

SHIMAA ELKOMY
SIMON MAIR
TIM JACKSON

Energy & Productivity

A REVIEW OF
THE LITERATURE

The **Centre for the Understanding of Sustainable Prosperity** is funded by the UK's Economic and Social Research Council (ESRC). The overall research question is: What can prosperity possibly mean in a world of environmental, social and economic limits?—We work with people, policy and business to address this question, developing pragmatic steps towards a shared and lasting prosperity. For more information, please visit: **cusp.ac.uk**.

Publication

Elkomy S, Mair S and T Jackson 2020. Energy and Productivity: a review of the literature. CUSP Working Paper No 23. Guildford: University of Surrey.

Online at: www.cusp.ac.uk/powering-productivity.

Acknowledgements

This report is a deliverable of the ESRC funded project Powering Productivity (ES/S015124/1). The project used a combination of desk research, surveys and participatory mapping workshops. We would like to thank Roger Bentley, Lina Brand Correa, Paul Brockway, Tim Foxon, Lukas Hardt, Andrew Jackson, Andy Jarvis, Ralf Martin, Mika Minio-Paluello, Roberto Pasqualino, Steve Sorrell, and Dimitri Zenghelis who participated in the workshop and survey providing references and themes, and contributing to the systems maps that framed this synthesis paper. We would also like to thank Andrew Brown, Yannis Dafermos, Roger Fouquet, Ben Gallant, Aled Jones, Maria Nikolaidi, Misato Sato, Stanley G. Smellie, and a number of anonymous participants who participated in the survey, providing references and themes that influenced this paper. The financial support for the Centre for the Understanding of Sustainable Prosperity (ESRC grant no: ES/M010163/1) is gratefully acknowledged.

Contact details

Dr Shima Elkomy, Centre for the Understanding of Sustainable Prosperity, University of Surrey;
Email: s.elkomy@surrey.ac.uk

Dr Simon Mair, Centre for the Understanding of Sustainable Prosperity, University of Surrey; Email:
s.mair@surrey.ac.uk

© CUSP 2020

The views expressed in this document are those of the authors and not of the ESRC or the University of Surrey. This publication and its contents may be reproduced for non-commercial purposes as long as the reference source is cited.



Executive Summary

The UK is experiencing a period of low productivity growth. Although exacerbated by the financial crisis of 2008, the underlying trend is longer and more persistent. Trend labour productivity growth has been declining since the mid-1960s. Conventional understandings fall short of explaining the reasons behind this decline. The quality and availability of energy has been proposed as one driver of productivity growth. However, the links between energy and productivity are mediated by many factors and the relationship is contested.

This report aims to expand conventional understandings of productivity by exploring the literatures which relate productivity to the availability, production and use of energy in the economy. The report is the result of a survey, a desk-based literature review, and a participatory mapping process (Boehnert et al 2019). We provide an introduction to key theoretical issues regarding productivity analysis and review work on the historical relationship between energy and labour productivity. We then review six channels through which it has been proposed that energy and productivity may be related. They are: 1) Capital; 2) Prices; 3) Energy Consumption; 4) Energy Return on Energy Invested; 5) Economic Structure; and 6) Climate Change. Key findings and research gaps are summarised below.

Key finding 1

There are numerous potential links between energy and productivity.

- Researchers have proposed a variety of links between energy and productivity. Key suggested links include the way that capital uses energy, and the way that economic actors respond to energy prices. There may also be more indirect links, particularly through climate change and the quality of the energy supply. Links often cut across physical and social aspects of economic systems.

Key finding 2

There is insufficient empirical evidence to prove or disprove many of the proposed links.

- While many researchers suggest that energy and productivity are linked, there is relatively little consensus in the empirical literatures either confirming or rejecting these views. In some cases (notably the relationship between capital and energy), we do not appear to have robust methodologies for making empirical assessments.

Key finding 3

Mitigating against the negative impacts of energy use may require transformative change.

- Fossil fuel energy use drives climate change, which is itself likely to reduce productivity levels. Reductions in the quality of available energy may also impact productivity in a number of ways. Mitigating these impacts could require transformative changes in the way we use energy, and potentially also a rethinking of productivity growth itself.

Table 1 | Recommended areas for further research.

Research area	Recommended topics for further research
Productivity measurement	<ul style="list-style-type: none"> • Different partial productivity measures give different understandings of the productive process. The literature would benefit from studies of the relationships between different partial productivity measures. • Many productivity measures use a narrow output measure based on market metrics. This dictates a particular relationship with energy. Productivity research would benefit from engaging with a wider set of output measures and associated methodologies.
Long run relationships between energy and labour productivity growth	<ul style="list-style-type: none"> • There is evidence that energy transitions have played some role in long-run productivity growth. However, there is no agreement on how. Further research is needed into the causal mechanisms underlying cultural or institutional shifts that gave rise to the simultaneous increases in fossil fuel use and labour productivity growth that we observe over the long run.
The capital-energy relationship	<ul style="list-style-type: none"> • There is no robust empirical basis for determining whether energy and capital are complements or substitutes. Establishing this key relationship requires us to examine empirical methods at a fundamental level. In particular research is needed that closely examines the core concepts of production theory, and the ways in which they are operationalised. • Likewise, we need more pluralism in the methods and concepts applied in energy-capital debates. Currently there is a homogeneity of methods and metrics that limits our ability to fully explore the energy-productivity relationship
Energy prices and productivity	<ul style="list-style-type: none"> • Further empirical research at the firm level is needed to examine the effects of the change in energy prices on their performance in different economic sectors. • Examination of the short-run adjustment costs associated with the reallocation of labour and their ability to shift from one sector to another due to the changes in the energy prices, specifically in the context of emerging technologies. • Work to clarify questions around asymmetry and the persistence of the relationship of energy prices and productivity.

Energy consumption	<ul style="list-style-type: none"> One way to reduce the potential impacts of energy price or supply shocks is to change our relationship to energy use. Marginal behaviour changes appear to have limited effectiveness. We recommend more research into transformation possibilities of the macro-level social structures that governing energy use.
Energy return on energy investment	<ul style="list-style-type: none"> Changes in energy return on energy investment (EROI) could have significant and long-lasting impacts on productivity. Although a number of potential impacts are clearly set out in the literature, work explicitly linking EROI and productivity is relatively scarce. We recommend further work on EROI-productivity links, particularly how they are mediated by socio-political systems.
Economic structure	<ul style="list-style-type: none"> The services-productivity link. On both an empirical and theoretical level, the issue of how services are linked to productivity is relatively poorly understood – especially in light of emerging technologies. The services-energy-social value link. As of yet it is unclear just how great a potential the service sector has to reduce our energy dependence. Further work in this area should focus on the social structures that drive demand growth for service sector activities, and the link with broader productivity measures beyond market value.
Climate change	<ul style="list-style-type: none"> Systematic comparison of the theoretical assumptions of different climate-economy models with respect to productivity. CGE models appear to find small impacts via productivity, while others find much more substantial impacts. Research into the specific mechanisms by which energy capital may influence productivity. There is little empirical work on the ways that capital may be impacted by climate change or mitigation efforts. Transformational strategies to avoid climate change. A substantial body of work suggests that productivity growth may be driving climate change. Consequently, structural transformation may be required to avoid it.

...

Contents

Executive Summary	1
1 Introduction.....	5
1.1 The context	6
1.2 This Report	8
2 Energy and Productivity: Theoretical Preliminaries	9
2.1 Partial Productivity Measures	9
2.2 Multi-factor productivity	12
2.3 Different types of labour, capital, and energy	13
2.4 Comments on output measures.....	15
2.5 Summary and Gaps.....	17
3 A Historical Perspective on Energy and Productivity.....	19
3.1 Energy and Productivity in the Long Run.....	19
3.2 Coal and The Great Divergence	20
3.2 Summary and Gaps.....	23
4 Capital as an energy-productivity mediator	24
4.1 Capital and Energy: substitutes or complements?	24
4.2 Do empirical studies find energy and capital to be substitutes or complements?	27
4.3 The Challenge of Constructing Capital Datasets.....	31
4.4 Model Structure.....	34
4.5 The focus of the model	36
4.6 Summary and Gaps.....	37
5 Energy Prices and Productivity	38
5.1 Energy-Productivity: Inflation	39
5.2 Uncertainty and Expectations	42
5.3 Adjustment Costs	42
5.4 Energy, Capital and the Marginal Productivity of Labour	43
5.5 Summary and Gaps.....	45
6 Energy Consumption	46
6.1 Energy and Behaviour	46
6.2 Energy and Societal Structures.....	48
6.3 Energy and the Rebound Effect	48
6.4 Summary and Gaps.....	50
7 Energy Return on Energy Invested.....	50
7.1 EROI Trends	51
7.2 Implications of a Declining EROI for Productivity	51
7.3 Summary and Gaps.....	54
8 Economic Structure.....	55
8.1 Energy use and the Service Sector	56
8.2 The Service Sector and Productivity.....	58
8.3 Summary and Gaps.....	60
9 Climate Change and Productivity	60
9.1 Productivity in Climate-Economy Models.....	61
9.2 Labour Productivity and Heat.....	63
9.3 Capital Productivity and Climate Change	67
9.4 Increasing investment in Renewable Energy and Kaldor-Verdoorn effects.	68
9.5 Innovation for a low-carbon economy and productivity	69
9.6 Productivity as a driver of Climate Change	71
9.7 Summary and Gaps.....	72
10 Conclusions.....	74
References	76

1 | Introduction

Britain is experiencing a period of persistently low labour productivity growth (McCann 2018, Jackson 2019a). Conventional responses to this ‘productivity puzzle’ point to the impact of the financial crisis in 2008/9. But analysis of the data suggests that the decline in labour productivity growth has been going on since the mid-1960’s (Figure 1), confounding both policy prescription and academic understanding. Some of the explanation for this decline might lie in new set of challenges faced by advanced economies in recent years. For example, in the past, technological innovation has been vital in terms of increasing productivity growth, but some economists are sceptical of the potential for current technological advances to fulfil this role (Gordon, 2017). However, it is also worth noting that many of the current explanations for the productivity puzzle have been mooted since the 1960s. For example, in 1966 Cambridge economist Nicholas Kaldor pointed to (and rejected) a number of common explanations for the UK’s declining productivity growth. Many of these reappear in the UK government’s recent industrial strategy (Table 2). Either we have made little progress in tackling these issues in the intervening half century, or we have missed a key element of productivity. In this report we explore the role that energy plays in mediating productivity growth and ask whether this relationship could provide some explanation for the missing link.

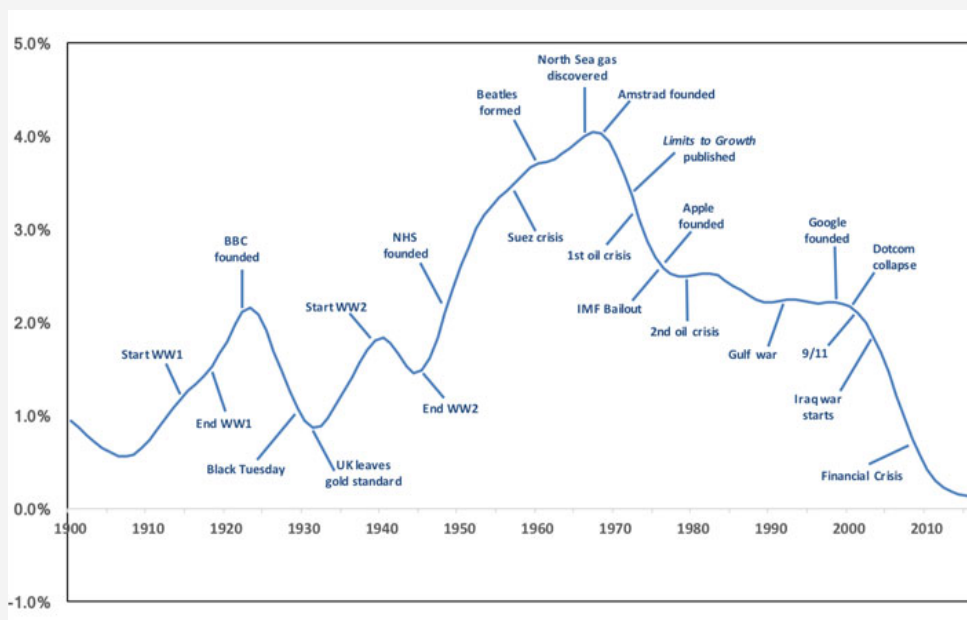


Figure 1: Labour productivity growth in the UK 1900 – 2016.

(Source: Jackson 2019b).

Kaldor's (1966)	UK Industrial Strategy (2018)
"...the nature of our education giving too little emphasis to science and technology" (p. 2)	"...we have given insufficient attention to technical education. We do not have enough people skilled in science, technology, engineering and maths" (p. 94)
"the insufficiency of investment..., or of the right kind of investment" (p. 2)	"...we still invest comparatively little. Business investment in R&D in the UK is relatively low" (p. 61)
"the inefficiency of our business management" (p. 2)	"Studies suggest that the average UK manager is less proficient than many overseas competitors, while management skills could account for a quarter of the productivity gap between the UK and the US." (p. 169)

Table 2: Explanations for poor UK productivity growth in 1966 and 2018
(Taken from Kaldor, 1966 and BEIS, 2018)

1.1 The context

There are substantial bodies of work that link energy and productivity. During the two oil crises of the 1970s, real terms oil prices grew by 221% and 115% (Figure 2). These spikes in energy prices preceded dramatic slowdowns in worldwide productivity growth. Consequently, the mainstream of the economics profession began to look in earnest at links between energy and productivity growth (e.g. Berndt and Wood, 1975, 1986, Baily, 1981, Jorgenson, 1982). Since then there has been substantial debate over the size and importance of any effects that energy price may have on productivity growth, as well as the channels through which they may operate.

