. In many of the sectors, the fraction is considerably lower, reaching below 10% in some cases (Tables A2 and A3, Appendix B). Similarly, the reliance on labour abroad is demonstrated by the large discrepancy between the employment share of Group 1 sectors in direct employment and in embodied employment (Figure 5-1 and Figure 5-2).

When only considering a direct perspective, the structural change resulting from international trade supports some of the post-growth goals. It has contributed to reductions in energy use, at least to a limited extent. In all likelihood it has also contributed to an increasing share of labour-intensive services in direct employment. It has certainly contributed to an increasing employment share of the service sector in general. But the goals of the post-growth economy are fundamentally global in nature. Structural change that only shifts energy use between countries does not contribute to efforts of moving environmental impacts back within planetary boundaries. Such shifts could be environmentally beneficial in some circumstances, for example if energy-intensive production is shifted to countries with better access to renewable energy sources. But the offshoring of energy-intensive industries has generally not been driven by such concerns (Jiborn et al., 2018). Similarly, there is no legitimacy in a post-growth transition that does not deliver basic needs and well-being to the whole global population. Any structural change that relies on the increasing appropriation of labour in low-income countries to satisfy demand in high-income countries raises serious questions about global inequality (Alsamawi et al., 2014; Simas et al., 2014).

5.3.2.2 Implications for the post-growth transition

We cannot develop strategies for achieving desired structural change without considering the interconnected nature of the global economy. Building a post-growth economy will not only require the prevention of future offshoring but also the partial reversal of historical offshoring. Global trade and complex domestic supply chains are an important source of transport energy use and carbon emissions (Sorrell et al., 2009; Cristea et al., 2013). The transport sector itself is part of Group 1, for which demand should be reduced. Reducing the share of the transport sector in the economy will not be possible without the shortening of supply chains. Shorter and more local supply chains also help to achieve other post-growth goals discussed in Section 5.3.1. Shorter supply chains allow for more effective democratic control over the production process and a closer connection between producers and consumers (Fournier, 2008; Kallis, 2011). Workers can more easily organise across shorter supply chains to obtain better working conditions. Consumers might be more inclined to accept higher prices caused by more labour-intensive production methods, if they know the people who benefit from the higher prices. Lastly, with shorter supply chains and less international trade, a larger part of production falls under the jurisdiction of domestic governments which will make it easier to achieve post-growth goals in the absence of global agreements (Daly, 2008).

Successful efforts for shortening supply chains would not affect all sectors equally. The offshoring of labour and energy use is most prominent in Group 1 and Group 2 sectors, with the exception of the construction sector. Bringing larger parts of the supply chains for Group 1 and Group 2 sectors back into high-income countries would considerably increase the direct employment in those sectors, possibly at the expense of employment in other sectors. Such an effect would be in addition to the increased labour requirements from the adoption of more labour-intensive production methods discussed in Section 5.3.1. It is unlikely that the increased labour requirements from the two effects could be met in high-income countries, unless there is a considerable reduction in demand for the products of Group 1 and Group 2 sectors. The sector goals identified in Chapter 4 therefore reinforce each other.

Despite the strong calls for shorter supply chains and localised production in the post-growth literature, the literature features no detailed assessment in which sectors it would make sense to produce locally and where it would not. There might well be sectors where local, or national, production is impossible or where it would be beneficial to produce in other countries. For example it might make sense to locate energy-intensive production to places with good access to renewable energy sources.

The post-growth literature also features only limited discussion on how we can design effective strategies for achieving shorter supply chains and more local production. Similar to labour productivity growth, an important driver of offshoring has been the pressure to reduce costs, both with regard to costs related to environmental regulation and labour (Kollmeyer, 2009; Fischer and

Fox, 2012; Tregenna, 2014), with labour cost likely to be the more important of the two (Barker et al., 2007). Producing Group 1 and Group 2 products more locally would likely make them more expensive. But many of the cost differentials are derived from weaker environmental regulations in other countries as well as global wage and income inequalities. The elimination of such environmental and income inequalities is an important goal of the post-growth economy in its own right (Demaria et al., 2013).

Global agreements on standards for environmental protection, workers' rights and acceptable business models could go a long way in reducing cost differences and encouraging more local production. But unravelling and reforming global rules of trade is not an easy task and needs to be handled with care. Most importantly, it must not exacerbate existing global inequalities. Without changes to the wider system of international power relations, capital flows and debt, reductions in global trade and shorter supply chains could have a detrimental impact on the livelihoods in many low-income countries (Dietz and O'Neill, 2013, p.189). In short, a successful post-growth transition, including the achievement of the necessary structural change, requires a complete overhaul of the governance of global trade and finance. There is an urgent need for the post-growth community to come up with concrete proposals on how international trade can be reduced equitably and what a fair trade and financial architecture in a global post-growth economy would look like.

Still, global agreements in line with post-growth goals are unlikely to come to pass anytime soon. It is more likely that post-growth strategies will be pursued by individual countries first. Countries will need to introduce restrictions on international trade in order to prevent offshoring effects undermining the structural change envisioned for a post-growth economy. Such restrictions can include traditional measures, such as tariffs, quotas and capital controls (Pettifor, 2019). In addition the climate change mitigation literature proposes a number of novel policies that can be used to counteract "carbon leakage", which describes the shifting of carbon intensive production abroad (Peters, 2010). For example such policies include border carbon adjustments, which levy prices on imports to correct for the effect of any domestic carbon prices (Fischer and Fox, 2012). While such adjustment policies look promising on paper, they face considerable challenges in implementation, for example with regard to determining the carbon content of imports, the interaction with domestic carbon trading schemes and the equity implications of levying tariffs on imports from low-income countries (Barrett, 2020).

5.3.3 Changes in final demand

5.3.3.1 Historical drivers

The third important driver of structural change is change in the composition of final demand. Baumol's cost disease suggests that sectors with higher rates of labour productivity growth, such as manufacturing, will reduce their share in nominal final demand, because they become relatively cheaper compared to labour-intensive sectors (Baumol, 1967; Nordhaus, 2006). I find some evidence for such price trends in Chapter 3. Such changes in nominal final demand are not helpful for the post-growth transition, because they are not matched by similar changes in real final demand. The relative price changes could even be a barrier, if they reduce the real demand share of labour-intensive services and increase the real demand share of energy-intensive industry sectors. But there is little evidence for such effects.

It is a key assumption of Baumol's cost disease that the demand for most labour-intensive sectors is inelastic to price changes because they are socially important, for example the demand for health care or education. It is the stable demand share of these sectors that causes the shift in employment towards such sectors in Baumol's theory. But Baumol also suggests that there are some labour-intensive sectors that have been pushed to the margins of the economy because they have become relatively more expensive, such as repair services or the performing arts (Baumol, 2012, pp.26–28). Such sectors might not be large enough to strongly influence the demand share of labour-intensive sectors as a whole, but they are important for a post-growth economy (Jackson, 2017, p.172).

The literature provides evidence that the composition of real final demand has shifted away from agriculture and manufacturing and towards service sectors over the past decades in most high-income countries (Schettkat and Yocarini, 2006; Comin et al., 2015; Peneder and Streicher, 2018). Increasing relative demand for energy-intensive sectors stimulated by falling relative prices therefore does not seem to pose an important problem. The results of my analysis are only partially in line with the findings from the literature. The UK shows a small shift in final demand away from Group 1 and Group 2 sectors (Figure 5-2), but in Germany the composition of final demand remains largely unchanged (Figure 5-1). The small shifts I observe highlight the slow nature of structural change. Such slow change poses a challenge for the post-growth transition because it needs to achieve drastic reductions in environmental impacts over just a few decades.

For the post-growth transition it is not only the overall shift towards service sectors that is of interest, but it matters what kind of service sectors benefit from the shift. I identify a shift in demand to labour-intensive services in Group 3 sectors as desirable, but the literature often does not separate labour-intensive services from other services. In my results, the shift in final demand towards service sectors in the UK has been driven by a rise in the share of Group 4 sectors, with the share of Group 3 sectors declining (Figure 5-2).

In many ways the shift in real final demand towards service sectors is welcome from a post-growth perspective, but it is not clear in how far the specific service sectors that are desirable from a post-growth perspective have benefitted. The literature suggests, however, that the shift towards service sectors has mostly been driven by increasing income, because the demand for services has a higher income elasticity (Schettkat and Yocarini, 2006; van Neuss, 2019). The demand for services has not replaced the demand for agricultural and manufactured products, but has simply grown faster with rising incomes. Continuing such a trend is not an option for a post-growth economy.

5.3.3.2 Implications for the post-growth economy

In the transition to a post-growth economy, final demand will need to shift from Group 1 and Group 2 sectors towards Group 3 sectors. Such shifts in final demand will likely have to be achieved in an environment where overall income and economic activity are stable or declining due to strong environmental protection measures. We can therefore not rely on the higher income elasticity of service sector demand to achieve the shifts.

The final demand for the different sector groups is not distributed equally between different actors (Figure 5-3). In both Germany and the UK, the majority of the final demand for the sectors in Group 3 comes from the government or from non-profit institutions serving households (NPISH). A straightforward way of increasing demand and employment in Group 3 sectors is therefore to increase public spending in those sectors, which is directly under the government's control. Such proposals of expanding the provision of public services are already a key pillar of post-growth policy packages because many of these services are directly important for human well-being (Cosme et al., 2017; Gough, 2019). The creation of jobs in such sectors could also help to reduce unemployment and could be delivered as part of a job guarantee (Hartley et al., 2020).

On its own, however, increasing public expenditure in Group 3 sectors will not create the structural change envisaged for a post-growth economy, in part because of second-round effects. The expansion of public expenditure would increase the income of the workers employed directly in such sectors and further

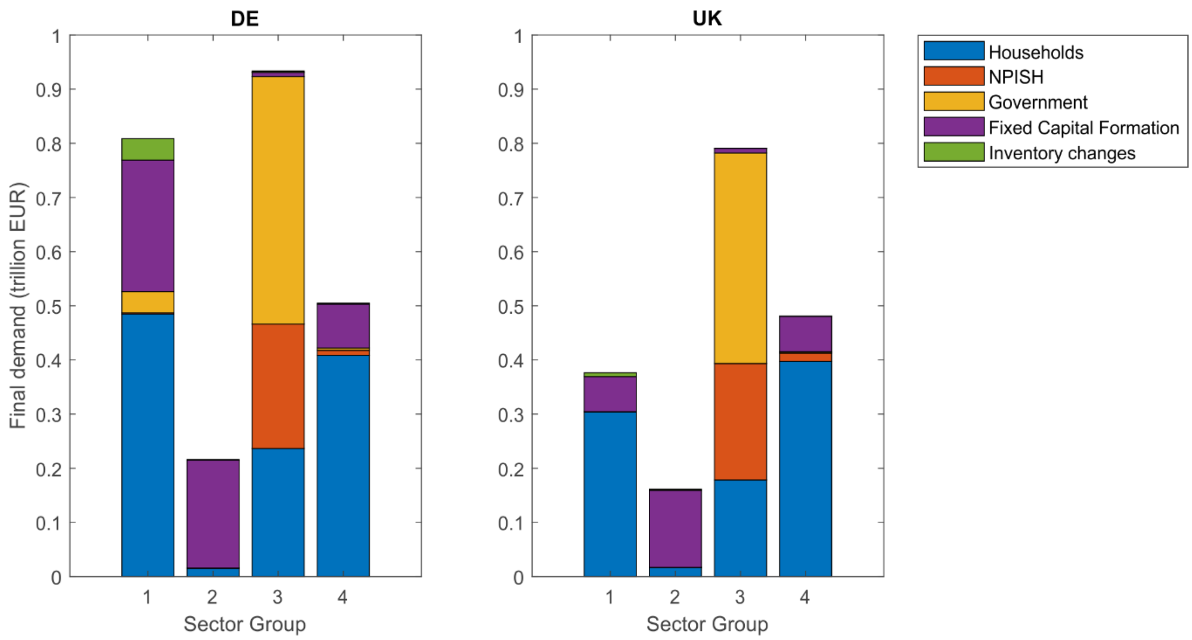

Figure 5-3: Composition of final demand in 2011 for the UK and Germany. The four sector groups are the ones identified in Chapter 4 (see Table 5-1).

down the supply chain. Without further policy intervention a large part of such an increase in incomes will be spent on demand sectors in Group 1 and Group 2, leading to increased energy use and other environmental impacts (Horen Greenford et al., 2020). In order to prevent such second-round effects, policies to increase public expenditure on Group 3 demand sectors will therefore need to be accompanied by explicit measures to reduce demand in Group 1 and Group 2 sectors and to curb environmental impacts in general. The framework presented in my thesis is fundamentally static in nature and can therefore not analyse such effects, which presents an important limitation. An important topic for future research would be the investigation of how the necessary structural change can be achieved without threatening the stability of the economy, for example using ecological macroeconomic models (Hardt and O'Neill, 2017; Jackson and Victor, 2020)

While it is often stated in the post-growth literature that overall demand and consumption is too high in high-income countries (e.g. Sekulova et al., 2013; Kallis, 2017; O'Neill et al., 2018), there is very little discussion about the specific sectors where demand should be reduced. My analysis in Chapter 4 presents a first indication. But we need more detailed research on the question in which sectors there actually is too much demand for goods (e.g. fashion), in which sectors we can maintain the user services while reducing the demand for goods (e.g. mobility rather than cars), and in which sectors we have to reduce the user services (e.g. air travel).

The transition to a post-growth economy will be characterised by strict policies for reducing environmental impacts, such as taxes, cap & trade schemes or rationing (Cosme et al., 2017; Baranzini et al., 2017). While such policies are not explicitly aimed at changing the composition of final demand, they will likely lead to relative reductions in the final demand for Group 1 and Group 2 sectors as these become relatively more expensive or even directly limited.

The big challenge for such blanket policies targeting environmentally-harmful consumption is their inequitable impact. Most of Group 1 and Group 2 sectors produce many goods and services that are crucial for human well-being, such as food, clothing or transport, but the demand is distributed highly unequally

(Oswald et al., 2020). While even in high-income countries some people are genuinely lacking goods and services from such sectors, others consume way above their need. Policies therefore need to be constructed in a way that simultaneously reduces demand from those people who consume too much, increases demand from those people who need more, and still reduces demand in aggregate (Owen and Barrett, 2020).

Stronger progressive taxation reducing the income of the affluent, for example by targeting income from wealth and rents, could go some way in reducing unnecessary consumption from Group 1 and Group 2 sectors. But such general taxation would not guarantee a proportionate reduction in demand for sectors in Group 1 and Group 2, because affluent people spend smaller parts of their income on consumption than less-affluent people (Dafermos and Papatheodorou, 2015). It might therefore be more effective to complement general progressive taxation with taxes and restrictions specifically targeted at the luxury consumption of energy-intensive goods and services. Examples of such taxes would be a frequent flyer levy (Devlin and Bernick, 2015) or higher rates of consumption taxes on luxury products (Werner, 2008, pp.212–216).

While reductions in demand for Group 1 and Group 2 sectors are vital for staying within planetary boundaries, they have potential implications for the stability of the financial system. Such reductions in demand will have severe impacts on the financial position of companies heavily involved in the supply chains of these sectors, leading to potential knock-on effects on the banking and finance sector. Such a negative impact on the finance sector could then jeopardise the availability of loans to those sectors of the economy that are expected to expand, presenting another potential challenge for the post-growth transition. This challenge cannot be analysed in the static framework I use for my analysis. Further research is required to investigate how financial stability can be ensured in the face of the structural change required for the post-growth transition. For example such research could draw on dynamic ecological macroeconomic models that incorporate a realistic representation of the financial system (e.g. Dafermos et al., 2018; Jackson and Victor, 2020).

Shifting final demand by expanding the public provision of Group 3 sectors and taxing luxury consumption of Group 1 and 2 sectors effectively constitutes a shift from private to public consumption. Such an approach would be able to make a good contribution to achieving the structural change goals of the post-growth economy. But it might not be sufficient, unless it is accompanied by a wider change in social norms, expectations and behaviours around consumption. There are important sectors in Group 3 that are not publicly provided but are expected to play a bigger role in the post-growth economy, such as restaurants, cafes, cultural and recreational services and other personal services. Such activities have been referred to as the "Cinderella economy" by Jackson (2017, p.143). Any increase in demand for such sectors will have to come mostly from households. In addition, as I have highlighted in Chapter 3, the structural change required for the post-growth transition would have to be large by historical standards. The necessary scale of changes in taxation and public spending needed to achieve such changes will likely meet with political resistance unless there is an accompanying shift in consumption culture.

The need for a shift in consumption is a key theme that has emerged from the previous discussions. In the transition to a post-growth economy consumption will have to shift from cheap, mass-produced, material products produced abroad, towards more expensive, high-quality, locally-delivered services. The post-growth literature has strongly focused on the role of advertisement in driving unnecessary consumption, proposing restrictions on advertisement to achieve reductions and shifts in consumption (Jackson, 2017, pp.203–204; Gunderson, 2018). Other proposed policies include measures to encourage businesses providing durable goods to shift from the sale of individual products, e.g. washing machines, to provide the user services provided by these products, e.g. clean clothes (Jackson, 2017, pp.141–144). In addition to these policy proposals, there exist a wide literature on the drivers of consumption that can help inform other strategies to shift consumption in the direction required for a post-growth economy (Witt, 2011; Safarzyńska, 2013; Lorek and Fuchs, 2013).

5.4 Contributions to knowledge

Overall my thesis has made two overarching contributions to knowledge, with regard to structural change and energy use in the context of post-growth economics.

The first overarching contribution is the development of a systematic approach to identify structural change goals for a post-growth economy. The post-growth literature recognises that structural change in the sectoral composition of the economy will be an important part of the transition to a post-growth economy. Kallis (2011, p.875) refers to "selective degrowth" and Jackson and co-authors promote a shift to labour-intensive service sectors with low rates of labour productivity growth (Jackson and Victor, 2011), such as "care, craft and culture" (Jackson, 2017, p.149). In my thesis I develop these ideas in a more systematic manner, by providing new empirical evidence of sector characteristics and linking the ideas from the post-growth literature to sectors in terms of the sectoral classification used in the national accounts. In this way my thesis makes the structural change proposed in the post-growth literature more clearly defined and more tangible.

In Chapter 3 I provide novel empirical estimates of the embodied energy intensity and embodied labour productivity growth of different demand sectors in the UK and Germany. The empirical analysis allows me to identify five demand sectors that show the characteristics of labour-intensive services proposed by Jackson and co-authors (Jackson and Victor, 2011; Jackson, 2015; Jackson, 2017, p.148). The five demand sectors correspond closely to the kind of activities that have been intuitively identified as labour-intensive in the post-growth literature. My analysis confirms that a shift in demand to such sectors would reduce the level of aggregate embodied energy intensity and the growth rate of aggregate embodied labour productivity in the UK and Germany. But my analysis also cautions that the reductions in aggregate embodied energy intensity that such a shift can bring on its own are unlikely to achieve the energy reductions required for a post-growth economy.