The physical aspects of energy provision have also been linked to productivity growth. Over the long run, labour productivity growth and energy use have been closely correlated (Jarvis, 2018). Some economic historians and ecological economists argue that this is because labour productivity growth has relied on the use of energy (Wrigley, 2016). It has been argued, for example, that the discovery of coal, allowed the

development of new machinery and ways of organising production which made production much more efficient (Malm, 2016, Foxon, 2017).

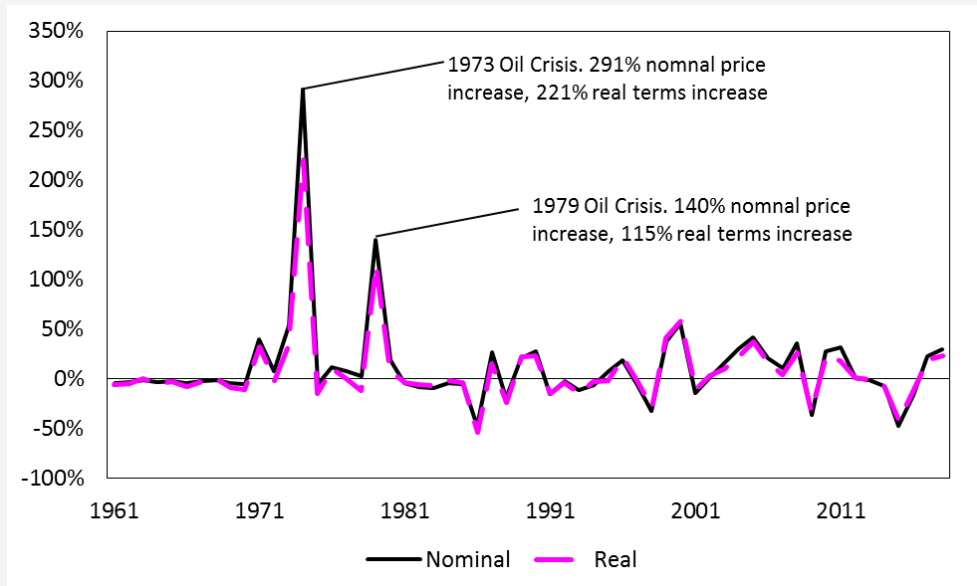


Figure 2: Annual growth rates in the average spot price of Brent, Dubai and West Texas Intermediate crude oil, equally weighed.

Data from World Bank Commodity Price Data (The Pink Sheet).

Today energy is still sometimes proposed as an answer to the productivity puzzle. In addition to more usual concerns, the UK industrial strategy does make indirect links to energy. Notably it makes infrastructure commitments of more than £30 billion, a substantial portion of which relate to energy provision (BEIS, 2018, 2017). This is framed by the UK government as a massive investment in renewable energy in response to climate change.

Climate change is an important part of the context for this report. The global energy system relies heavily on fossil fuels. Figure 3 shows that between 1900 and 2014, global use of all fossil fuels has grown dramatically. Use of fossil fuels is a key driver of climate change. Climate change has been linked to negative impacts on productivity growth (e.g. Kahn et al., 2019), and through this relation to broader macro-economic challenges (Dafermos et al., 2017, Lamperti et al., 2018). In addition, avoiding catastrophic climate change requires a huge shift in the energy base of both the British and global economy (Wrigley, 2016, Smil, 2017, UK Committee on Climate Change, 2019). Consequently, if there is a link between the supply and use of energy,

then our response to climate change is likely to have wider economic impacts.

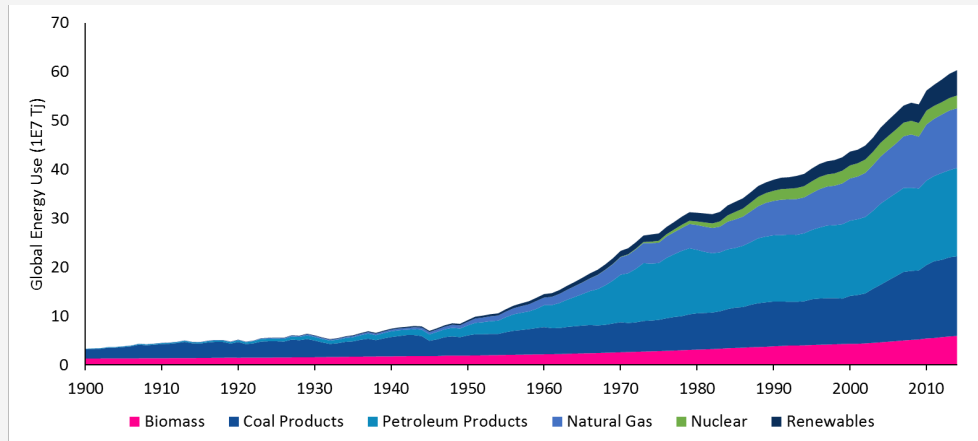


Figure 3: Primary energy use by carrier 1900-2014.

Data from De Stercke (2014)

1.2 This Report

The links between energy, energy prices, and productivity are not clear cut. This is because these relations are mediated by many factors, any one of which may disrupt, hide or enhance links between the three concepts. Various authors have wrestled with the numerous political, cultural and social factors that mediate physical and economic components of an energy-productivity link (Jackson, 2019b, Berndt and Wood, 1986, Georgescu-Roegen, 1979, Mohaddes and Pesaran, 2016, Kallis and Sager, 2017). However, there is in general a split between those communities that focus on the physical aspects of energy and its relation to the economy, and those that focus on factors such as politics and price (Kallis and Sager, 2017). In this report we aim to map the wide ranging literatures on each of these areas and point to possible connections between the two.

At a workshop held in the summer of 2019, we brought together researchers from a wide range of disciplines to discuss the energy-productivity relationship. What emerged was a complex picture of productivity and energy as interconnected. Participants felt that productivity was a function of social structures (such as technology, the state, markets and the financial system), subjective interpersonal and cultural beliefs (such as the

expectations of economic actors and the collective construction of social value) and the physical characteristics of the energy supply and its interaction with the environment. The discussion was used as the basis for a visual representation (giga-map) of the relationship between energy and productivity (Boehnert et al 2019).

In this report we set this picture in the context of the existing literature. Section 2 sets out key theoretical links between energy and productivity measurements. Section 3 outlines debates in economic history as they relate to energy. In section 4, we turn to the role that capital may play in the energy-productivity relationship. Section 5 explores the literature on energy prices and links to productivity. In section 6 we discuss the role of energy consumption. Section 7 reviews work linking the Energy Return on Energy Invested (EROI) and productivity. In section 8, we turn to the issue of economic structure and energy dependence. Finally, in section 9, we discuss how the energy system impacts climate change and the evidence base on the ways that climate change (and our responses to it) may then impact productivity.

2 | Energy and Productivity: Theoretical Preliminaries

Productivity refers to a ratio of outputs to inputs. Productivity growth is the increase in outputs over and above what we would expect from a change in the quantity of the inputs. When measuring productivity, we are free to choose almost any measure of input and output. Here we provide a brief introduction to different inputs and outputs.

2.1 Partial Productivity Measures

One of the most widely used productivity measures is labour productivity, where the output measure is GDP, and the input measure is hours worked or people employed. It is particularly widely used by policymakers. For example, the UK industrial strategy only provides productivity figures in terms of GDP per hour worked or GDP per capita (BEIS, 2018). Labour productivity also occupies a central place in the history of economic thought with Adam Smith (1776) making labour productivity the centre of his growth theory (Schumpeter, 1954/2006, p. 182). Labour productivity also plays an important role in analyses of the distribution of income (Griffell-Tatje et al., 2018a).

Labour productivity is an example of a partial productivity measure. It is partial in the sense that most theories of economic production suppose that

production relies on multiple elements. This is exemplified by the system of production approach, which analyses production as a function of labour, machinery, land, intermediate goods, and social relations (such as structures of ownership) that surround these factors (Kurz and Salvadori, 1995, Kurz, 2006). From this perspective, measuring productivity in terms of labour alone can only ever give us a partial image of the production process. However other partial productivity measures based other elements of production can provide complementary pictures of the productive process.

Capital productivity, measured as GDP per unit of capital, is taken as a reflection of the contributions of capital to production (OECD, 2015). Like labour productivity, capital productivity has played a central role in the history of economic thought. After the classical economists (Smith, Ricardo, and Marx) came the American marginalists. The classical economists considered capital an extension of labour, while the marginalists argued that capital was distinct from labour and productive in its own right (Kurz and Salvadori, 1995, Pirgmaier, 2019).

GDP per unit of resource or energy use per have also been used as a productivity metric. This is particularly common within environmentally focussed fields of study. Gollop and Swinand (1998) propose a framework for measuring resource productivity and suggest it can be used to assess how production impacts the environment. More recently, Steinberger and Kraussman (2011); Giljum et al., (2014); Wiedmann et al (2015) and Schandl et al. (2018) explore trends in resource productivity. In general, they find that resource productivity is sensitive to system boundaries and indicator selection. Measured as the energy or resources used within an economic boundary, energy and resource productivity has tended to increase over recent decades. However, if ‘embodied’ energy or material resources are accounted for the picture is often more nuanced. Embodied energy is energy used in the production of imports that are then used by a given nation in their domestic production processes. Inclusion of embodied factors tends to reduce productivity growth measures.

Capital and labour productivity are much more commonly used than energy or resource productivity measures. For example, in the Economic and Social Research Council’s flagship productivity project the Productivity Insights Network (PIN), energy is not considered in any detail. Energy receives only a passing mention in PIN’s infrastructure report (Docherty and Waite, 2018), and does not appear at all in their synthesis report (McCann, 2018). Likewise, *The Oxford Handbook of Productivity Analysis* (Griffell-Tatje et al., 2018b), does not have an entry for ‘energy’ in its index. This is surprising given that the handbook includes a chapter on the environment, and one introducing

the KLEMS framework (the ‘E’ in KLEMS stands for Energy!). References to electricity in the handbook focus on the characteristics of the energy sector as regulated industry, rather than electricity as an energy carrier. By contrast, labour and capital receive detailed treatment across multiple chapters and have detailed index entries. Institutional measures of productivity also tend to look past energy. For instance, the UK office for national statistics provides estimates of labour, capital and ‘multi-factor’ (a residual) contributions to output growth in the UK. It does not consider energy as a standalone contributor (Franklin, 2019).

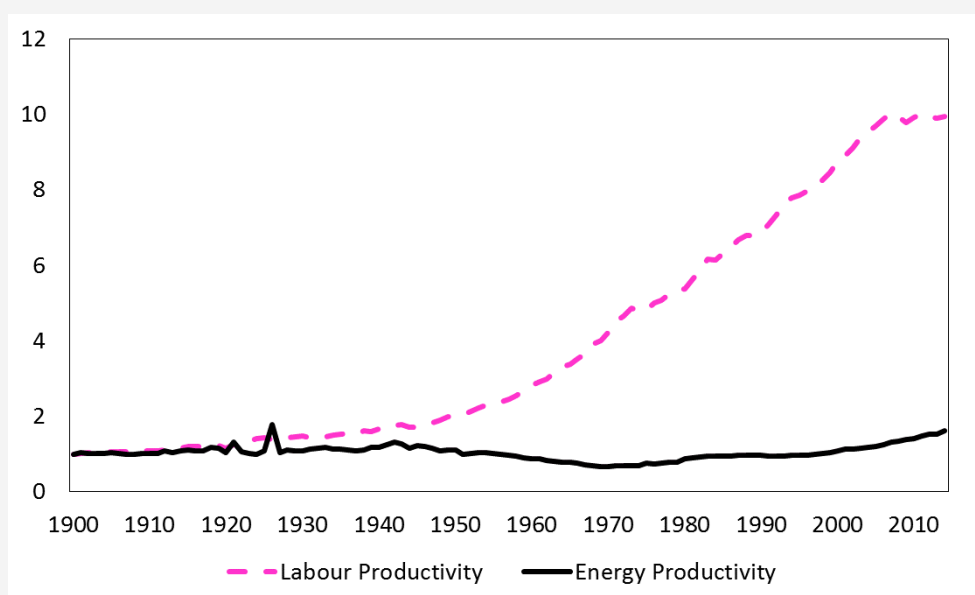


Figure 4: GDP/hours worked and GDP/Useful Exergy for the UK.

Data from Bank of England (2019) and De Stercke (2014). For definitions see Section 2.3.

The choice of partial productivity measure is relevant to the question of the energy productivity relation because different productivity measures show different trends and point us in different policy and research directions. For instance, Figure 4 plots the growth in labour productivity vs the trend in energy productivity, and Figure 5 plots their respective growth rates. Here we can see that labour productivity growth has consistently outpaced energy productivity growth and periods of high labour productivity growth have been accompanied by periods of negative energy productivity growth.

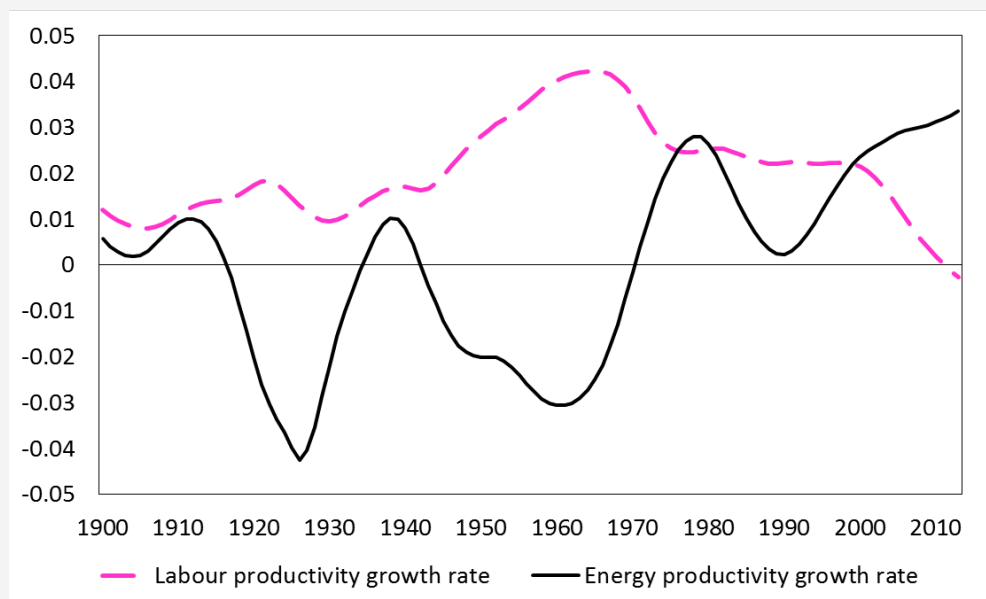


Figure 5: Growth rate of GDP/hours worked and GDP/Useful Exergy for the UK.

Data from Bank of England (2019) and De Stercke (2014). For definitions see Section 2.3.

2.2 Multi-factor productivity

Multi-factor productivity is an attempt to remedy the partial nature of indicators such as labour, capital and resource/energy productivity. It is derived from the marginalist economic tradition (Abbott, 2018). The theory underlying multi-factor productivity sees production as the result of a combination of different inputs but says that the contribution of each input can be determined in isolation from the others.

Multi-factor productivity, also known as ‘total-factor productivity’ measures a change in output after changes in all individual inputs (measured in value terms) to production have been accounted for. Franklin (2019) describes the theory of multi-factor productivity growth as a measure of the ways in which various inputs are employed. But he notes that in practice multi-factor productivity also reflects measurement errors.

In multi-factor productivity analysis, the individual contribution of a given factor of production to output is given by the marginalist theory of distribution. This theory says that any element of production will be paid (by a rational actor), that value which it adds to production. This is most clearly set out by John Bates Clark (1908):

“The effective value of any man to his employer is what would be lost if he were to cease working. That amount—the effective product of any man in the force—sets the standard to which the pay of labor generally conforms...Employers of capital must pay for the final increment of it just what that increment produces, and they must pay for all other increments at the same rate”.

Franklin (2018) provides an account of how marginalist theory is applied in a modern context. Based on the reasoning set out above, different categories of labour are valued at their wage rates, because: *“highly-paid footballers create more value than the ground staff”* while capital’s contribution to production is based on an estimate of what it would be rented for in a perfectly competitive market. In essence we assume that the ‘wages’ paid to any given element of production are determined by its marginal productivity. Consequently, we can look at how the productivity or quantity of each individual factor of production changes over time (because we know their marginal productivities). Any additional productivity gains are captured in a residual. We call this residual ‘multi-factor productivity’.

Multi-factor productivity measured in terms of GDP or gross economic output is very widely used and often incorporates a measure of energy use. Perhaps the most widely used framework is the KLEM framework. This forms the basis of most of the studies reviewed in section 4.4. KLEM refers to four inputs, typically understood as two ‘primary’ factors of production, capital (K) and labour (L), and two intermediate inputs, energy (E) and materials (M). More recently, substantial empirical work has focused on building large KLEM databases and expanding KLEM to add an explicit services component (S). There are now KLEMS databases for the European Union, Latin America, and Asia¹. Jorgenson (2018) provides an overview of these initiatives, while O’Mahony and Timmer (2009) provide a detailed account of the construction of the EU data set.

Multi-factor productivity analysis traditionally considers labour and capital, but can also be extended to other factors, typically energy and materials. Multi-factor productivity analysis is the basis of much modern productivity accounting. Notably, it forms the basis of the production function analyses we review in Section 4.2.

2.3 Different types of labour, capital, and energy

It is useful here to introduce different metrics that can be used in both partial and multi-factor productivity measures. A landmark article in modern productivity analysis is Solow’s (1957) paper. In this paper Solow

¹ | Links can be found at <http://www.worldklems.net/data.htm>

uses a Cobb Douglas production function to decompose labour productivity growth into two component parts: growth of capital and ‘technical change’. He concludes that 87.5% of labour productivity growth between 1909 and 1949 is due the latter. This result was widely deemed to be unsatisfactory. Despite the terminology, ‘technical change’, Solow’s model left a lot to be explained. Solow’s ‘technical change’ (and its younger sibling: total factor productivity) has been referred to as a “*measure of our ignorance*” (Abramovitz, 1956, Hulten, 2001, Santos et al., 2018). In order to reduce our ignorance analysts have added new components to Solow’s framework and made adjustments to its core components.

A common approach is to add more detailed descriptions of labour and capital (Crafts, 2009). One popular form of this is to make adjustments for different qualities of labour and capital (Franklin, 2019, 2018, Barnett et al., 2014, Goodridge et al., 2016). We have already introduced this briefly: the UK Office for National Statistics differentiates between different types of labour on the basis of their wages, for example (Franklin, 2018). They also produce quality adjusted labour series based on education level (Johannsson, 2017).

Capital measures can also be quality adjusted. However, as we will cover in more depth in Section 4.3, measurement of capital is complicated by a number of factors. Notably, within economics capital is simultaneously a measure of income and wealth, and of production and productivity (OECD, 2009, O’Sullivan, 2017, Mair, 2018). The standard measure of capital is an estimate of the value of capital based on what was paid for it, or an estimate of its future profit generation. However, in their guide to capital measurement, the OECD (2009) argue that for productivity analysis measures of capital should be adjusted to better reflect its ‘productive characteristics’. Once adjusted, these are known as measures of ‘capital services’. They attempt to account for the loss of efficiency of capital goods in terms of their production capabilities. In Section 4, we review a variety of studies that have used adjusted and unadjusted measures of capital and cover the methodology for these in some detail.

Though substantially less common than adjustments to labour and capital, a number of energy economists have developed and adapted concepts from the physical science analysis of energy, in order to quality adjust energy metrics (Ayres and Warr, 2005, Warr et al., 2008, Ayres et al., 2013, Ayres and Voudouris, 2014). In particular it is useful to be aware of the energy conversion chain.

The energy conversion chain describes the transformation of energy from primary sources (raw fuels, such as coal), to the delivery of final energy

services (such as heating a house), accounting for the conversion and process losses between the two stages (Grubler et al., 2012). Primary energy is a measure of energy before it has been converted or transformed (OECD, 2001). An example of primary energy would be coal. This primary energy then goes through a number of conversion steps. For example, it may be turned into electricity (secondary energy), which is then distributed to households, where it becomes final energy. Once in the household that electricity then enters appliances where it is converted from electricity into an energy service, such as light or heat.

An energy metric that is analogous to quality adjusted capital and labour is ‘useful exergy’ (Miller et al., 2016, Brockway et al., 2019a). Exergy can be understood as the capacity of energy to do physical work. Exergy is independent of the appliance used to convert the electricity into an energy service: it is a theoretical maximum based on thermodynamic principles. ‘Useful’ exergy is defined as the portion of the theoretical maximum exergy that actually performs a useful service. It is determined by the theoretical limits on exergy and the efficiency of the final conversion device. An example of useful exergy is the portion of the energy inputs that actually generates the heat warming a house, vs that lost to the area around the house (Brockway et al., 2019a).

Relatively few studies have attempted to use both quality adjusted capital and labour and useful exergy. A notable exception are Santos et al. (2018) who use quality adjusted labour and capital measures and useful exergy. They argue that their analysis shows energy is central to economic growth.

2.4 Comments on output measures

Although beyond the scope of this report to explore in full detail, it is worth commenting on the fact that most applications of productivity measures focus on market output, typically in the form of GDP. For example, the UK industrial strategy principally discusses productivity in a commercial context and only provides productivity figures in terms of GDP per hour worked or GDP per capita (BEIS, 2018).

Likewise, standard productivity analysis tools were developed to explore market dynamics. As a result, non-market activities are difficult to analyse in standard productivity frameworks (Griffell-Tatje et al., 2018a, Diewert, 2018). This is not surprising, most productivity analyses today draw heavily from the marginalist tradition, which takes the market as its starting point (Nelson, 1995, Foster, 2016, Raworth, 2017). Feminist and ecological economists have argued that market starting points specifically exclude the

value created by nature and the work traditionally done by women (Dengler and Strunk, 2017, Saunders and Dalziel, 2017, Rentschler et al., 2018). Where non-market activity does enter productivity analysis, the analysis often attempts to adapt market principles, rather than start afresh.

There are a number of conceptual problems associated with adapting market frameworks to deal with non-market goods. As Diewert (2018) points out, markets have specific dynamics and there is no reason to believe that non-market processes conform to these dynamics. Bringing a good or service into a market changes our relationship to the good or service (Sandel, 2012). Once a good has been commodified we are interested in it not only for how we might use it but also how we might exchange it. Market goods are stores of wealth as well as useful items in their own right (Marx, 1873/2013). By contrast, nonmarket goods are not typically exchanged. Therefore, it is their use or intrinsic value that is of interest to us. The process of bringing a good into a market is known as commodification. It is a multi-factor process of enabling exchangeability via money. Amongst other factors, commodification emerges from the establishment of property rights and changes in the logics of valuation being applied to a good (Castree, 2003, Victor, 2019).

A market focus can lead to the exclusion of non-market factors from the output side of productivity analysis altogether. A good example of this is Firfiray et al.'s. (2018) analysis of the labour productivity of family firms. They discuss the fact that many family owned firms have multiple objectives beyond production of market value. Firfiray et al., define this “socio-economic wealth” produced by family firms in terms of social ties, emotional attachment, and family bonds. But this distinct form of nonmarket value produced by family owned firms is not taken as a relevant output measure for productivity. Rather, Firfiray et al., ground themselves in the multi-factor productivity literature discussed above. This uses market output measures. Their analysis then looks at how such market measures of value will be impacted by firm attempts to produce non-market value. Non-market value is therefore positioned as secondary to the production of market value, and the latter remains the object of productivity analysis.

It is notable that the exclusion route has tended to be the path taken by psychologists who have engaged substantially in work on the relation between wellbeing and productivity. As is evident in our review of the literatures on the wellbeing-productivity link (Isham et al., 2020). Most work in this area focuses on ways that improvements in wellbeing can be used to improve productivity understood in exchange value terms.

Wellbeing is rarely considered an appropriate output measure for productivity analysis.

This is all relevant to the question of how energy and productivity are related because the output measure of productivity can fundamentally change the role of energy in the analysis. As we will discuss in more detail in Section 6, our use of energy can be conceptualised in terms of having particular needs met. Markets are one way of meeting our energy needs, but others have been proposed (Brand-Correa and Steinberger, 2017). It is possible that by focussing only on market measures of output, we are missing a key part of the energy-productivity picture. This is visualised in Figure 6 which plots energy productivity in terms of both market output and a wellbeing measure (based on disability adjusted life years²), as an example of a non-market output measure. We can see a striking divergence between the two over the time period.

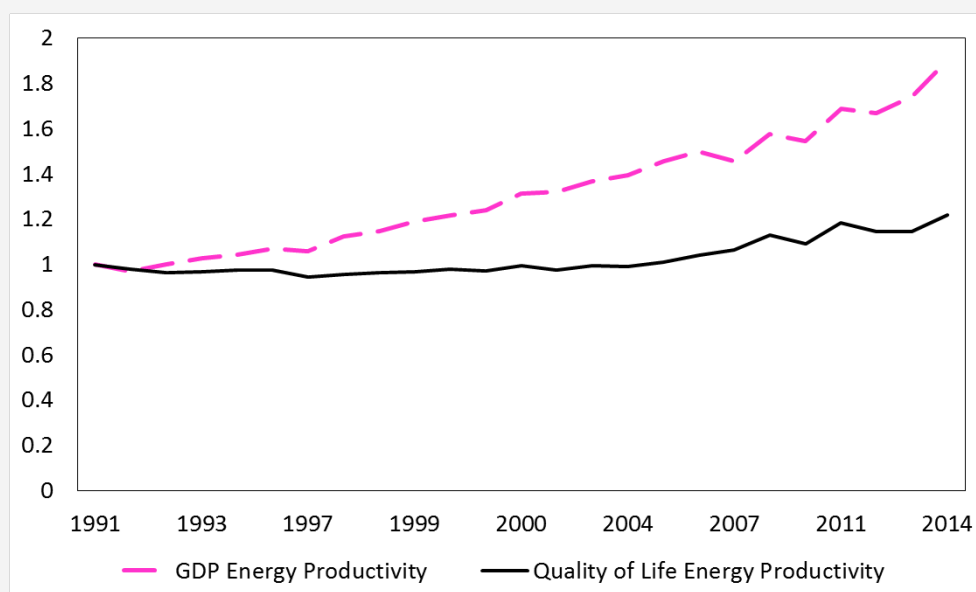


Figure 6: GDP/Useful Exergy vs DALY⁻¹/Useful Exergy.