In Chapter 4 I take the analysis one step further and propose a framework for systematically identifying structural change goals for the post-growth transition based on empirical evidence. The framework determines in which sectors we would expect a falling or increasing share in GVA, demand and employment, and how such goals are related to goals for labour productivity and energy intensity within sectors. I identify four sector groups with similar characteristics and similar structural change goals. As part of the analysis I also provide new evidence on the relationship between labour productivity and the energy-labour ratio at a sectoral level, an important factor in determining the trade-offs between labour productivity and energy intensity goals. Although I do not perform a statistical analysis, my results indicate support for the findings in the literature that direct labour productivity is more strongly related to the direct energy-labour ratio in the industrial and transport sectors than in other sectors (Mulder and de Groot, 2004; Witt and Gross, 2019).

My analysis only provides a very first step in defining structural change goals for a post-growth economy and it poses as many questions as it answers. But it opens up the discussion on the important question of what structural change for a post-growth economy would look like in concrete terms.

The second overarching contribution consists of bringing the insights of the literature on structural change to the literature on post-growth economics. The literature on structural change can bring important insights about the drivers of structural change and how they have been related to energy use. Such insights inform the discussion in my thesis of how we can achieve the structural change goals I have identified. In Chapter 1 I identify three important drivers of structural change in the literature, namely differential rates of labour productivity growth, international trade and changes in the composition of final demand. My thesis provides new insights into how these relate to post-growth goals.

According to the theory of Baumol's cost disease, differential rates of labour productivity growth in different sectors are an important factors shifting employment as well as nominal output and demand towards sectors with low rates of labour productivity growth, as such sectors become relatively more expensive (Baumol, 1967; Baumol et al., 1985; Baumol, 2012). My results in Chapter 3 provide some qualified support for the theory by indicating that the five labour-intensive demand sectors I identify show higher price inflation than other sectors. Baumol's cost disease might therefore constitute a barrier to the post-growth transition, as it might make it more difficult to achieve shifts in demand and output towards labour-intensive sectors in real terms, if they become relatively more expensive.

International trade has been an important factor shaping the sectoral composition of direct nominal output, employment and energy use within countries (Saeger, 1997; Simas et al., 2015; Peneder and Streicher, 2018). The complementary insights that my thesis has provided from an embodied perspective are therefore important to assess in how far such structural change has been in line with post-growth goals. In Chapter 2 I provide new empirical evidence on the relationship between energy use and structural change in the UK. My results support findings from the literature that structural change in real output has been less important than energy intensity reductions for reducing direct energy demand in the UK (Henriques and Kander, 2010; Marrero and Ramos-Real, 2013; Mulder and de Groot, 2013). But I also show that the contribution from structural change in real output to energy demand reductions in the UK has been non-negligible and that it has been driven almost completely by offshoring. Hence, structural change driven by international trade has also not been in line with post-growth goals. Re-writing the rules of international trade is therefore an important challenge for achieving the structural change goals of a post-growth economy.

Changes in the composition of demand have been an important driver of structural change in direct output and employment in the economy (Schettkat and Yocarini, 2006; Kollmeyer, 2009; Comin et al., 2015). In my thesis I propose that a post-growth economy will require a shift in real demand towards labour-intensive and energy-light demand sectors. However, structural change in demand in the past has only been partially in the right direction and it is generally considered to be driven by rising aggregate incomes. The post-growth transition will therefore require new strategies for achieving the desired shifts in final demand.

Overall, combining the insights from the structural change literature and the results of my own analysis, provides the important insight that none of the drivers of structural change in the past are in line with post-growth goals.

Together the two overarching contributions to knowledge my thesis provides constitute the first substantive discussion of the structural change that is required for a post-growth economy and of the potential challenges for achieving it.

5.5 Research limitations

Structural change is a complex phenomenon and interconnected with many other economic processes, such as innovation, demographic changes, the development of social norms around consumption, the competition within and between countries and changes in economic policy. In my thesis I have presented novel research that develops a vision of structural change for a post-growth economy and provides new evidence on the drivers of structural change and their relationship to energy use. Given the complexity of the topic, my research presents only a small step in the endeavour of understanding structural change for the transition to a post-growth economy. In many ways my research raises more question than it answers. In the following I discuss five specific limitations of my analysis.

Firstly, most of my analysis relies on empirical estimates of embodied output, energy and labour in different sector supply chains. Such estimates, which I derive from MRIO databases, come with significant uncertainties. Uncertainties arise from the incomplete availability of economic data used in the construction of MRIO databases, the construction method of the MRIO database as well as the collation and construction of the labour and energy extensions (Peters et al., 2012; Inomata and Owen, 2014; Owen et al., 2014). As such uncertainties are difficult to quantify, they are not commonly reported (Owen et al., 2014). Most importantly for my thesis, uncertainties of embodied measures are larger for individual sectors than for estimates of the economy as a whole (Lenzen et al., 2010). In order to limit the uncertainty of the embodied measures I have presented my results at a relatively high level of sector aggregation, but this introduces another set of limitations, as discussed in the second point. In order to assess the uncertainty of my estimates it would be useful to complement my analysis with research investigating sector characteristics and structural change using alternative MRIO databases and extension vectors.

Secondly, my analysis of structural change is limited by adopting a high level of sector aggregation, which does not go beyond the 2-digit NACE classification. I have adopted this approach in order to limit the uncertainty from the MRIO databases and in order to reflect the limited resolution of the data available on energy use. But using such aggregated sectors comes at the cost of limiting my analysis, because many of these aggregate sectors contain a number of very heterogeneous sub-sectors. My analysis does not capture the structural change, or other transformations, happening at the level of such sub-sectors. For example an increasing share of pharmaceuticals within the chemicals sector would register as a reduction in energy intensity rather than structural change. Weber (2009) demonstrates that the inclusion of a more detailed sectoral resolution in structural and index decomposition analysis can have a considerable impact on the strength of the structural change effect reported. Many important aspects of structural change for a post-growth economy will play out at a more granular level of sectoral resolution. For example an important part of the transition to a post-growth economy and of climate mitigation will be a shift in food production towards more plant-based foods (Creutzig et al., 2016; Gomiero, 2018). But the level of my analysis only captures the agriculture and food production sectors in aggregate and could not depict such changes. Future research on structural change for a post-growth economy would therefore benefit from considering a more detailed sectoral classification, such as the 4-digit NACE classification. Such research could draw on existing work that has classified economic sectors according to their relevance for climate change mitigation in order to assess risks to the financial system (Battiston et al., 2017; EU Technical Expert Group on Sustainable Finance, 2020).

Thirdly, structural change is a long-term phenomenon that unfolds over decades (Kuznets, 1966; Kongsamut et al., 1997). Structural change is also closely linked to the transformation of international trade and supply chains. In my research I focus on examining the international supply chains of different sectors by using MRIO models. MRIO databases cover only recent and relatively short time periods. The use of MRIO models has therefore come at the cost of investigating longer-term trends. Where possible, I have put my results into the context of the literature spanning longer time periods. The reliance on short time periods makes it difficult to determine whether the trends in sectoral characteristics and structural change I observe are representative of long-term patterns or are specific to the time period in question. One example are the low rates of structural change and embodied labour productivity growth that I observe in German manufacturing sectors between 1995 and 2011. Are such low rates a historical aberration owing to circumstances in Germany at the time? Or are they part of a longer-term slowing of growth and structural change? I use the estimated rates of change in order to classify sectors into different groups with different structural change goals. In order to make sure that such a classification serves its purpose, more research is needed to investigate how far my results represent general trends or are particular to a specific time period.

Fourthly, and related to the previous point, the sectoral classification is reliant on the estimation of sector characteristics from historical data. Technical progress might change these characteristics in the future and hence change the sectoral classification I have presented in my thesis. For example the estimation of embodied energy, labour and output throughout the thesis, and the demand-shift scenario in Chapter 3, rely on technical coefficients that are fixed for each year, representing the trade flows between different sectors. Such coefficients are constantly evolving and will change the characteristics of embodied sectors in the future (Barrett and Scott, 2012). Similarly, technological change will impact the characteristics of direct sectors. My results show that direct energy intensity is continuously decreasing in many sectors. The increased possibilities offered by automation and artificial intelligence have the potential to drastically reshape the labour requirements in many sectors, although it is debated in how far they will translate into job losses (Frey and Osborne, 2017; Spencer, 2018). Such technologies could break the stable pattern of relative sectoral growth rates in labour productivity identified in my thesis and the wider literature if it allows for increases in labour productivity in sectors that have so far resisted such increases, for example the health care sector or other labour-intensive service sectors. Any research on structural change for a post-growth transition is motivated by the desire to understand and shape structural change in the future. Future research on structural change for a post-growth economy therefore needs to take into account such trends in technological change as best as possible in order to provide a realistic vision for a post-growth economy.

Fifth, my research focuses on two specific countries, the UK and Germany. I restrict my analysis to two countries to allow for the preparation of detailed data on energy use, especially in the service sectors. The literature shows that different high-income countries can show very different patterns regarding the relationship between structural change, energy use and labour productivity growth (Henriques and Kander, 2010). The differences between countries highlight that structural change in the post-growth transition will take somewhat different shapes in different countries. Further research is needed to expand the study of structural change from an embodied and post-growth perspective to other countries.

Sixth, while the use of the sector classification from the national accounts has many advantages, it also has limits for capturing the effect of newly emerging sectors. New products are usually assigned to existing sectors. The issue is important when considering structural change for a post-growth economy, because the pursuit of novelty is an important driver of consumption and the innovation of new products is an important objective for businesses (Saviotti and Pyka, 2017; Jackson, 2017, p.113). Future research on structural change for a post-growth transition should investigate more explicitly the interlinkages between innovation and novelty and structural change.