Data from De Stercke (2014) and WHO (2016)

² | DALY stands for Disability Adjusted Life Years. It is a measure of years of high quality life lost due to disability. We use it here because it is broadly comparable to GDP, in that it is additive across the whole economy (in ways that, for example, self-reported happiness is not). As DALY is a negative measure (i.e. a higher DALY means more years lost, which has a negative impact on wellbeing), we use its inverse as our numerator.

2.5 Summary and Gaps

Productivity is measured in many different ways. At a high level it is a measure of inputs over outputs. Productivity growth is a measure of how outputs change relative to inputs over time. Partial measures of productivity relate output to just one element of production. This is usually labour or capital but can also be an energy or resource measure. Multi-factor productivity attempts to present a more complete picture of productivity growth. Based on a theoretical relationship between inputs and outputs, it decomposes productivity change into changes in particular inputs, and a residual which measures the changes that cannot be attributed to changes in one individual factor. Multi-factor productivity analyses often include energy via the KLEMS framework.

Within both partial and multi-factor productivity analyses, analysts must choose what metrics to use. Different metrics lead to different narratives about productivity. When using labour, capital, and energy, there are choices to be made around just how these are measured. Quality adjusted measures of capital and labour are available. Energy analysts must choose where on the energy conversion chain they draw their energy measure from. Relatively few analysts use quality adjusted measures of capital and labour and

Most productivity analyses use market measures (GDP, or gross output) as their output measure. This means that much productivity analysis has a narrow focus that may exclude other ways of meeting our needs with respect to energy. Using different output measures may change our understanding of productivity and its relationship to energy.

Based on the literature, we recommend the following areas for further research:

1. Different partial productivity measures give different understandings of the productive process. The literature would benefit from studies in the relationships between different partial productivity measures.
2. Many productivity measures use a narrow output measure based on market metrics. This dictates a particular relationship with energy. Productivity research would benefit from engaging with a wider set of output measures and associated methodologies.

3 | A Historical Perspective on Energy and Productivity

Amongst economic historians it is widely accepted that the 300 year trend in productivity growth we have seen since the industrial revolution is in part due to the transition from an economy dominated by wood and water, to one dominated by fossil fuels (Wrigley, 2016, Malm, 2016, Debeir et al., 1991, Pomeranz, 2000, Hall and Klitgaard, 2012). In this section we introduce some of the evidence for this argument, and then review subsequent debates over just how fossil fuels came to boost labour productivity growth

3.1 Energy and Productivity in the Long Run

Over the long run, energy appears to be closely linked to growth in economic activity. Figure 7 shows the close relationship between labour productivity measured as global Gross Domestic Product (GDP) per capita and global primary energy use since 1900. GDP is a measure of the market value of all goods and services produced in the economy at a given point in time (ONS, 2016). Primary energy is a measure of energy before it has been converted or transformed (OECD, 2001). Using the same dataset that we use to construct Figure 1, Jarvis (2018) shows that the growth rates of global GDP and global primary energy use have growth rates that are statistically indistinguishable from one another: global primary energy use has grown at $2.7 (\pm 0.04)$ percent per year since 1900, while global GDP has grown at $3.1 (\pm 0.04)$ percent per year over the same period.

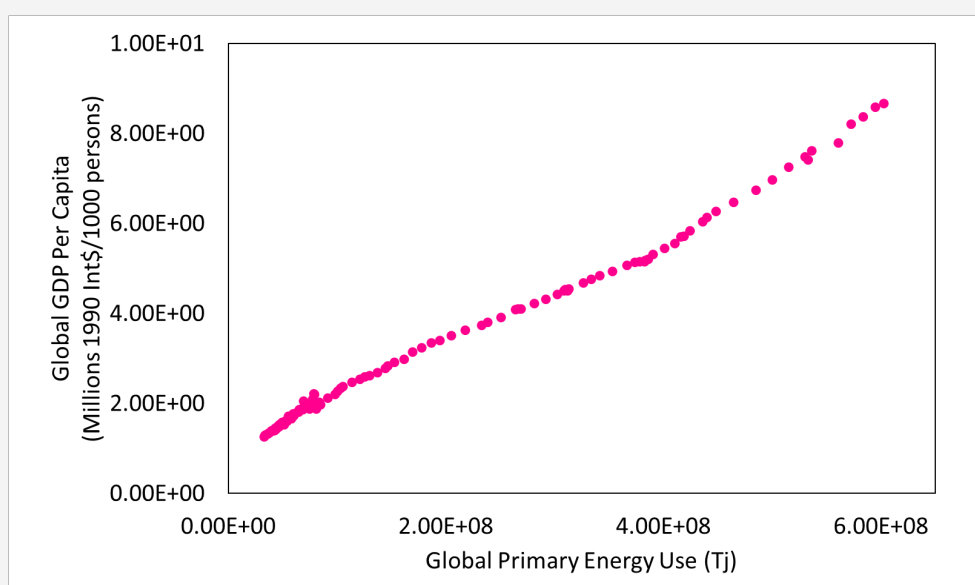


Figure 7: Long run relationship between global primary energy use and labour productivity.
Data from (De Stercke, 2014)

Although constructing reliable long run datasets is challenging, there is evidence that there may have been a link between energy and labour productivity growth prior to 1900. Figure 8 shows English coal use and labour productivity between 1561 and 1859. Over this period there was a widespread uptake and use of fossil fuels, which expanded the pool of energy that could be used to produce material goods (Otojanov and Fouquet, 2018). Historians suggest that this enabled the industrial revolution to improve labour productivity through the introduction of new machinery and ways of organising labour (2016, Malm, 2016, Wrigley, 2010). However, there is little agreement over just how, or why, this transition occurred.

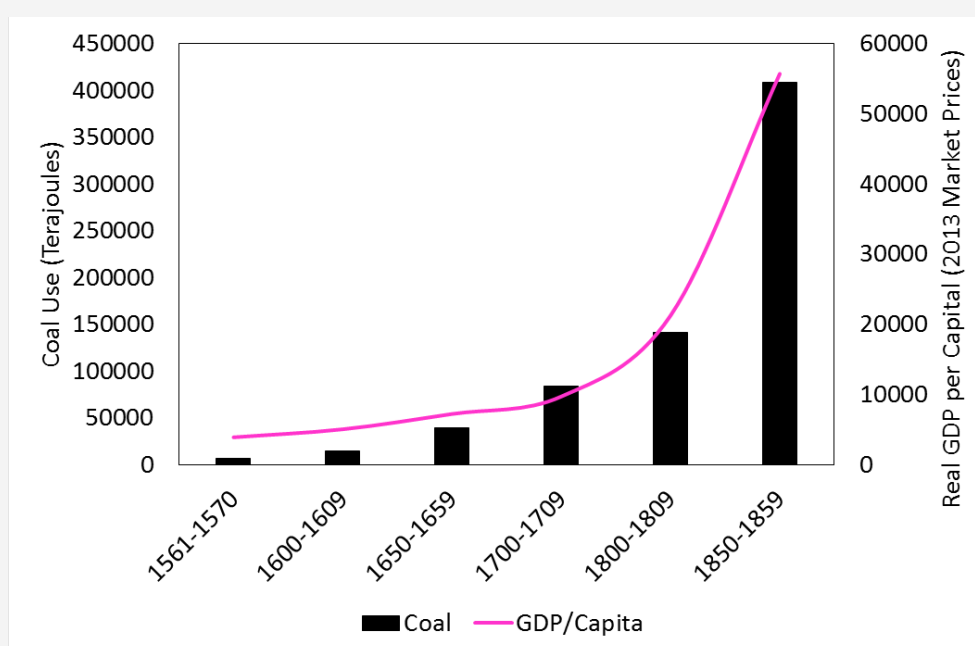


Figure 8: English Coal use and GDP per Capita between 1561-1570 and 1850-1859.
Coal data from Warde et al., 2007, and GDP per Capita data from Bank of England 2016.

3.2 Coal and The Great Divergence

The question of how energy use and long run productivity growth may be linked has been a key part of ‘the great divergence’ debate. This term was brought to prominence by Kenneth Pomeranz, in his book of the same name (Pomeranz, 2000). It has been widely used by the historians working in the ‘Californian School’ of economic history (so named because most of the authors writing in this tradition worked at universities in California, see de Vries, 2010 for more details).

The great divergence refers to an apparently sudden shift in key economic dynamics. The precise dates are heavily debated (Broadberry et al., 2018), but the narrative for historians in the Californian School is that until sometime in the 16th-18th centuries, economies in the East and West either had comparable levels of economic development, or the East, notably China, was substantially more economically developed than the West. Then, something happened and the West (principally England) ‘took off’ suddenly achieving rapid and sustained economic growth in terms of both output and living standards.

Pomeranz (2000) follows historical demographer EA Wrigley (2016, 2010, 2013) in explaining why coal must have been important: to run the machinery required for the industrial revolution in England, would have required around a huge amount of forest over and above that which existed in Britain at the time. Pomeranz suggests that somewhere between an additional 15 and 21 million acres (equivalent to about 25-35% of the total area of Britain). Pomeranz notes that the use of coal required machinery, such as the steam engine, and well-developed markets in order to incentivise use of machinery to increase output. Both these conditions were met in parts of China as well as Britain. The key difference in Pomeranz’s (2000) narrative is one of “*geographic accident*” (p.62).

Pomeranz (2000) argues that the great divergence can in large part be explained in terms of how easy it was to access coal deposits. In his narrative, British coal mines were located close to water which made the coal relatively easy and cheap to transport. Moreover, coal deposits in Britain were geographically very close to commercial centres. On the other hand, major coal deposits in China were located a long way from commercial centres and away from water transport. Pomeranz also argues that the location of coal deposits in China meant that they were so arid that they threatened to spontaneously combust. By contrast the climatic challenge faced by British coal mines was that they were wet and had to have water pumped out of them – a much simpler task. However, Pomeranz’s account of the role of coal is far from accepted. A number of others argue that ease of access was less important than the social context of the coal.

De Vries (2001) critiques Pomeranz for ignoring the role of culture almost entirely. Resources like Coal, de Vries argues, only become ‘resources’ by virtue of their social context, otherwise they just remain in the ground, unused (2010, 2001). For de Vries, it is not enough to explain why it was

more convenient for Britain to use coal, than it was for China. What is needed is an account of why either of Britain or China would recognise coal as a resource to be used in the first place. Two such accounts are found in alternative perspectives on the development of capitalism.

On such account is found in McCloskey (2010). For McCloskey the central driver of the great divergence was what she calls the cultural shift towards what “bourgeois values” in England. This value shift meant that entrepreneurs went from being looked down upon, to being highly-respected. McCloskey argues that this shift in cultural opinion made it attractive to be an entrepreneur, and in turn this injected the dynamism into the British economy which was necessary for the widespread uptake of fossil fuel energy sources.

An alternative perspective is found in Marxist works that position the consolidation of capitalist social relations as the central turning point in how energy was used. For Malm (2016), fossil fuels came to be used in a big way because they offered new tools of social control. Unlike the relatively distributed energy provided by wood and water, fossil fuels required large scale, highly centralised production to work effectively. Consequently, fossil fuels offered not only a direct productivity improvement by providing more energy output per unit of fuel, but also enabled new organisational forms, such as factories. Under these new ways of organising the workforce, Malm argues, workers could be more actively controlled and managed and therefore made more productive.

On the other hand, Debeir (1991) and Mair (2019) both argue that the central way that capitalist markets drove fossil fuel use was by creating a context in which there was pressure and incentives for firm to grow their productivity and expand their production. In these accounts capitalist markets force firms to compete on the cost and scale of production and fossil fuels proved a useful means to this end. By contrast, in pre-capitalist China the use of coal had a different social context and consequently:

“...did not create new social needs, did not constantly push the borders of its own market outwards...proto-industrialisation and economic growth were remarkable achievements but failed to generate an accelerated division of labour.” (Debeir et al., 1991).

In the accounts of Debeir et al. (1997), Mair (2019), McCloskey (2010), and Malm (2016) there is a cultural shift that comes with the rise of capitalism

and this new culture drives fossil fuel use into productivity growth. However, there are other accounts that see the channelling of fossil fuels into productivity growth as a more organic process.

For Allen (2009) fossil fuel use boosted labour productivity growth because of the relative cost of labour and coal in pre-industrial England. According to Allen, wages in Britain were relatively high compared to the price of coal, whereas in China, this relationship was reversed. In Britain, Allen argues, the unique combination of high wages and cheap energy incentivised innovation that would reduce the amount of labour used in production at the expense of the relatively cheaper factor of production: coal.

Finally, we turn to Parthasarathi (2011) who emphasises the role of the state in his discussion of why coal became widely used in Britain but not China. For Parthasarathi the key difference between Chinese and British coal use was the attitude and goals of the two states. In Britain, he argues, coal had become an essential commodity for the population of London, where it was used extensively to heat homes. At the same time, coal was used in the manufacture of military equipment. These two facts meant that the British state actively intervened in the British coal industry to ensure its continued production and to discourage its export. By contrast, Parthasarathi argues that in China the state did little to support the use of coal. Consequently, in Parthasarathi's account it was active state intervention on the part of Britain that led to widespread coal use and productivity growth.

3.2 Summary and Gaps

Long run datasets suggest a correlation between energy use and labour productivity. Economic historians are in broad agreement that the transition from an economy based on water and wood, to one based on fossil fuels was key to driving labour productivity growth.

Disagreement comes in analysis of why there is a correlation between energy use and labour productivity growth over the long run. Factors that have been suggested by economic historians include socio-economic shifts like the rise of capitalist markets, or changes in the social status of entrepreneurs. Alternatively, others see the link as an organic outgrowth of pre-existing systems. In these narratives the sudden uptake of fossil fuels is down to factors such as relative price differentials (energy being cheaper than labour), or choices made by the state. There is no consensus position on the

defining factor in the long run relation between energy and labour productivity.

Based on the literature we suggest further research on to the causal mechanisms underlying cultural or institutional shifts that led to the increase in fossil fuel use and productivity growth.

4 | Capital as an energy-productivity mediator

Ecological Economist Herman Daly writes that: “*physical capital is essentially matter that is capable of trapping energy and channelling it to human purposes*” (Daly, 1968, p. 397). If this is the case, we would expect capital productivity to be impacted by changes in the energy supply, or in the way that an existing energy supply is used. In this section we elaborate these mechanisms in more detail and evaluate the evidence to support them.

4.1 Capital and Energy: substitutes or complements?

One of the key questions in the energy-capital relation is of substitutability and its opposite concept, complementarity. We review the nuances of substitutability definitions in section 4.4. However, it is worth being aware of the headline definitions of substitutability and complementarity.

We can understand substitutability in terms of both prices and quantities (Seidman, 1989, Stern, 2011). Two goods are *price* substitutes if an increase in the price of good A, leads to increased expenditures on good B. Two goods are price complements, if an increase in the price of good A leads to a decrease in expenditures on good B. The intuition here is that if good A and good B perform the same role in a production process, then they are substitutes. So a firm will swap one for the other if the price of one of them rises. On the other hand, if two goods perform different roles in production, they are complements. Therefore, when the price of one of them increases, a firm will also reduce their use of both goods.

This is distinct from the concept of *quantity* substitutability and complementarity. Two goods are quantity complements if an increase in the use of good A increases the *productivity* of good B. Two goods are quantity substitutes if an increase in the use of good A reduces the productivity of good B.

A number of researchers suggest that energy and capital are quantity complements. The argument here is that capital requires energy to be used (Finn, 2000, Keen et al., 2019). Keen et al., formalise the dependency between the factors of production and energy as:

$$Y = f(L(E), K(E))$$

This equation represents an absolute dependency of the factors of production on energy. If energy reached zero, there would be no production: energy is required for any level of productivity from capital (or labour).

In a series of papers between 1991 and 2000, Finn (2000) made the same case, but restricted the energy dependency to capital alone. In its simplest form, Finn defines capital utilisation (U) as reliant on energy:

$$U = \frac{E}{K}$$

(Finn used a moderating parameter so that U was not exactly equal to $\frac{E}{K}$. For ease of exposition we have dropped this). This can be entered into a standard production function:

$$Y = f(L, KU) = f\left(L, K\left(\frac{E}{K}\right)\right)$$

Here, again, we have quantity complementarity because the productivity of a given capital stock depends on the use of energy.

Quantity complementarity between capital and energy can be explained in terms of the energy conversion chain and useful exergy (introduced in Section 2.3. See also: Grubler et al., 2012, Brockway et al., 2019a, Heun et al., 2018). If capital requires energy to produce goods, then capital productivity is improved by making every stage of the energy conversion chain more efficient, because this frees up more energy that can be directed by capital into the production process. In practice this means moving to higher quality energy carriers (e.g. electricity rather than coal) and improving the efficiency of conversion processes (Brockway et al., 2019a). Both of these processes help to ensure the portion of energy accessed by capital and used to do *economically valuable work* will be maximised. The flipside of this is that decreases in energy quality (see Section 7) and energy efficiency will reduce capital productivity because more energy will be wasted (Fagnart and Germain, 2016).

Inherent within the concept of useful exergy is the implication of limits to this form of capital productivity gain. The concept of exergy derives from thermodynamics. The first law of thermodynamics tells us that energy can neither be created nor destroyed. The implication of this is that the energy into a process must be equal to the energy coming out of a process. The second law tells us that a given quantity of energy becomes less available to us over time, it is less able to do useful work. The implication of this is that it is impossible to achieve 100% conversion rates from an energy source to useful work (Grubler et al., 2012, Jackson, 1996, Cullen and Allwood, 2010). Any given task has a maximum theoretical energy conversion rate. This maximum has a major impact on the productivity of capital in terms of its ability to transform materials (Carnahan et al., 1975). Once we have achieved that physical maximum, if changes in productivity are to be possible, they must come from increasing the value of goods and services in intangible ways. Here we have an interaction between social and physical that is hard to separate and has been underexplored in economics. On the other hand, energy and capital may be quantity substitutes. If old capital is upgraded or replaced with new capital that is able to use energy more efficiently, then energy use will decline, and capital productivity may increase. Energy still plays a central role in production via capital in this context, but the behavioural relations around this energy use are changed.

Price substitutability plays a different role to quantity complementarity in the energy-productivity relation. If energy and capital are price complements, then an increase in the price of energy will reduce the demand for capital. This is central to the discussion in Section 5, but in brief, if energy price increases reduce demand for capital this amounts to a reduction in investment. There is a literature which suggests this could lead to recession. On the other hand, if energy and capital are price substitutes then an increase in energy prices should prompt an increase in capital productivity. This is explained by Broadstock et al., (2007) in engineering terms: as energy prices rise there is an incentive to use more energy efficient forms of capital.

In summary, whether energy and capital are complements in either the quantity or price terms this has implications for productivity. The question is, are they substitutes or complements?

4.2 Do empirical studies find energy and capital to be substitutes or complements?

There is no conclusive empirical position on the relation between energy and capital. In their comprehensive review, Broadstock et al., (2007) report that 20% of studies find a complementary relation, 20% are inconclusive and around 60% find a substitutability relation. Around half of the latter studies (35% of the total) find only a weak substitution relation. Broadstock et al., (p.67) conclude that

“energy and capital appear at best to be weak substitutes ... and possibly may be complements ... But very little confidence can be placed in this statement.”

In Table 3 we adapt and update the analysis carried out by Broadstock et al. (2007). We replicate their analysis for 52 papers published between 1975 and 2005. These papers estimate 61 relationships between energy and capital. We then add an additional 24 papers published between 2006 and 2019. These studies represent 45 additional estimates of the relationship between energy and capital. Across the entire sample, we find that ~60% report substitutability, while ~20% report complementarity and ~20% are inconclusive.

The reason for the diverse findings and subsequent low confidence, is because of the assumptions analysts have to make when testing the relation between energy and capital. All of the studies in Table 3 use some form of production function analysis. Production functions define economic output (Y) as a function of the combination of number of different inputs, known as factors of production. In energy analysis, these factors are typically Capital (K), Labour (L) and Energy (E), or Capital (K), Labour (L), Energy (E) and Materials (M). The assumptions made in production function analysis have substantial impacts on the reported finding between energy and capital (Broadstock et al., 2007, Costantini et al., 2019). In the next subsections we explore how analysis of the capital-energy relation is impacted by: 1) data issues (particularly with respect to capital), 2) choice of model form and 3) choice of substitution measure.

Table 3: Survey of studies empirically estimating the relationship between energy and capital.

Citation	Model Structure			Productive Capital/Wealth Capital	Substitutability Measure	Result
	Base Form	Cost/ Production	Materials Included?			
(Berndt and Wood, 1975)	Translog	Cost	Materials	Productive	Allen	Complements
(Christensen and Greene, 1976)	Translog	cost	No Materials	Unknown	Allen	Substitutes
(Griffin and Gregory, 1976)	Translog	Cost	No Materials	Unknown	Allen	Substitutes
(Denny et al., 1978)	Leontief	Cost	Materials	Unknown	Allen	Complements
(Berndt and Khaled, 1979)	Box-Cox	Cost	Materials	Productive	Allen	Complements
(Berndt and Wood, 1979)	Translog	Cost	Materials	Unknown	Allen	Complements
(Magnus, 1979)	Cobb Douglas	Cost	No Materials	Productive	Allen	Complements
(Özatalay et al., 1979)	Translog	Cost	Materials	unknown	Allen	Substitutes
(Williams and Laumas, 1981)	Translog	Cost	Materials	Wealth	Cross Price	Substitutes
(Turnovsk et al., 1982)	Translog	Cost	Materials	Productive	Allen	Substitutes
(Dargay, 1983)	Translog	Cost	Materials	Productive	Allen	Complements
(Norsworthy et al., 1979)	Translog	Cost	Materials	Productive	Allen	Complements
(Pindyck and Rotemberg, 1983)	Translog	cost	Materials	Productive	Not explicitly stated	Complements
(Atkinson and Halvorsen, 1984)	Translog	Cost	No Materials	Wealth	Allen	Substitutes
(Garofalo and Malhotra, 1984)	Translog	Cost	No Materials	Productive	Allen	Both, time dependent
(Hunt, 1984)	Translog	Cost	No Materials	Wealth	Allen	Complements
(Hunt, 1984)	Translog	Cost	No Materials	Wealth	Cross Price	Complements
(Westoby and McGuire, 1984)	Translog	Cost	No Materials	Unknown	Allen	Complement
(Olson and Jonish, 1985)	Translog	Cost	Materials	unknown	Allen	Complements
(Halvorsen and Smith, 1986)	Translog	Cost	Materials	Wealth	Allen	Substitutes
(Hunt, 1986)	Translog	Cost	No Materials	Wealth	Allen	Both, dependent on technical change modelling
(Iqbal, 1986)	Translog	Cost	Materials	Unknown	Allen	Both, dependent on sector and aggregation
(Chung, 1987)	Translog	Cost	Materials	Productive	Allen	Substitutes
(Gopalakrishnan, 1987)	Translog	Cost	No materials	Wealth	Allen	Substitutes
(McElroy, 1987)	Translog	Cost	Materials	Productive	Allen	Complements
(Pollak and Wales, 1987)	Translog	Production	Materials	Productive	Allen	Complements
(Pollak and Wales, 1987)	Leontief	Production	Materials	Productive	Allen	Complements
(Pollak and Wales, 1987)	Cobb Douglas	Production	Materials	Productive	Allen	Complements
(Struckmeyer, 1987)	Translog	Cost	Materials	unknown	Allen	Both, dependent on assumptions made in the estimation of the translog function.
(Bjorndal et al., 1988)	Translog	Cost	No Materials	Unknown	Allen	Substitutes
(Kim, 1988)	Translog	Cost	Materials	Productive	Allen	Substitutes
(Klein, 1988)	Translog	Cost	Materials	Productive	Allen	Substitutes
(Gopalakrishnan et al., 1989)	Translog	Cost	No materials	Wealth	Allen	Substitutes
(Garofalo and Malhotra, 1990)	Translog	Cost	No Materials	Unknown	Allen	Complements
(Huang, 1991)	Translog	Cost	No Materials	Unknown	Allen	Both
(McNown et al., 1991)	Translog	Cost	No Materials	wealth	Allen	Substitutes
(Harris et al., 1993)	Translog	Cost	No Materials	Wealth	Allen	Both, sector dependent