Finally, while using the sectoral classifications from the national accounts has many advantages it also imposes important limitations on analysing structural change for a post-growth economy. The national accounts do not capture activities that are not part of market transactions but are important for the post-growth economy; unpaid care and other household work; volunteer work in the community; time spent on political organisation and activism. Many of such activities are crucial for social functioning and well-being and will be expanded in the transition to the post-growth economy. By restricting my analysis to the economic sectors in the national accounts I do not capture structural change towards such activities. A key task for future research on structural change for a post-growth economy will be to develop novel approaches for taking into account market and non-market activities. In addition the current sectoral classification is not well suited to capture other, more transformative, aspects of structural change that go beyond shifts between different kinds of sectors. The transition to a post-growth economy will likely see a transformation of the way that different products and services are delivered and used, for example shifts from product to service delivery and the adoption of alternative business models, such as cooperatives and not-for-profit enterprises. While such transformations were not the topic of this thesis, they will interact with and shape the structural change in terms of shifts between sectors. Such interactions therefore constitute a fruitful topic for future research on structural change for a post-growth economy.

5.6 Concluding remarks

Building a post-growth economy that can deliver wellbeing within planetary boundaries requires an urgent transformation of our economic system. Such a transformation will inevitably change the composition of goods and services that we, in high-income countries, produce and consume. Strategies for the transition to a post-growth economy need to account for such structural change and need to be tailored to the challenges in specific sectors.

In my thesis I have set out a systematic approach to identifying the structural change needed for a post-growth economy and the associated implications for sector-specific strategies. A broad vision emerges. We should aim to reduce demand and production in energy-intensive industries, such as agriculture, manufacturing and transport as much as possible. For the remaining production in such sectors we should encourage local, small-scale and labour-intensive production methods as long as it is consistent with environmental limits. Demand for labour-intensive services can be increased in order to create meaningful employment in areas of care, education, culture or restaurants. For the remaining services, such as finance, real estate, retail and communications, we need to develop strategies to make sure that they deliver for the common good.

Much more research is needed to work out the details of such a vision. Where exactly should demand be reduced and how can it be done fairly? Where exactly are more labour-intensive production methods desirable and feasible? Where would it make sense to reverse historical offshoring and where would it not? What are the implications for employment and energy use if such changes are adopted at scale? The post-growth community needs to answer such questions in order to build a coherent strategy for the post-growth transition.

Structural change in high-income countries has already taken us towards the vision, but only part of the way. Shifts in output have made a small contribution to reductions in direct energy intensity in many countries, but not so much in embodied energy intensity. Direct employment has shifted towards service sectors, including some labour-intensive services, but the majority of embodied employment remains in the supply chains of energy-intensive goods. Such structural change has been intertwined with economic growth. It has been driven by strong labour productivity growth in the manufacturing sectors, the offshoring of energy- and labour-intensive production abroad and continuously rising incomes. A post-growth economy will work on different principles and we cannot rely on any of those drivers to produce the desired structural change.

Discussing structural change makes the vision of a post-growth economy more concrete because it helps us to imagine what kind of things we will produce and consume. Thinking about strategies to achieve structural change also helps us to integrate different policy proposals for a post-growth economy into a bigger picture and to tease out fundamental challenges. Reducing demand in energy-intensive sectors cannot be done fairly without tackling inequality and redistributing income and wealth. Reversing offshoring of energy- and labour-intensive sectors forces us to confront the injustice of the global system of trade and finance. Simultaneously achieving labour productivity growth in some sectors, and the adoption of labour-intensive methods in others, requires a fundamental rethinking of the way we conceptualise, distribute and remunerate work. Creating more employment in labour-intensive services needs a strong government and other collective institutions to deliver public goods.

Many undesired aspects of structural change in the current system are driven by fundamental features of our market economy, such as competition, profit and the need to cut costs. In order to develop effective strategies to achieve the desired structural change for a post-growth economy we need to re-evaluate where markets in their current form are useful, where they need to be more strongly regulated and where they have to be replaced by other systems of provision.

Confronting all these challenges to achieve a post-growth economy presents an immense task that will meet political resistance from powerful vested interests. The sector-based vision of structural change illuminates the struggles lying ahead. Most of the biggest and most powerful companies operate in sectors that will need to be fundamentally transformed. Giant fossil fuel companies will have to disappear within years. Retail chains built around continuously increasing sales of cheap, manufactured products will not be sustainable. Tech companies relying on advertising revenues will be hard hit by any regulations that restrict advertising and consumption. Post-growth research can therefore not stop at the development of policies but also needs to analyse realistic pathways of change that can actually lead to the implementation of such policies. Such an analysis will need to take a systemic perspective and consider power relations, historical trajectories of change and the reform of our democratic systems (Pirgmaier and Steinberger, 2019).

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Appendix A: Additional results for Chapter 2

Table A 1: Change in final energy consumption between 1997 and 2013 attributed to the different decomposition factors for each sector. The results are obtained by first applying equation 2-4 to each effect, sector and year and then summing the results for each sector across the whole time period.

ktoe	F-to-U efficiency	U. exergy intensity	Off-shoring	Embodied output	Demand	Popu-lation	Total
Industrial Sectors							
Iron & Steel	-163	-1767	-1727	-64	702	175	-2844
Non-ferrous Metals	-329	-13	-671	55	309	88	-561
Mineral Products	-163	-25	-554	-201	760	285	102
Chemicals	-1935	-2494	-1816	239	1843	491	-3673
Mechanical Engineering and Metal Products	-166	-342	-377	-432	476	138	-704
Electrical and Instrument Engineering	-95	-26	-428	78	258	86	-127
Vehicles	-270	-542	24	-243	440	122	-469
Food, Beverages & Tobacco	-554	-254	-306	-1354	1028	316	-1125
Textiles, Clothing, Leather & Footwear	-83	532	-836	-279	301	92	-273
Paper, Printing and Publishing	-501	-20	-555	-485	677	212	-674
Other Industries	-761	-152	-1159	-1039	2168	753	-189
Construction	13	-397	20	-90	209	65	-181
Total industrial	**-5007**	**-5501**	**-8385**	**-3817**	**9172**	**2821**	**-10717**
Non-industrial sectors							
Agriculture	-475	404	-286	-384	315	95	-332
Commercial Services	-1404	-4130	11	2896	3245	1190	1808
Public Administration	-911	-5509	78	1496	2042	647	-2156
Total non-industrial	**-2790**	**-14737**	**-197**	**4008**	**5602**	**1932**	**-681**
Overall total	**-7797**	**-14737**	**-8582**	**191**	**14773**	**4754**	**-11398**

Appendix B: Additional results for Chapter 3

Table A 2: Distribution of UK sectoral embodied labour by source region (%)

Demand Sector	UK	Rest of Europe	North America	South & Central America	China	Asia and Oceania	Africa
Agriculture							
Agriculture, Forestry, Fishing	4.8	4.9	0.4	6.6	2.4	30.2	50.7
Production & Construction							
Mineral Products	19.1	6.4	1.3	2.2	4.5	53.5	13.0
Food, Beverages and Tobacco	14.2	12.8	1.1	4.1	6.7	46.1	15.0
Textiles, Clothes, Leather	3.7	6.2	0.6	1.5	36.9	45.4	5.6
Paper, printing, Publishing	34.1	9.5	1.6	1.9	7.0	40.5	5.4
Chemicals	6.7	12.7	4.2	4.1	17.9	44.0	10.4
Metals and Fabricated Metal Products	21.2	13.2	3.0	2.3	8.8	45.1	6.4
Machinery, Electrical, Equipment, Computers	8.5	14.1	3.5	1.8	27.5	39.2	5.4
Transport Equipment	11.4	22.1	3.1	2.3	8.3	45.8	7.0
Other Manufacturing	9.4	12.8	4.5	2.2	21.4	43.4	6.3
Construction	73.0	4.1	0.8	0.8	3.3	14.5	3.5
Labour-light Services							
Wholesale and Retail Trade	85.1	5.3	0.2	0.5	0.6	5.9	2.4
Transport	32.6	11.6	2.5	2.2	4.9	33.8	12.4
Finance and Insurance	62.9	4.5	1.9	1.7	2.9	20.3	5.8
Real Estate Activities	59.1	4.8	2.3	1.0	2.9	25.0	4.9
IT and Communication	76.9	4.3	1.0	0.5	1.7	11.7	3.8
Business Services	61.9	6.1	3.1	1.0	2.9	20.8	4.3
Labour-intensive Services							
Hotels and Restaurants	28.6	7.8	3.2	1.3	14.3	22.6	22.3
Public Administration	70.0	4.0	1.4	0.8	3.0	17.0	3.7
Health	72.7	2.2	0.6	0.5	1.7	20.0	2.3
Education	62.7	3.2	1.1	0.9	3.4	25.0	3.6
Other Services	71.2	4.0	1.3	0.8	2.4	16.5	4.0

Table A 3: Distribution of German sectoral embodied labour by source region (%)