Citation	Model Structure			Productive Capital/Wealth Capital	Substitutability Measure	Result
	Base Form	Cost/ Production	Materials Included?			
(Chang, 1994)	CES	Cost	Materials	Unknown	Allen	Substitutes
(Goodwin and Brester, 1995)	Translog	Cost	Materials	Unknown	Morishima	Substitutes
(Burney and Al-Matrouk, 1996)	Translog	Cost	No Materials	Productive	Allen	Substitutes
(Applebaum and Kohli, 1997)	Translog	Production	Materials	Unknown		Substitutes
(Casler, 1997)	General	Cost	Materials	Wealth	Allen	Complements
(Casler, 1997)	Translog	Cost	Materials	Wealth	Allen	Complements
(Kant and Nautiyal, 1997)	Translog	Cost	Materials	Unknown	Allen	Substitutes
(Kant and Nautiyal, 1997)	Translog	Cost	Materials	Unknown	Morishima	Substitutes
(Nguyen and Streitwieser, 1997)	Translog	production	Materials	wealth	Morishima	Substitutes
(Kemfert, 1998)	CES	Production	No Materials	Wealth	Hicks	Substitutes
(Raj and Veall, 1998)	Translog	Cost	Materials	Productive	Allen	Both, dependent on assumptions made in the estimation of the translog function.
(Serletis and Kumbhakar, 1990)	Translog	Cost	Materials	Productive	Slutsky	Substitutes
(Dahl and Erdogan, 2000)	Translog	Cost	No Materials	productive	Allen	Substitutes
(Kemfert and Welsch, 2000)	CES	Production	No Materials	Wealth	Hicks	Substitutes
(Vega-Cervera and Medina, 2000)	Translog	Cost	No Materials	Unknown	Allen	Both, dependent on location
(Medina and Vega-Cervera, 2001)	Translog	Cost	No Materials	unknown	Allen	Both, depending on location
(Medina and Vega-Cervera, 2001)	Translog	Cost	No Materials	Unknown	Cross Price	Both, dependent on location
(Truett and Truett, 2001)	Translog	Cost	No Materials	unknown	Cross Price	Substitutes
(Frondel, 2002)	Translog	Cost	Materials	productive	Allen	Complements
(Frondel, 2002)	Translog	Cost	Materials	Productive	Morishima	Substitutes
(Kuper and Van Soest, 2003)	CES	production	No Materials	unknown	Hicks	Both, depending on time period
(Welsch and Ochsens, 2005)	Translog	Cost	No Materials	Unknown	Morishima	Complements
(Welsch and Ochsens, 2005)	Translog	Cost	No Materials	Unknown	Cross Price	Complements
(Roy et al., 2006)	Translog	Cost	Materials	Unknown	Allen	Both, dependent on country and industry
(Arnberg and Bjorner, 2007)	Translog	Cost	No Materials	Productive	Cross Price	Complements
(Arnberg and Bjorner, 2007)	Linear Logit	Cost	No Materials	Productive	Cross Price	Complements
(Fan et al., 2007)	Translog	Cost	No Materials	Wealth	Morishima	Both, dependent on time
(Fan et al., 2007)	Translog	Cost	No Materials	Wealth	Cross Price	Both, dependent on time
(Okagawa and Ban, 2008)	CES	Production	No Materials	unknown	Not explicitly stated	Substitutes
(Van der Werf, 2008)	CES	production	No materials	Unknown	Not explicitly stated	Substitutes
(Ma et al., 2009)	Translog	Cost	No materials	Wealth	Allen	Substitutes
(Li, 2009)	Translog	Cost	Materials	Unknown	Allen	Substitutes
(Li, 2009)					Morishima	Substitutes
(Li, 2009)					Cross Price	Substitutes
(Smyth et al., 2011)	Translog	Production	No Materials	Wealth	Not explicitly stated	Substitutes
(Stern, 2011)	Translog	Cost	Materials	Productive	Allen	Complements
(Stern, 2011)	Translog	Cost	Materials	Productive	Morishima (Gross)	Substitutes
(Stern, 2011)	Translog	Cost	Materials	Productive	Morishima	Complements

Citation	Model Structure			Productive Capital/Wealth Capital	Substitutability Measure	Result
	Base Form	Cost/ Production	Materials Included?			
(Stern, 2011)	Translog	Cost	Materials	Productive	Hotelling-Lau	Substitutes
(Stern, 2011)	Translog	Cost	Materials	Productive	Hicks	Complements
(Stern, 2011)	Translog	Cost	Materials	Productive	Allen (Complements)	Complements
(Stern, 2011)	Translog	Cost	Materials	Productive	Morishima (Complementary)	Complements
(Stern, 2011)	Translog	Cost	Materials	Productive	Pigou	Complements
(Stern, 2011)	Translog	Cost	Materials	Productive	Symmetric	Complements
(Stern, 2011)	Translog	Cost	Materials	Productive	Symmetric	Complements
(Hassler et al., 2012)	CES	Production	No Materials	Unknown	Not explicitly stated	Substitutes
(Stern and Kander, 2012)	CES	Production	No Materials	Wealth	Not explicitly stated	Substitutes
(Tovar and Iglesias, 2013)	Translog	Cost	Materials	unknown	Cross Price	Complements
(Tovar and Iglesias, 2013)	Translog	Cost	No Materials	unknown	Cross Price	Complements
(Tovar and Iglesias, 2013)	Leontief	Cost	Materials	unknown	Cross Price	Complements
(Haller and Hyland, 2014)	Translog	Cost	Materials	Wealth	Morishima	Substitutes
(Lin and Li, 2014)	Translog	Cost	Materials	Unknown	Cross Price	Complements
(Zha and Zhou, 2014)	Translog	Cost	No Materials	Wealth	Cross Price	Substitutes
(Zha and Zhou, 2014)	Translog	Cost	No Materials	Wealth	Morishima	Substitutes
(Zha and Zhou, 2014)	Translog	Cost	No Materials	Wealth	Allen	Substitutes
(Pablo-Romero and Sánchez-Braza, 2015)	Translog	Production	No Materials	Unknown	Not explicitly stated	Both, depending on region
(Fiorito and van den Bergh, 2016)	Translog	Cost	Materials	Wealth	Morishima	Both, depending on country
(Fiorito and van den Bergh, 2016)	Translog	Cost	No Materials	Wealth	Allen	Both depending on time and region
(Heun et al., 2017)	CES	Production	No Materials	Wealth	Hicks	Substitutes
(Heun et al., 2017)	CES	Production	No Materials	Productive	Hicks	Substitutes
(Wang and Lin, 2017)	Translog	Cost	No Materials	Wealth	Allen	Substitutes
(Wang and Lin, 2017)	Translog	Cost	No Materials	Wealth	Cross Price	Substitutes
(Lin and Liu, 2017)	Translog	Production	No Materials	Wealth	Not explicitly stated	Substitutes
(Henningsen et al., 2018)	CES	Production	No Materials	Wealth	Not explicitly stated	Substitutes
(Wurlod and Noailly, 2018)	Translog	Cost	No Materials	Unknown	Cross Price	Both dependent on sector
(Costantini et al., 2019)	Translog	Cost	No Materials	Wealth	Allen	Substitutes
(Wang et al., 2019)	Translog	Cost	Materials	Wealth	Allen	Substitutes
(Wang et al., 2019)	Translog	Cost	Materials	Wealth	Cross Price	Substitutes

Before delving into the details of methodological differences, it is worth noting that across all the studies we looked at there is a striking homogeneity in methods and a striking irregularity in findings. Around 80% of the studies we reviewed use the same core model structure (a translog

cost function, see Section 4.4), while half use the same substitution indicator (Section 4.5). Moreover, as Broadstock et al. (2007) note, there appears to be little correlation between specific methodological choices, and the finding of capital-energy complementarity or substitutability. Rather (as Miller (1990) and Sorrell (2014) have both argued) it appears that methodological challenges make empirical estimates of energy-capital relations unreliable, rather than biasing them in a particular direction.

4.3 The Challenge of Constructing Capital Datasets.

Methodological challenges begin with the selection of data sources the various inputs to a production function. These problems are particularly acute for capital itself, and the issue of the reliability and availability of capital data is regularly raised (e.g. Miller, 1990, Robinson, 1953, Thompson, 2006).

Although capital is often considered to be a homogenous collection of ‘machine hours’ (Keen et al., 2019, Thompson, 2006), capital actually consists of a very heterogeneous collection of goods. The System of National Accounts sets out 7 categories of capital asset, ranging from intellectual property (which includes original literary works) to Machinery and Equipment (European Commission et al., 2008, p. 203). A key challenge in estimating a capital dataset is how we aggregate across these very different goods (Robinson, 1953).

Some studies attempt to navigate the heterogeneity issue by using more specific definitions of capital. Tovar and Iglesias (2013) use two categories of capital: buildings and machinery. They take the market value of each and then divide this by a price deflator. Similarly, Nguyen and Streitwieser, (1997) use the book values (the price paid by the firm) of buildings and structures, and machinery. This approach does not appear to give a decisive answer on the question of whether energy and capital are complements or substitutes: Tovar and Iglesias (2013) find a complementary relation, Nguyen and Streitwieser, (1997) report that energy and capital are substitutes.

In Section 2.4 we introduced the idea that capital can be quality adjusted in the form of producing estimates of ‘capital services’ – measures that adjust capital in order to better account for its productive nature of capital rather. This is opposed to using a pure wealth estimate of capital. In practice,

studies of the role of the energy-capital relation in production have used both ‘productive’ measures of capital and measures of the capital stock more closely related to income and wealth. Often there is not sufficient information given on the construction of the capital stock dataset to enable others to assess which measure was used (Table 3).

Whether wealth or productive capital measures are used, the most common estimation method is the Perpetual Inventory Method (PIM). PIM is based on the idea that capital stocks are the accumulation of investment flows adjusted for deterioration in the stock over time. The process starts by estimating the average and maximum life of a given capital good. For income/wealth-based measures of capital, this will be done on the basis of a relationship between age and depreciation. For productive measures of capital stock, it will be done on the basis of estimates about loss of productive efficiency over time. In either case the information is used to estimate a relationship between the age of capital, and its retirement. The next step is to take this information and combine with information on investments over time. To see how this works in practice let us look at a recent study.

In their analysis of energy-capital substitutability in manufacturing industries in the OECD, Costantini et al., (2019) use the PIM approach to estimate capital stocks. They take gross fixed capital formation (GFCF, a measure of investment flows) from the OECD-STAN database (OECD, 2012). To estimate their initial capital stock, they divide the investment flow at year 1 by a constant depreciation rate (15%, taken from OECD, (2009) manual) plus the average investment growth rate. The latter is specific to each sector and country they study. Formally this is:

$$K = \frac{I^{t0}}{g+d} \quad (1)$$

Where I^{t0} is investment at time zero, g and d are the sector specific growth and depreciation rates. The capital stock in subsequent time periods is:

$$K^t = K^{t-1}(1 - d) + I^t \quad (2)$$

Though simple to implement, the PIM method throws up complications for analysis of the energy-capital relation.

Miller (1990) argues that PIM is likely to contain systematic biases that make it difficult to reliably estimate a relationship between capital stock and any other economic variables. As we saw, the PIM method uses on investment

flows and the average lifespan of capital assets to estimate capital stocks. By national accounting convention, investments data are measured as the average flow of investment within a given time period (OECD, 2009). Because of a lack of good data, the lifespan of capital assets is assumed to be a function of age alone. Miller points out that two capital stocks can have the same average life span and investment profile, and yet have very different relationships to other relevant factors. This is because 1) investment within the period may vary systematically with other economic variables. But provided average investment is the same over the period, two investment timeseries with different relations to other economic variables would look identical. 2) Capital may be scrapped in response to changing economic conditions that do not relate to its age. Miller makes the argument specifically with respect to the cost of capital services. However, the argument also applies to other factors that may be expected to co-vary with capital.

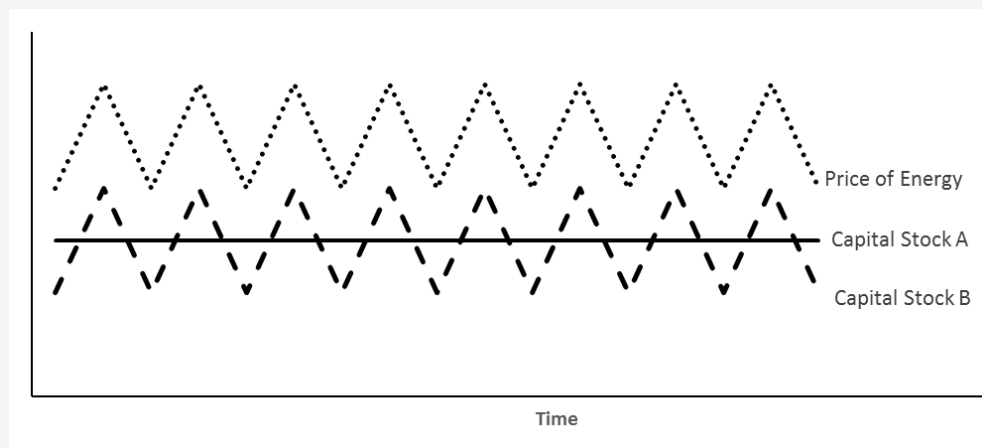


Figure 9: Diagram showing challenges of the PIM approach to capital investment with relation to testing the relation to energy prices. Capital Stock A has no relation to energy prices by construction. Capital Stock B follows energy prices by construction. Both are equally well described by the same constant depreciation rate and investment time series. Data underlying diagram is given in Table 3.

Figure 9 recreates Miller's (1990) graphical example applied to the price of energy instead of the price of capital services. To construct Figure 9, we define 2 capital datasets and an energy price dataset (see Table 4 for the numerical example). Both of the 2 capital datasets have the same average lifespan and the same investment flow over two timesteps. But (by

construction) Capital Stock A has no relation to energy, while Capital Stock B varies systematically with the price of energy. The energy price fluctuates every timestep. If we only have investment data averaged over 2 timesteps plus the average lifespan of capital, then both datasets look exactly the same under the PIM approach and we are none the wiser as to the relationship between energy and capital. As Miller notes, the data in the schematic would not even allow us to test the sign of the relation between the capital stock and the potentially co-varying factor. The *inverse* of Capital Stock B would have the exact opposite relation to energy prices but would still be consistent with same the average lifespan and investment flow data.

Time Step	Energy Price	Capital Stock		Investment		Available depreciation/efficiency loss data		Investment Data	
		A	B	A	B	A	B	A	B
1	0.8	0.6	0.4	0.3	0.6				
	1.2	0.6	0.8	0.3	0	0.6	0.6	0.3	0.3
2	0.8	0.6	0.4	0.3	0.6				
	1.2	0.6	0.8	0.3	0	0.6	0.6	0.3	0.3
3	0.8	0.6	0.4	0.3	0.6				
	1.2	0.6	0.8	0.3	0	0.6	0.6	0.3	0.3
4	0.8	0.6	0.4	0.3	0.6				
	1.2	0.6	0.8	0.3	0	0.6	0.6	0.3	0.3
5	0.8	0.6	0.4	0.3	0.6				
	1.2	0.6	0.8	0.3	0	0.6	0.6	0.3	0.3

Table 4: Constructed Datasets showing challenges of the PIM approach to capital investment with relation to testing the relation to energy prices. In line with National Accounting Convention, available investment data is the average investment flow in the period. Depreciation rate is 0.5. Capital Stock A has no relation to energy prices by construction. Capital Stock B follows energy prices. Both are equally well described by a constant depreciation rate of 0.5 and average investment flow data of 0.3 and would look identical under a PIM construction.

4.4 Model Structure

When implementing a production function analysis, economists operationalise a general function by choosing 1) a particular functional form, and 2) the factors to include within that functional form. A functional form describes the specific mathematical relationship that relates the terms in the general function: $Y = f(KLEMS)$. There are numerous possible functional forms. By far the most common in empirical applications is the

translog functional form (Table 3). On the other hand, CES functions are common in macroeconomic models incorporating energy use. Brockway et al., (2017) provide a comprehensive overview of the estimation and implications of CES functions in energy-economy models. Other possible choices include the Cobb Douglas, the Box-Cox and the Leontief. We avoid an in-depth discussion of the mathematics of the various forms here. Broadstock et al., (2007) provide introductions to the Translog, Cobb Douglas and the CES.

The Translog functional form was developed by Christensen et al., (1973) as a response to concerns that other functional forms may be too restrictive when analyses move beyond 2 factors of production. Both CES and Cobb Douglas functional forms place restrictions on substitutability between factors. Notably they require nesting of factors. Nesting emulates a two-stage decision making process. Producers are assumed to make a decision about the mix of two factors and then make a decision about the third. This implies two sets of substitution parameters. One between the first two factors and one between their composite and the third production factor (Broadstock et al., 2007). Nesting structures can have an impact on estimates of substitutability/complementarity of factors (Broadstock et al., 2007, Brockway et al., 2017, Frondel and Schmidt, 2002). An advantage of the translog form is that it does not require nesting. However, it is still sensitive to certain assumptions. One such issue arises from the practical implementation of the function, which is typically as a *cost* function rather than a *production* function (Table 3).

Where a production function models output in terms of physical quantities, a cost function models it in terms of cost shares. The translog cost function is obtainable from the production function under neoclassical assumptions. If firms are (in the neoclassical sense) rational, and markets competitive so that factors of production rapidly move to their long-term equilibrium positions, then it is possible to the production function to a cost function (Broadstock et al., 2007). The cost function is generally preferred by analysts (Table 3).

The first issue with using the translog cost function is that its underpinning neoclassical assumptions are highly contested. Many economists believe that firms are not ‘rational’ and that the economy is rarely (if ever) in equilibrium (e.g. Lavoie, 2014). Consequently, a cost function need not be

related to a production function, and the estimated substitutability may be suspect.

Cost shares may bring an additional consideration. Cross-price, Allen and Morishima substitutability coefficients (see section 4.5) estimated with a translog cost function are sensitive to the relative size of the cost shares of each factor (Broadstock et al., 2007, Frondel and Schmidt, 2002). Frondel and Schmidt (2002) argue that in energy-capital, energy and capital are more likely to appear complements if the relative size of the energy and capital cost shares are both relatively large. On the other hand, if their cost shares are small, they are more likely to appear to be substitutes. The concern is that the relative cost shares of energy and capital will decline as more factors are included in the analysis. The majority of studies are either 3 sector (K,L,E) or 4 sector (K,L,E,M).

However, the importance of the effect of the number of sectors is disputed. In their meta-analysis Koetse et al., (2008) use a dummy variable to account for the effect of including or not including a materials sector. They find that this does not have a significant impact on the size of substitutability parameters. In Table 3 we highlight whether models include a materials sector. In our survey we identified 46 translog models that include materials. 38% of these find substitutability, 40% find complements and 20% are inconclusive. So in our sample, including an additional sector gives a higher proportion of complementarity than the full sample average, which is the opposite of the concern raised by earlier analysts.

4.5 The focus of the model

An additional problem with issues of substitutability is that the term itself has numerous different definitions. Opening this section, we pointed to the difference between price substitutes and quantity substitutes. However, the differences go beyond this. In a review article, Stern (2011) suggests a typology of substitution measures that distinguishes substitution measures on the basis of whether they are price measures or quantity measures and a number of other factors including whether the measure allows for changes in output (gross), or whether output is held constant (net). Here we discuss the three most commonly used measures: Allen-Uzawa, Cross-Price or Morishima elasticities of substitution. We avoid mathematical detail which can be found in Broadstock et al., (2007) and Stern (2011).

In the early days of the energy-capital literature, the most widely used measure of substitution was the Allen-Uzawa elasticity of substitution (‘Allen’, in Table 3). The Allen-Uzawa elasticity of substitution is often referred to as a “partial” elasticity of substitution because it measures how the quantity of one factor is impacted by a change in the price of a factor as opposed to measuring how the change in a price ratio effects demand for a factor. More recently, this has relatively fallen out of favour and studies increasingly report Morishima and Cross-Price Elasticities of Substitution. The Allen-Uzawa elasticity of substitution is a price based, net-substitution measure. This means that it measures how the demand for a factor changes when the price of a factor changes, *assuming output is held constant*.

As we can see in Table 3, more recent studies have tended to use either the Cross-Price elasticity of Substitution or the Morishima elasticity of substitution. Like the Allen-Uzawa elasticity of substitution, the Morishima elasticity of substitution is a net measure – it assumes output is held constant. Unlike the Allen-Uzawa, it measures the impact of a change in a price ratio, rather than one price alone. The cross-price elasticity of substitution can be either a net or gross measure. In its net form it is very close to the Allen-Uzawa elasticity of substitution.

Our survey results do not provide a particularly strong basis for making claims about relationships between substitution measure and findings. Of those studies that used the Allen-Uzawa elasticity of substitution, 41% found substitutability, 33% complementarity, and 26% inconclusive. Of those using the cross-price, 38% found substitutability, 44% complementarity, and 16% inconclusive. Of those using the Morishima, 66% found substitutability, 16% complementarity, and 16% inconclusive. While there is a difference with the Morishima, it is also worth noting that only 10 studies in our sample use Morishima elasticity measures.

4.6 Summary and Gaps

The question of whether energy and capital are substitutes or complements is key to understanding the energy productivity relationship. A number of analysts have proposed that energy and capital are quantity complements: the use of one makes the other more productive. They argue that this is because capital requires energy to function. On the other hand, it is also possible that energy and capital are price substitutes: as the price of energy

rises, capital is made more energy efficient (so less is required). This will be important for our later discussion of energy price effects.

No form of substitution/complementarity has a solid empirical basis. The results are mixed, despite homogeneity of methods. Reviewing 106 studies we find 60% report some level of substitution (including very weak substitution), 20% find complementarity and the remaining 20% are inconclusive. The reasons for this lack of empirical evidence are rooted in difficulties operationalising fundamental concepts of production theory. In particular, capital datasets are very unreliable, and the choice of model structure and substitution measure directly impact the results.

In summary, we have reasonable understandings of the way that energy could drive productivity via capital. But the proposed mechanisms rest on a relationship between energy and capital which has never been proved or disproved empirically. On this basis we recommend:

1. Revisiting the core concepts of production theory, and the ways they are operationalised. Finding a solid empirical basis for questions of capital-energy complementarity requires examination of our empirical methods at a fundamental level.
2. Critical exploration of the ways that different concepts of substitutability are used in energy-capital debates. The homogeneity of methods and metrics used in energy-capital analysis limits our ability to fully explore the energy-productivity relationship.

5 | Energy Prices and Productivity

Four of the five deep recessions since 1970 were preceded by significant shocks in oil prices and consequently a decline in productivity growth (Jones et al., 2004). However, there is no consensus on why this happened. Some have argued that economies have become more resilient to energy price shocks compared to the past (Blanchard and Galoi, 2008). Others have argued that the relationship between energy prices and productivity is nonlinear. For instance, Hamilton (2003, 2009) argues that an increase in oil prices has a more significant and persistent effect on the productivity growth than a decrease. The reason for these changes in the effect of an energy price change is because they are mediated by a number of social factors. It is empirically very challenging to investigate a general

relationship between energy prices and productivity growth across periods with significantly different economic conditions, market endowments and behaviour of economic agents.

5.1 Energy-Productivity: Inflation

One suggested channel from energy prices to productivity is the potential for inflation to drive recessionary spirals. It has been suggested that higher energy prices would directly affect the cost of production for sectors that are energy intensive. This may then increase prices across other sectors of the economy, reducing purchasing power and dampening aggregate demand (Berndt and Wood, 1986, Rotemberg and Woodford, 1996, Berg et al., 2015, Herrera et al., 2019).

A large inflationary effect from energy price increases is in some ways surprising, because energy is typically only a small share of total production costs. Most industrialised countries at the late 1970s have experienced productivity slowdown and recessionary pressures caused by increase in energy prices of 3 percent of GDP (Jones et al., 2004). A large literature suggests that the largest impacts on the economy actually come from the way that prices rises impact on consumption, rather than the way cost increases directly affect production (Hamilton, 1988, 1996, Mork, 1989)

The intuition is that energy is directly required for much domestic production, and therefore price rises are likely to be passed through to consumers so that firms maintain their profitability (Berndt and Wood, 1986, Szilagyiova, 2014). This is particularly notable for energy intensive goods such as transport (Stuber, 2001, Edelstein and Kilian, 2009). But energy price spikes can also have substantial impacts on the price of other goods. A number of studies use input-output models to examine these effects (Berg et al., 2015, Logar and van den Bergh, 2013, Kerschner et al., 2013, Valadkhani et al., 2014). Input-output models emphasise the fact that all sectors in an economy are linked: to produce a given good firms have to purchase goods from other sectors of the economy. In this way, energy ends up as a direct input to all production cycles. There may also be more nebulous links. For instance, house prices have been linked to the cost of energy used in commuting (Cortwright, 2008).

Another stream of empirical literature suggests that the size of energy price increases on general inflation is mediated by monetary policy (Tobin, 1980,

Bohi, 1991). Bernanke et al. (1997) using vector autoregressions (VARs) find that the difference in the response of the economic activity to the changes in energy prices is mainly due to the monetary policy response and the increase in the interest rate to contain inflationary pressures. However, Hamilton and Herrera (2004) using the same method find contractionary monetary policy to contain inflation driven by increase in energy price is overestimated. They show that the direct effect of the increase in energy prices on slowing-down productivity is large and statistically significant and that monetary policy has little effect.

A large body of literature has evolved to study the mechanism, attribution and stability of the relationship of oil price fluctuations on GDP growth. Hamilton (1983) had an influential work that showed evidence that the increase in oil prices had significantly affected the business cycle. He showed granger causality between energy price rises, recessions and slowdown in overall productivity growth. Later analysis using microeconomic foundations showed that any oil price changes would have an adverse effect on productivity by causing costly resource allocation adjustments (Gilbert and Mork, 1986). These adjustment costs are incurred due to the reallocation of labour and the costs associated with changing job, sector or industry.

Based on empirical evidence showing that oil price increases had more predictive power for US GDP growth than decreases in oil prices, Mork (1989) argue that there may be an asymmetric relationship between energy price and GDP growth. This became widely accepted in the literature (Bernanke et al., 1997, Balke et al., 2002, Ramey and Vine, 2011, Cunado and De Gracia, 2005). According to Kilian and Vigfusson (2011) this became an *a priori* belief that led analysts to favour models that found this response. More recent papers cast doubt on the existence and size of the asymmetry (e.g. Herrera et al., 2015, Karaki, 2018). In their recent review, Herrera et al., (2019) conclude that there is some evidence of an asymmetric effect, principally for larger price rises.

There is also considerable uncertainty over how the relationship between energy prices and inflation is shaped by different geographical factors (Szilagyi, 2014, Blanchard and Gali, 2008). In the wealthy economies of the Global North, sensitivity to oil price shocks appear to be highly variable over time. There is evidence that in the UK and US the energy price-inflation relationship became weaker between the 1980s and 1990s but has since

begun to rise (Clark and Terry, 2010, Baumeister and Peersman, 2013., Rafiq, 2014). It has been suggested that decreasing sensitivity to oil price from the 1980s to the late 90s was because of a decreasing dependence on oil in the wealthy economies (Stuber, 2001). However, over the same period, Baumeister and Peersman found that the US economy became more sensitive to restrictions in oil supply (Baumeister and Peersman, 2013.). Long-run evidence for the UK suggests that sensitivity to oil price shocks is dependent on the diversity of energy carriers used in the energy supply. This is because a greater diversity of supply implies greater possibilities for substitution (Jan van de Ven and Fouquet, 2017).