Demand	Germany	Rest of Europe	North America	South & Central America	China	Asia and Oceania	Africa
Agriculture							
Agriculture, Forestry, Fishing	4.5	7.5	0.4	7.8	2.9	38.4	38.6
Production & Construction							
Mineral Products	12.6	10.5	1.6	3.3	5.8	53.3	13.0
Food, Beverages and Tobacco	19.8	14.1	0.8	5.8	8.1	32.4	19.0
Textiles, Clothes, Leather	2.8	11.9	0.7	2.0	34.0	41.8	6.8
Paper, printing, Publishing	27.5	22.0	2.0	1.5	6.7	33.8	6.5
Chemicals	12.4	14.3	4.8	3.3	17.0	38.6	9.6
Metals and Fabricated Metal Products	20.9	24.1	1.6	2.3	7.0	37.2	6.9
Machinery, Electrical, Equipment, Computers	12.7	17.0	2.6	1.9	23.9	36.4	5.6
Transport Equipment	14.8	24.8	4.2	4.0	10.2	33.7	8.2
Other Manufacturing	22.0	23.5	1.6	2.0	13.5	30.9	6.5
Construction	53.2	10.5	1.2	1.0	6.3	22.6	5.2
Labour-light Services							
Wholesale and Retail Trade	69.9	15.5	0.5	0.8	1.2	7.7	4.4
Transport	19.9	13.3	3.0	1.6	5.2	42.9	14.2
Finance and Insurance	59.2	5.0	2.4	1.9	4.0	21.3	6.3
Real Estate Activities	61.5	6.2	2.0	0.9	3.8	20.6	4.9
IT and Communication	58.8	7.7	2.1	0.6	2.9	19.9	8.0
Business Services	72.8	4.5	4.3	0.7	2.2	12.8	2.8
Labour-intensive Services							
Hotels and Restaurants	40.6	7.0	4.9	1.8	11.7	17.2	16.8
Public Administration	67.2	5.4	2.9	1.1	3.4	14.6	5.3
Health	80.9	3.3	1.5	0.5	1.8	9.1	2.8
Education	66.1	5.8	1.4	1.7	4.3	15.3	5.4
Other Services	65.9	5.1	1.6	0.8	4.2	17.2	5.2

Table A 4: Rates of change in embodied energy intensity and embodied labour productivity as well as in the embodied energy-labour ratio for domestic demand sectors between 1995 and 2006. Intensities represent embodied energy and labour inputs per unit real demand (const. 2010 EUR).

	Cumulative Annual Growth Rate between 1995 and 2006 (%)					
	UK			**DE**		
Sector	**Energy Intensity**	**Labour Prod.**	**Price Index**	**Energy Intensity**	**Labour Prod.**	**Price Index**
Agriculture						
Agriculture, Forestry, Fishing	–6.1	4.7	–2.2	–2.8	3.1	–1.1
Production & Construction						
Mineral Products	3.7	–2.6	3.1	0.5	–0.5	–0.5
Food, Beverages and Tobacco	0.0	–1.0	2.7	–0.3	–1.0	0.9
Textiles, Clothes, Leather	1.1	3.4	0.3	–2.0	–0.5	–0.2
Paper, printing, Publishing	1.5	0.5	3.3	0.5	1.3	–0.8
Chemicals	–4.1	3.3	–0.8	–1.6	0.8	–0.8
Metals and Fabricated Metal Products	–4.8	3.0	0.1	–2.7	0.7	0.5
Machinery, Electrical, Equipment, Computers	–4.0	3.2	–0.5	–1.7	0.3	–1.6
Transport Equipment	–3.4	2.3	0.9	–0.5	–2.0	1.3
Other Manufacturing	1.0	–0.3	3.5	0.3	–0.1	0.8
Construction	–0.4	–0.8	6.2	0.0	–0.2	–0.2
Labour-light Services						
Wholesale and Retail Trade	–2.6	3.3	3.6	–1.0	1.8	–0.6
Transport	–2.0	1.3	1.9	0.5	–0.1	0.9
Finance and Insurance	–5.9	5.1	2.1	8.9	–6.5	12.0
Real Estate Activities	–2.9	1.2	1.9	–0.9	1.3	–0.6
IT and Communication	–7.7	8.4	–3.0	–0.7	3.1	–3.3
Business Services	–3.6	2.4	3.2	2.1	–1.4	0.6
Labour-intensive Services						
Hotels and Restaurants	–1.0	0.0	5.1	1.0	0.3	2.4
Public Administration	–1.4	–0.9	4.8	–1.5	0.2	0.7
Health	–0.9	–2.5	7.3	–1.5	–0.8	1.9
Education	0.7	–0.3	4.6	–1.2	0.1	0.2
Other Services	0.0	–0.6	6.3	0.3	–0.8	1.6
Total domestic demand	–1.6	0.6	3.7	–0.9	0.1	0.5

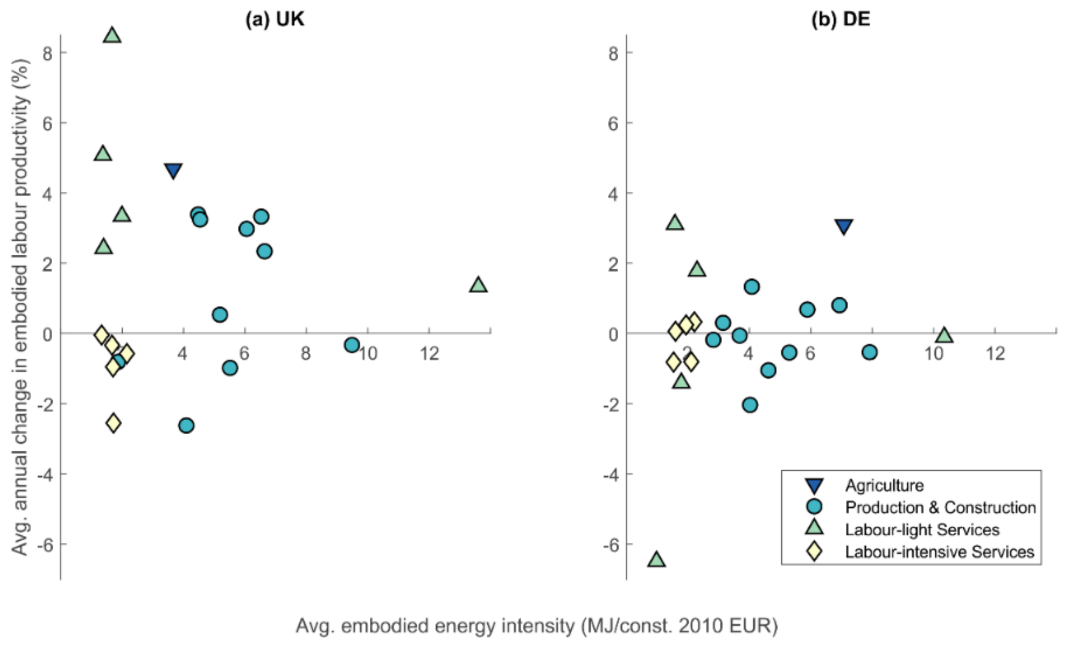

Figure A 1: Relationship between change in embodied labour productivity and the average embodied energy intensity for domestic demand sectors between 1995 and 2006 in (a) the UK and (b) Germany.

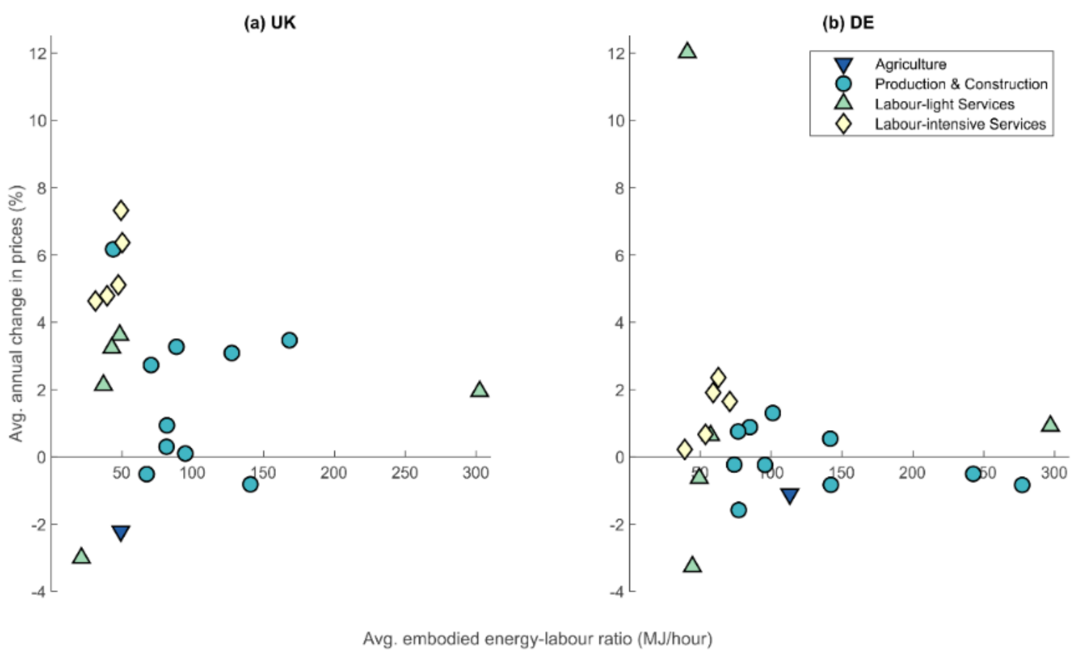

Figure A 2: Relationship between change in sector price indices and the average embodied energy–labour ratio between 1995 and 2006 in (a) the UK and (b) Germany.

Table A 5: Sectoral rates of change in direct labour productivity in the UK and Germany between 1995 and 2011.

Sectors	**Cumulative rate of change in direct labour productivity * (%)**	
	UK	**DE**
Agriculture		
Agriculture, Forestry, Fishing	4.1	4.3
Production & Construction		
Mineral Products	–1.2	3.3
Food, Beverages and Tobacco	3.7	–1.3
Textiles, Clothes, Leather	4.8	3.7
Paper, printing, Publishing	3.0	6.4
Chemicals	6.4	2.1
Metals and Fabricated Metal Products	3.1	2.0
Machinery, Electrical, Equipment, Computers	5.6	4.2
Transport Equipment	5.4	3.3
Other Manufacturing	3.2	2.5
Construction	–0.2	0.1
Labour-light Services		
Wholesale and Retail Trade	2.6	2.0
Transport	3.0	4.6
Finance and Insurance	6.6	–0.6
Real Estate Activities	-	-
IT and Communication	7.9	4.2
Business Services	3.8	–2.2
Labour-intensive Services		
Hotels and Restaurants	1.0	1.9
Public Administration	–0.6	1.7
Health	–2.8	–1.7
Education	1.1	1.0
Other Services	0.8	0.2
Total	2.4	1.7

*: Direct labour productivity is calculated as sectoral GVA (in constant 2010 prices) per hour of work in the sector, using data from EXIOBASE V3.4 and GVA deflators from Eurostat.

Appendix C: Supplementary information on the energy extension vector

C.1 Introduction

For our study we construct a global extension vector for EXIOBOASE specifying direct final energy consumption across sectors and regions. We construct this vector in two steps. In the first step we use data on final energy consumption provided by the International Energy Agency (IEA) in combination with information on monetary output and expenditure from EXIOBASE to construct a complete vector for all countries and regions outside Germany and the UK (described in Secion C.2). In a second step we use national data sources to construct more detailed vectors of direct energy inputs for the UK and Germany respectively (described in Sections C.3 and C.4).

C.2 Global energy extension vector

C.2.1 Data sources

We construct the vector of direct energy inputs to match the data on monetary flows from the EXIOBASE database. We use the symmetric input-output tables of EXIOBASE version 3.4. The EXIOBASE 3.4 database is available at http://exiobase.eu/index.php/data- download/exiobase3mon. The database covers the period from 1995 to 2011 and represents the global economy in 44 countries and 5 rest-of-the-world regions. Each national/regional economy is disaggregated into 163 sectors based on NACE rev.1.1 classification. However, for our purposes we aggregate the database to a level of 70 sectors, largely by removing detailed sub-classifications in the sectors of agriculture, food production, metal mining and processing and recycling. We perform this aggregation to 70 sectors because our energy data do not provide a similar level of detail and it simplifies computation and analysis (Table A6). The term “EXIOBASE sectors” will be used from hereafter to describe the 70 aggregated sectors and sector numbers will refer to the numbers in Table A6, ranging from 1 to 70.

Table A 6: Sector classification used in the MRIO analysis

No	Sector	NACE 1.1
1	Agriculture	01
2	Forestry	02
3	Fishing	05
4	Mining of coal and lignite	10
5	Extraction of crude petroleum and nat. gas	11
6	Other mining and quarrying	12-14
7	Manufacture of food products	15.1-8
8	Manufacture of beverages	15.9
9	Manufacture of tobacco products	16
10	Manufacture of textiles	17
11	Manufacture of clothes	18
12	Manufacture of leather products	19
13	Manufacture of wood products	20
14	Manufacture of paper and paper products	21
15	Publishing, printing and reproduction of recorded media	22
16	Manufacture of coke oven products	23.1
17	Petroleum refinery	23.2
18	Processing of nuclear fuel	23.3
19	Manufacture of chemicals	24
20	Manufacture of rubber and plastic products	25
21	Manufacture of non-metallic minerals	26
22	Manufacture of basic iron and steel	27.1-3, 27.5
23	Manufacture of non-ferrous metals	27.4
24	Manufacture of fabricated metal products	28
25	Manufacture of machinery and equipment nec	29
26	Manufacture of office machinery and computers	30
27	Manufacture of electrical machinery and apparatus nec	31
28	Manufacture of radio, television and communication equipment and apparatus	32
29	Manufacture of medical, precision and optical instruments, watches and clocks	33
30	Manufacture of motor vehicles, trailers and semi-trailers	34
31	Manufacture of other transport equipment	35
32	Manufacture of furniture; manufacturing nec	36
33	Recycling	37
34	Production of electricity from coal	40.11
35	Production of electricity from gas	40.11
36	Production of electricity from nuclear power	40.11
37	Production of electricity from renewables and other sources	40.11
38	Transmission and distribution of electricity	40.12,40.13
39	Manufacture and distribution of gas	40.2

No	Sector	NACE 1.1
40	Steam and hot water supply	40.3
41	Water collection, purification and distribution	41
42	Construction	45
43	Sale, maintenance, repair of motor vehicles	50
44	Wholesale and commission trade	51
45	Retail trade	52
46	Hotels and restaurants	55
47	Transport via railways	60.1
48	Other land transport	60.2
49	Transport via pipelines	60.3
50	Water transport	61
51	Air transport	62
52	Supporting and auxiliary transport activities	63
53	Post and telecommunications	64
54	Financial intermediation except insurance	65
55	Insurance and pension funding	66
56	Activities auxiliary to financial intermediation	67
57	Real estate activities	70
58	Renting of machinery and equipment	71
59	Computer and related activities	72
60	Research and development	73
61	Other business activities	74
62	Public administration and defence; compulsory social security	75
63	Education	80
64	Health and social work	85
65	Sewage and refuse disposal	90
66	Activities of membership organisation nec	91
67	Recreational, cultural and sporting activities	92
68	Other service activities	93
69	Private households with employed persons	95
70	Extra-territorial organizations and bodies	99

For the construction of the energy extension vector we draw on data from the Extended World Energy Balances provided by the International Energy Agency (IEA, 2018) to produce information on the direct final energy inputs for each sector and each country/region in EXIOBASE. However, the direct energy inputs for the UK and Germany are later replaced by more detailed information from domestic sources. The energy balances provide details on the energy production, transformation and use in more than 140 countries.

Given that we are only interested in final energy data, we only use the information on Total Final Consumption (TFC) in the energy balances, which is subdivided into 27 energy flows (Table A7). We download the data for the 27 flows for all countries available in the energy balances and aggregate the data of individual countries to the 49 countries/regions used in EXIOBASE. We then exclude the two flows of non-energy use and residential energy consumption, because our study focuses on energy inputs into economic production. This leaves us with the relevant final energy consumption in each EXIOBASE country/region disaggregated into 25 IEA flows.

In the following we describe how we map the 25 IEA flows onto the 70 EXIOBASE sectors.

C.2.2 Industry

Table A7 describes how the 13 industry-related direct energy flows were mapped onto the relevant 25 industry and construction sectors in EXIOBASE (6-15,19-33,41-42 in Table A6). IEA flows that only correspond to one EXIOBASE sector are directly assigned to that sector. IEA flows that correspond to multiple EXIOBASE sectors are split in proportion with the total monetary expenditure on energy in each sector. The expenditure on energy of each sector was obtained by summing the intermediate expenditures on the energy-producing sectors (4-5,16-18,34-40 in Table A6) from the EXIOBASE tables.

We used expenditure on energy rather than total sectoral output for splitting the IEA flows, because a comparison of the results of both methods for the UK revealed that the energy expenditure approach produced results that better matched the more detailed information available from domestic data UK sources.

The IEA flow of “non-specified industry” includes both the energy use in industry sectors that are not covered by the other industry flows, as well as any energy use that cannot be allocated to a specific industry due to lack of information. We allocate this flow only to the EXIOBASE industry sectors that are not covered by the other IEA flows (i.e. sectors 25, 32,33,41 in Table A6) in proportion to the energy expenditure in these sectors.

Table A 7: IEA energy flows from TFC and corresponding EXIOBASE sectors (sector numbers refer to Table A6).

IEA TFC flow	EXIOBASE sectors	Method for allocation
Industry		
Iron and steel	22,24	EXIOBASE energy expenditure
Chemical and petrochemical	19	Direct
Non-ferrous metals	23	Direct
Non-metallic minerals	21	Direct
Transport equipment	30-31	EXIOBASE energy expenditure
Machinery	25-29	EXIOBASE energy expenditure
Mining and quarrying	6	Direct
Food and tobacco	7-9	EXIOBASE energy expenditure
Paper, pulp and print	14,15	EXIOBASE energy expenditure
Wood and wood products	13	Direct
Construction	42	Direct
Textile and leather	10-12	EXIOBASE energy expenditure
Non-specified (industry)	25,32-33,41	EXIOBASE energy expenditure
Transport		
Domestic aviation	51	See details in text
Road	48	See details in text
Rail	47	Direct
Pipeline transport	49	Direct
Domestic navigation	50	See details in text
Non-specified (transport)	47-51	See details in text
World aviation bunkers	51	See details in text
World marine bunkers	50	See details in text
Other		
Commercial and public services	43-46, 52-68	EXIOBASE output
Agriculture/forestry	1-2	EXIOBASE output
Fishing	3	Direct
Non-specified (other)	1-3,6-15,19-33, 41-68	See details in text
Excluded flows		
Residential	-	-
Non-energy use	-	-

C.2.3 Transport

C.2.3.1 Rail, pipeline and non-specified transport

The IEA energy flows for rail and pipeline transport are directly assigned to the respective EXIOBASE sectors. The IEA flow of "non-specified (transport)" is allocated across all transport sectors in proportion to economic output in the sectors.

C.2.3.2 Road transport

The treatment of the IEA energy flow for road transport is more difficult and poses several challenges. Firstly, it includes the energy used by private households, which we have to exclude for our analysis, as we are only interested in energy used for commercial purposes. Information on the share of non-commercial road transport energy use in total road transport energy use is not available in a single consistent database.

Therefore we rely on different data sources to obtain the necessary information. For those countries that publish greenhouse gas (GHG) inventories under the UNFCCC, we use the share of CO_2 emissions produced by cars in the total road transport CO_2 emissions as a proxy for the share of non-commercial road transport energy use. For all remaining countries we tried to obtain estimates from the academic literature or from other statistical sources. Where such sources were not available, we used the shares obtained for different countries that we considered to be sufficiently similar. For the rest-of-the-world regions we obtained the information for a single country in the region as an estimate for the share of non-commercial transport in the whole region.

Secondly, IEA energy balances are assembled based on a territorial principle, while national economic accounts and EXIOBASE follow a residency principle (Stadler et al., 2018). This is particularly problematic for the transport sector. In the IEA balances, transport energy use is recorded where the fuel is used (or sold), no matter whether the company (or person) using the fuel is resident in the country. In contrast the economic activity is recorded in the country of residency of the company or person. This means that ideally the figures for road transport energy use provided by the IEA need to be adjusted for energy used by foreign vehicles in the country and the energy used by domestic vehicles outside the country. However, such information is not easily obtained and detailed modelling would be beyond the constraints of this study. We therefore do not perform any adjustments of this nature, essentially assuming that energy use by domestic vehicles abroad is similar to energy use by foreign vehicles domestically. This is not the case in many countries and this assumptions therefore adds to the uncertainty of this analysis. However, we consider it unlikely that taking into account such adjustments in road transport would significantly alter our overarching conclusions.

Thirdly, once the total energy use for commercial road transport is estimated, this figure cannot simply be allocated to the direct EXIOBASE sector for road transport, which only captures the logistics sector. Instead the IEA data capture all road energy by commercial vehicles, many of which are directly operated by companies in direct sectors outside logistics, for example supermarket distribution lorries. The data on commercial road transport energy use therefore need to be split and allocated across a range of direct economic sectors. The only country for which we found information of this nature is Germany for the years 1995 to 2001 (see Section C.3). Therefore we use the German data to estimate the allocation of commercial road transport energy use across the direct EXIOBASE sectors for all other countries/regions. We achieve this in three steps. Firstly, we obtain the German road transport intensity of each sector by dividing sectoral road transport energy use by industry sector output from EXIOBASE. As the intensities are relatively stable, we obtain the average German intensities over the seven years provided to apply them to all other countries and years. Secondly, we multiply the average German road transport energy intensities for each sector with total output in each sector and each year in the other countries. Thirdly, we scale these results in each country so that the sectoral road transport energy use adds up to the total energy use for commercial road transport in the country.

C.2.3.3 Aviation and marine transport

The energy use of internal aviation and marine transport (i.e. international marine and aviation bunkers) pose similar challenges to road transport, again due to the fact that the IEA data are reported based on the territorial principle while EXIOBASE is built on the residency principle. A detailed modelling of aviation and marine trade flows to allocate international bunkers to the right countries is, again, beyond the constraints of this study.

For simplicity we therefore assume that the aviation sectors across all countries/regions have the same direct energy intensity of output set to the global average. The economic output of the aviation sector in EXIOBASE does not distinguish between domestic and international aviation, as the IEA data do. To obtain the global average intensity we therefore add international aviation bunkers and energy use for domestic aviation across all countries to obtain the total global energy use for aviation. We then divide the total aviation energy use by the sum of economic output in the aviation sectors across all countries/regions in EXIOBASE to obtain the global average direct energy intensity. The global aviation energy use is then reallocated to the direct aviation sectors in the individual countries based on their economic output and the average global intensity. For marine transport energy use we adopt the same process.

Our process of allocation therefore relies on very simplified assumptions, but we considered that they represent the best possible solution within the constraints of this study. Aviation and marine transport each make up about 5% of commercial global final energy consumption in 2011 (i.e. excluding residential, private transport and non-energy use). The assumptions therefore add a degree of uncertainty to our results.

C.2.4 Other flows

Of the remaining flows, the energy use for fishing and construction are assigned directly to the respective direct EXIOBASE sectors. The agriculture/forestry flow in the IEA balances was split according to sector output as reported in EXIOBASE.

The IEA extended energy balances only feature a single flow describing all direct final energy consumption in the commercial and public service sectors. We split this flow into the relevant direct EXIOBASE sectors (43-46, 52-68 in Table A6) in proportion to the total output in these sectors as reported in EXIOBASE. In contrast to the industry sectors, we use total output and not energy expenditure for the service sectors because the energy expenditure approach produces unrealistically low values of direct energy consumption in some service sectors.

Finally, the energy balances include a flow labelled as "Non-specified (other)" which includes all energy use that is not assigned to other categories (including for military use). Values for this category are mostly between 0 and 2% of overall final energy use (excl. non-energy use) for most countries/regions but can reach higher values (up to 10%) in some years and some countries/regions. The category is therefore non-negligible but there is no information on what the energy is used for. In the absence of better information we distribute the flow across all energy-using sectors in proportion to sectoral output.

C.2.5 Sectors without final energy consumption

Some of the 70 EXIOBASE sectors were not assigned any direct final energy use from the IEA flows. This includes those sectors that produce primary energy carriers (e.g. coal mining) or transform them into final energy carriers (e.g. electricity production). By definition, these sectors (4-5,16-18,34-40 in Table A6) are not users of final energy and therefore do not feature a direct final energy consumption in the IEA balances. In addition we also did not assign any final energy consumption to the sectors "Private Households with Employed Persons", because we consider that the sector does not have energy use separate from private residential use. We didn't assign any energy consumption to the sector "Extraterritorial bodies and organisations" as this sector does not feature any monetary flows in EXIOBASE.

C.3 Energy extension vector for the UK

In our study we focus on the embodied energy and labour of final demand in the UK or Germany. To reduce some of the uncertainty associated with the IEA data, we construct more detailed extension vectors for these two countries drawing on domestic data sources describing energy use.

C.3.1 Data sources

For the UK we make extensive use of the 2018 version of the Energy Consumption in the UK (ECUK) dataset, published by the Department for Business, Energy & Industrial Strategy (Department for Business Energy & Industrial Strategy, 2018). This was complemented by monetary flows from the EXIOBASE database if necessary.

C.3.2 Industry

For industry sectors, the ECUK dataset provides data on direct energy consumption at the 2-digit level of the SIC2003 classification. This classification mostly matches the industry and construction EXIOBASE sectors (6-15,19-33,41-42 in Table A6). The only exception is the aggregated food and beverages sector which we split into food and beverages according to EXIOBASE energy expenditure. For the years 2010 and 2011 the ECUK database provides data in SIC2007 classification (corresponds to NACE rev. 2) which we transformed into NACE rev1.1 classification to match our EXIOBASE sectors.

The industrial energy use listed as "unclassified" in ECUK provides a difficult choice for allocation. We decided to add it to the sector "Manufacture of furniture; manufacturing nec" because the sectors featured unrealistically low values of direct energy intensity otherwise. However, some of the unclassified energy is also likely to be used in other sectors. As a result our estimates of direct and embodied energy intensity for the sector "Manufacture of furniture; manufacturing nec" is an overestimate, while the direct and embodied intensities in the other manufacturing sectors are underestimated.

C.3.3 Transport

We do not recalculate direct energy use for marine transport and aviation for the UK but instead take it from the global extension vectors (described in Section C.2.3) to make sure that it is consistent with our global assumptions.

The ECUK dataset provides separate information on road transport energy use for passenger and freight transport as well as for different transport modes. This allows an estimation of the commercial road transport energy use. However, there is no information provided on the sectors in which the transport energy is used. We therefore estimate the allocation of road transport energy use to EXIOBASE sectors using the German data as described in Section C.2.3.

Data on rail transport energy use are provided in the ECUK. We obtain energy use for pipeline transport (which is very small in the UK) from the IEA data, as no information is provided in ECUK.

C.3.4 Other energy users

The ECUK dataset provides information on the aggregate energy use for the sectors agriculture, forestry and fishing. We split this energy use according to sector proportions in EXIOBASE output to obtain the direct energy use in the three individual sectors.

For the commercial and public service sectors the ECUK dataset provides the aggregate direct energy use for all years covered in this study as well as a more detailed breakdown for the years 2010 and 2011. Table A8 describes the sub-categories for which data are provided in 2010 and 2011 and the EXIOBASE sectors we assigned to these sub-categories. We estimate the energy consumption in each sub-category for the years 1995-2009 from the data for 2010/2011 using the following steps. Firstly, we obtain the total economic output for each sub-category by summing the output of the relevant sectors from EXIOBASE.

Table A 8: ECUK energy use in service sector sub-categories and corresponding EXIOBASE sectors (sector numbers refer to Table A6).

ECUK service sector sub-category	EXIOBASE sectors	Method for allocation
Commercial offices	54-61	EXIOBASE output
Communication and transport	52-53	EXIOBASE output
Education	63	Direct
Government	62	Direct
Health	64	Direct
Hotel and Catering	46	Direct
Other	65-66, 68	EXIOBASE output
Retail and warehouses	43-45	EXIOBASE output
Sport and Leisure	67	Direct

Secondly, we use the output figures to calculate the average direct energy intensity of output in each subcategory for the years 2010 to 2011.

Thirdly, we multiply the average direct energy intensity with the economic output in the sub-categories for the years 1995-2009. Finally, we scale these results so that the sum of direct energy use in all sub-categories matches the aggregate direct energy use in the services sectors reported. In essence this process assumes that the relative direct energy intensities in the sub-categories stay constant at their 2010/2011 value for the whole time period.

Once we have obtained the direct energy use in each sub-category and each year, the sub-categories are allocated to the relevant EXIOBASE sector in proportion to EXIOBASE sector output (Table A8).

C.4 Energy extension vector for Germany

C.4.1 Data sources

To create a more detailed extension vector for Germany we draw on three important data sources. To obtain direct energy use in the industrial sectors as well as aggregate direct energy use in commercial and public services we use the data provided in the German energy balances (AG Energiebilanzen, 2019). In addition, we use statistical reports on direct energy use in the sector “Gewerbe, Handel, Dienstleistungen” (GHD), which provides detailed estimates of direct energy use in the non-industrial and non-transport sectors for the year 1994 (Geiger et al., 1999) and the years 2001-2011 (Schlomann et al., 2004; Schlomann et al., 2009; Schlomann et al., 2013). In combination these reports will be referred to as GHD reports hereafter. Finally, the Berichtsmodul Verkehr und Umwelt (Adler, 2005) provides information on the transport energy use allocated to different sectors for the years 1995 to 2001.

C.4.2 Industry

We obtain information on direct energy use in industry for the years 1995 to 2011 from the Germany energy balances. Table A9 outlines the direct energy flows provided in the balances and the EXIOBASE sectors to which we allocate them. As the disaggregation in the energy balances is less detailed than in our

Table A 9: Energy use in the industrial sectors from German energy balances and corresponding EXIOBASE sectors (numbers refer to Table A6).

German energy balance flow	EXIOBASE sectors	Method for allocation
Gewinnung von Steinen und Erden, sonst. Bergbau	6	Direct
Ernährung und Tabak	7-9	EXIOBASE energy expenditure
Papiergewerbe	14	Direct
Grundstoffchemie and Sonstige chemische Industrie	19	Direct
Gummi- u. Kunststoffwaren	20	Direct
Glas u. Keramik and Verarbeitung v. Steine u. Erden	21	Direct
Metallerzeugung	22	Direct
NE-Metalle, -gießereien	23	Direct
Metallbearbeitung	24	Direct
Maschinenbau	25-29	EXIOBASE energy expenditure
Fahrzeugbau	30-31	EXIOBASE energy expenditure
Sonstige Wirtschaftszweige	10-12,15,32-33	EXIOBASE energy expenditure

EXIOBASE sectors, we allocate the direct energy use to the relevant EXIOBASE sectors in proportion to EXIOBASE energy expenditure. Contrary to the IEA and UK energy data, the construction and water sectors are not treated as part of the industrial sectors. They are instead allocated to the GHD category treated in the reports mentioned above.

C.4.3 Transport

We do not recalculate direct energy use for marine transport and aviation for Germany but instead take it from the global extension vectors (described in Section C.2.3) to make sure that it is consistent with our global assumptions.

The German energy balances provide information on the total road transport energy use in Germany. We obtained estimates of the proportion of commercial road transport energy for the years 1994 to 2001 from Adler (2005) and for the year 2016 from Statistisches Bundesamt (2018). We obtain the value of the proportion of commercial road transport energy use for the years 2002 – 2011 using linear interpolation and use the values to estimate total commercial road transport energy use for the whole time period covered in this study.

Adler (2005) also gives the allocation of road transport energy use to different economic sectors for the years 1994 to 2001. The sector shares in transport energy use remain relatively stable. Therefore we assume constant sector shares for the years 2002 to 2011, set to the values for 2001, and use these shares to estimate direct sectoral transport energy use from total commercial road transport energy use. The resulting values are then aggregated to EXIOBASE sectors and the energy use added to non-transport forms of energy use in the sectors.

Data on rail transport energy use is provided in the German energy balances. We obtain energy use for pipeline transport from the IEA data, as no information is provided in the German energy balances.

C.4.4. Other flows

In the German energy balances all other flows are covered in a single category labelled "Gewerbe, Handel, Dienstleistungen" (GHD). The GHD reports provide a more detailed investigation of direct energy use split into 37 different sub-sectors for the years 1994 (Geiger et al., 1999) and 2001-2011 (Schlomann et al., 2004; Schlomann et al., 2009; Schlomann et al., 2013) in a mostly consistent format. Direct sectoral energy use for the 37 sectors and years 1995 to 2000 was obtained using linear interpolation. The GHD reports produce results that are not completely consistent with the total GHD energy use reported in the energy balances, although differences between the totals are small. To make the energy extension for Germany as consistent as possible with the German energy balances, we scale the sectoral energy use in the GHD reports to match the total GHD use in the energy balances.

We then transform the energy use in the 37 GHD sectors for the years 1995 to 2011 into the relevant EXIOBASE sectors. Where energy use had to be split from one GHD category into multiple EXIOBASE sectors we allocated the energy use in proportion to EXIOBASE output. The GHD category mostly covers the non-transport public and commercial service sectors (41, 43-46, 52-68 in Table A6), as well as construction (42) and agriculture, forestry and fishing (1-3). However, it also contains small amounts of energy use in small enterprises (less than 20 employees) in the industry sectors (e.g. artisan bakeries), as well as some energy use that is used in the transport sector for non-transport purposes (e.g. energy use in airports).

C.5 References

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Appendix D: Additional information for Chapter 4

Table A 10: Rates of change in direct and embodied energy intensity in the UK and Germany (DE).

	Annual rate of change in direct energy intensity (%)		Annual rate of change in embodied energy intensity (%)	
Sector	UK	DE	UK	DE
Group 1				
Agriculture, Forestry, Fishing	-4.5	-2.5	-4.7	-3.3
Food, Beverages and Tobacco	-2.6	1.0	-2.4	-0.1
Textiles, Clothes, Leather	1.8	-1.7	0.0	-1.8
Paper, Printing, Publishing	-1.0	-1.2	-1.8	-1.9
Chemicals	-5.9	0.3	-4.8	-0.3
Metals and Fabricated Metal Products	-6.4	-1.8	-3.6	-2.4
Machinery, Electrical Equipment, Computers	-3.2	-3.5	-4.3	-2.5
Transport Equipment	-4.4	-2.3	-4.6	-1.5
Other manufacturing	1.5	0.2	0.7	0.6
Transport	-2.1	-1.9	-2.4	0.1
Group 2				
Mineral Products	4.4	-1.3	1.6	-0.7
Construction	-2.9	0.7	-0.3	0.3
Group 3				
Hotels and Restaurants	-2.1	-1.2	-1.4	-0.9
Public Administration	-3.8	-3.5	-1.6	-2.1
Health	-2.2	-1.0	-0.8	-0.9
Education	-4.0	-3.2	-0.7	-1.0
Other Services	-0.9	-1.9	-0.7	-1.0
Group 4				
Wholesale and Retail Trade	-2.0	-2.8	-2.0	-3.8
Finance and Insurance	-4.0	0.2	-4.5	6.0
IT and Communication	-6.0	-4.5	-6.5	-2.6
Business Services	-2.9	0.5	-3.8	-0.2
Real Estate	-	-	-	-

Table A 11: Average labour intensity and energy-labour ratio, both direct and embodied, for sectors in the UK and Germany between 1995 and 2011 (constant 2010 EUR).

	Labour intensity (hours/EUR)				**Energy-labour ratio (MJ/hour)**			
	Direct		Embodied		Direct		Embodied	
Sector	UK	DE	UK	DE	UK	DE	UK	DE
Group 1								
Agriculture, Forestry, Fishing	0.067	0.066	0.074	0.063	52	149	49	113
Food, Beverages and Tobacco	0.040	0.033	0.078	0.055	177	176	70	85
Textiles, Clothes, Leather	0.051	0.026	0.056	0.056	102	253	81	96
Paper, Printing, Publishing	0.048	0.017	0.059	0.029	108	468	88	142
Chemicals	0.032	0.011	0.046	0.025	266	701	141	277
Metals and Fabricated Metal Products	0.046	0.022	0.063	0.042	188	496	95	142
Machinery, Electrical Equipment, Computers	0.047	0.018	0.067	0.041	39	36	67	77
Transport Equipment	0.057	0.016	0.081	0.040	60	94	82	101
Other manufacturing	0.031	0.034	0.057	0.048	385	102	168	77
Transport	0.037	0.017	0.045	0.035	369	775	302	297
Group 2								
Mineral Products	0.015	0.018	0.032	0.033	255	596	127	243
Construction	0.041	0.035	0.043	0.038	16	29	44	74
Group 3								
Hotels and Restaurants	0.022	0.034	0.028	0.035	51	63	47	63
Public Administration	0.041	0.031	0.043	0.036	30	36	39	54
Health	0.033	0.023	0.036	0.026	43	50	49	59
Education	0.053	0.037	0.054	0.041	14	23	31	39
Other Services	0.039	0.025	0.043	0.030	50	65	50	71
Group 4								
Wholesale and Retail Trade	0.040	0.041	0.041	0.046	45	51	48	49
Finance and Insurance	0.028	0.019	0.037	0.024	9	23	37	41
IT and Communication	0.085	0.029	0.078	0.036	8	30	21	44
Business Services	0.022	0.026	0.032	0.031	33	42	43	57
Real Estate	-	-	-	-	-	-	-	-

Table A 12: Sector classification used for presenting the results

Sector	NACE codes (rev. 1.1)
Agriculture, Forestry, Fishing	01, 02, 05
Mineral Products	13, 14, 26
Food, Beverages and Tobacco	15, 16
Textiles, Clothes, Leather	17, 18, 19
Paper, Printing, Publishing	21, 22
Chemicals	24
Metals and Fabricated Metal Products	27, 28
Machinery, Electrical Equipment, Computers	29, 30, 31, 32, 33
Transport Equipment	34, 35
Other Manufacturing	20, 25, 36, 37
Construction	45
Wholesale and Retail Trade	50, 51, 52
Hotels and Restaurants	55
Transport	60, 61, 62, 63
Finance and Insurance	65, 66, 67
IT and Communication	64, 72
Professional Services	71, 73, 74
Public Administration	75
Health	85
Education	80
Other Services	41, 90, 91, 92, 93
Sectors not presented in empirical results	
Energy Producers	10, 11, 23, 40
Real Estate Activities	70
Private households with employed persons	95