Energy-driven price inflation has the potential to lead to recessionary pressures. Berg et al., (2015) use a stock-flow consistent input-output model to show that energy price increases can reduce demand via inflation. This result is supported by Edelstein and Kilian (2009) who find that personal consumption is impacted by oil price increases. Likewise, Baumeister and Kilian (2016) in an analysis of a wide range of macroeconomic, financial and survey data argue that the sharp decline in oil price experienced in the UK after June 2014 stimulated consumer spending. However, this view is not uniform. Ramey (2017) suggests that what appears to be a decline in consumption is actually other effects rooted in trade. It is also important to note that the size of a reduction in purchasing power is not clear Baumeister and Kilian (2016), for example posit that the effect of this on output must be limited to the size of the reduction in purchasing power.

Energy-driven price inflation is more likely to dampen demand in nations where energy sources are imported. This is because some portion of the price increase is transferred from the importing nation to the exporting nation (Baumeister et al., 2017). Conversely, where a price shock is domestic (i.e. comes from a rise in local energy sources), it is less clear cut that demand will fall. This is because the price increase represents a transfer from one actor to another but the aggregate spending in the economy remains constant. In this case the energy price increase impact on demand will depend on the nature of the income transfer. For example, if energy prices rise because of an increase in the wages of workers in energy industries it is feasible that the increase in wages could offset the increase in energy prices and actually stimulate aggregate demand.

5.2 Uncertainty and Expectations

It has been suggested that higher energy prices could have significant effects on slowing-down the economy through business uncertainty and consumer expectations about looming recessions (Brown and Yücel, 2002). Using firm level data, Bloom (2009) argues that energy price increases can lead to reduced consumer confidence and a high tendency to postpone current consumption due to the fear of job loss and a reduction in income. Likewise, using a dynamic stochastic general equilibrium model, Punzi (2019) argues that expectations about fluctuations in energy price can significantly affect output growth as firms start to delay their investment decisions due to uncertainty of the future costs of production, and consumers delay their current spending for precautionary savings reasons. As the increase in energy prices is sustained for longer, the expectations of its future increase are higher and its effect on the marginal propensity to consume is more significant (Matutinović, 2009). Moreover, Wirl (1991) argues that energy price reductions do not trigger accelerated productivity growth because of actors' expectations that this will be followed by a subsequent increase in energy prices.

It is also worth noting that multiple effects can cancel each other out. Baumeister and Kilian (2016) suggest that although the reduction in US oil prices following June 2014 stimulated consumer demand, this had no effect on overall output. This is because it was offset by a reduction in investment in the oil sector. Here we see an inflationary effect offset by an expectations effect.

5.3 Adjustment Costs

An Increase in energy prices can impact productive capacity by forcing firms to change their technologies and or by modifying their existing technology to make it more energy efficient (Hamilton, 1983, Gilbert and Mork, 1986). These shifts in production arise from an increase in energy prices. It has been suggested that increased energy prices will cause a reduction in the size of energy-intensive sectors and growth in energy-efficient ones, but that this cannot be achieved in the short-term because of the time frames required to change production technologies (Hamilton, 1988, Kydland and Prescott, 1982). Therefore, we may expect energy price increases to reduce production in the short run, creating unemployment, inefficiencies and resource underutilisation (Finn, 2002; Brown and Yucel, 2002). Indeed,

Killian (2008) has shown evidence that a sudden increase in prices of energy due to supply shocks (for example exogenous political events) can cause a significant slowdown in the economic performance and productivity growth that could last up to 5 quarters.

Changing production technology to accommodate a price increase takes time. Atkeson and Kehoe (1999) show that increase in energy price would cause significant disruption to the economic activity and slow adjustment process to install new capital with lower energy to output ratio and higher labour/capital to output in the short-run. Conventional neoclassic theory assumes that firms make frequent small adjustments to their production technologies based on the surrounding market conditions (Doms and Dunne, 1998). However, empirical studies that used firm-level evidence find that adjustment costs are significantly large, so that firms tend to wait to adjust their capital (Veracierto, 2002, Thomas, 2002).

Another stream of literature argues that adjusting capital implies significant costs, and that these are a major cause of potential asymmetrical effects of energy price changes on economic performance (Dixit et al., 1994, Ferderer, 1996, House, 2014). This is due to the irreversibility of the investment decisions (Bernanke, 1983). Moreover, the uncertainty in predicting future energy prices increases these adjustment costs, creating a more sluggish investment behaviour (Kuper and Van Soest, 2003). The main argument is that firms would not be involved in a new investment that adjusts to higher energy prices except if there is zero probability that energy price change would not reverse and hence firms would tend to wait for new information (Dixit et al., 1994). Kuper and Van Soest (2006) argue that these adjustment costs have a profound impact on the relationship between energy prices and production growth. Ayres et al. (2013) bring the demand side to this adjustment process and argue that as the energy prices soar, the demand for energy-intensive goods would decline, this might trigger a decline in oil prices in the short-run that is demand-driven. This could slow down the adjustment of capital and discourage investment in energy conservation technologies.

5.4 Energy, Capital and the Marginal Productivity of Labour

Kokkelenberg and Bischoff (1986) use a simulation model to show that that an increase in energy price will reduce capital stock, reducing labour productivity. The model assumes that capital and energy are quantity

complements (see Section 4.1). The intuition for how this energy-capital complementarity may impact labour productivity via energy price is that an increase in energy price decrease the use of existing capital. It may also lead to investors to postpone investment in capital, especially if future energy prices are uncertain as discussed in adjustment cost section. Finn (2000) makes a similar case using her analytical model (introduced in Section 4.1) in which the utilisation rate of capital is dependent on energy price.

Similarly, Brown and Yucel (2002), suggest that a decline in capital utilisation would lower the marginal products and real wages consequently would drop. If wages tend to be nominally sticky downward, the failure of real wages to decrease in response to the fall in labour productivity would generate further unemployment (and further reduction in the aggregate consumption) and exacerbate output losses. In this way, Rotemberg and Woodford (1996) find an empirical evidence that a 10 percent increase in energy price would decrease output by 2.5 percent in one-year time that is beyond the direct effect of the adverse supply shock of the increase in energy prices. This linkage between energy prices and productivity growth through declining marginal productivity is significant and long-lived even if the share of energy in output is low (Finn, 2000; Rotemberg and Woodford, 1996). These studies show that the effect of the increase in energy prices is extensive due to the long process of costly reallocation of labour and revision of investment plans.

Davis and Haltiwanger (2001) find the job losses following an energy price increase to be ten times higher than employment creation following an energy price decrease. They also find that that the magnitude of the effect of oil price shock is twice that of a monetary policy shock and that the reallocative effect of energy price shock (for example 1973 oil crisis) on the labour market constituted an average of 11 percent of the total employment in the manufacturing sector. This effect would persist up to 15 following quarters.

Keane and Prasad (1996) showed that an increase in energy prices caused a 4 percent decline in average real wages in the long-run and this was not associated with a labour flow to high productivity sector due to skill differences. This suggests that energy price changes could deter productivity growth through labour reallocation. This process could result in unemployed labour urged to relocate to lower skilled sectors with lower productivity.

Sakai et al. (2019) also suggest that energy prices will impact labour productivity. However, they argue that this is a less important factor than demand for energy services themselves. In their model the latter is a key driver to improvements in how efficiently energy is used. They argue that this supports the idea that energy-price relationship is misleading (Ayres and Warr, 2005, Stresing et al., 2008). These arguments are supported by the results of recent meta-analysis which finds that energy goods are relatively price-inelastic, although in the long run commercial energy goods are more price elastic than domestic energy goods (Labandeira et al., 2017).

5.5 Summary and Gaps

There is broad consensus in the literature that rising energy prices may slow-down economic activity and cause losses in real output. A number of channels have been proposed which relate to energy prices to productivity directly. The most direct effect of energy prices on productivity slowdowns is through inflation. Some empirical studies suggest that monetary policy that attempts to counter the inflationary pressures of the increase in energy prices increase the productivity loss. Other indirect channels that aggravate the effects of increase in energy prices on productivity include investment uncertainty and lack of consumer confidence due to recessionary expectations and job loss. Adjustment costs are seen in the literature as mechanism which could potentially amplify the effect of the change in energy prices on productivity due to the reallocation of labour and shifts in the production technologies.

However, the size and importance of many of these potential channels is disputed. Therefore, we suggest the following areas for further research:

1. Further empirical research at the firm level that examines the effects of the change in energy prices on their performance in different economic sectors.
2. Examination of the short-run adjustment costs associated with the reallocation of labour and their ability to shift from one sector to another due to the changes in the energy prices, specifically in the context of emerging technologies.
3. Work to clarify questions around asymmetry and the persistence of the relationship of energy prices and productivity.

6 | Energy Consumption

The potential link between productivity and energy prices is in part because of the way that our lifestyles are heavily dependent on energy use. Two opportunities for further research are in how we change our relationship to energy, either so we need less of it or so that we can manage without it. One way to interpret this is as a change in the elasticity of demand for energy intensive goods. Broadly speaking, the greater the elasticity of demand for energy intensive goods, the lower the productivity impact of a price increase should be, because consumers can switch to alternative goods, avoiding the recessionary spiral (Herrera et al., 2019).

The relationship between the country's income level and the demand on energy is very strong and little is known about the effect of policies that aim to reduce the energy demand on the economic productivity (Sorrell, 2015). The latter study argues that the complexity of the economic systems makes it difficult to predict the unintended and unanticipated repercussions of the economic policies that aim to reduce the demand on energy through regulations and tax interventions.

6.1 Energy and Behaviour

Behavioural approaches to consumption suggest that energy consumption is the result of certain embraced values, attitudes and perceptions towards the environment (Becker et al., 1981). For example, beliefs about the health effects of cooling needs in the summer might be different than their beliefs about the health effects of heating needs in the winter. Although, consumer tolerance for heat and cold might be tremendously different, it is usually thought that people might find it easier to stay warm in the winter with energy-saving methods (e.g. by putting extra layers of garments) than to keep cooler in the summer without using energy-intensive methods (e.g. air condition or fans) (Becker et al. 1981).

The revealed preference theory assumes that consumer preferences are revealed by their purchasing habits and define utility functions by observing behaviour (Samuelson, 1948). According to the rationality assumption of the neoclassical economics, consumers are well informed about the pros and cons of their actions and their incentives are clear and they rationally choose actions with relatively higher benefits. Although, the revealed preference theory has been the main driver of information campaigns and awareness

wave for benefits of energy saving and energy conservation that mobilised the public opinion in the late 1970s, it did not show neither evidence of effectiveness nor impact on habits, perceptions, notions and attitudes toward energy demand (Asensio and Delmas, 2015).

The ineffectiveness of values and information-based campaigns can be explained in a number of ways. Sanne (2002), for instance, argues that consumers are constrained by structural factors. For instance, they argue that as individuals become more productive this may lead them to get accustomed to excessive consumption and create commitments that require them to spend any additional income. This is called a “ratchet effect” that could transform productivity gains into energy-intensive spending. Likewise, Jackson (2005) and Druckman and Jackson (2008) argue that those who embrace pro-environmental stances belong demographically to the higher income and social classes. Therefore, any pro-environmental values tend to be offset by the spending of their higher income levels.

Darby (2006) and Martiskainen (2007) have argued that feedback on energy consumption could have an impact on energy consumption behaviours. This feedback can be direct (such as pay-as you-go meters or smart meters) or indirect (such as historical analysis of energy consumption). Routinely providing feedback on energy consumption and savings with its cost reductions and environmental impact can affect energy behaviours (Martiskainen, 2007).

Behavioural research divides energy behaviour into short-run behaviours which are repetitive and operational and long-run behaviours which are bigger and more considered. Repetitive changes include checking whether appliances are switched off or switching to commuting by walking or cycling (Dwyer et al., 1993, Abrahamse et al., 2005). Geller (2002) argued that changing these short-term repetitive behaviours towards energy can sustain long-term changes in the energy demand. On the other hand, Abrahamse et al. (2005) see interventions in longer-term energy as having more significant potential for reducing energy demand.

Consumer response to energy price changes may be a function of their expectations around the permanence of the increase, or the size of the increase. Matutinovic (2019) argues that if consumers believe price increases to be temporary, their adaptive response to an increase in energy price might not be instantaneous. Conversely, if consumers expect higher energy prices in the future, they might start adopting new energy-saving

habits. This might include buying energy saving cars, installing house insulation and having bigger double-glazed windows that retain heat and allow for maximum lighting (Abrahamase et al., 2005; Garling et al., 2002).

6.2 Energy and Societal Structures

A more sociological perspective sees consumption patterns, including energy use, as the product of institutions, socio-economic structures, and social practices (Sanne, 2002, Jackson, 2005, Gärling et al., 2002, Shove and Walker, 2014). One way to understand the interplay of these factors is human need theory (Doyal and Gough, 1991, Max-Neef, 1992). Human need theory posits a finite set of universal and non-hierarchical (thus distinguishing human need theory from the hierarchy associated with Maslow, 1943) dimensions of human wellbeing. While all humans share the same needs, we satisfy them in different ways. The form of 'satisfier' that we use is determined by our material, socio-economic and cultural circumstances.

Brand-Correa and Steinberger (2017) argue that energy services are a form of satisfier. They point out that this means they are subject to both technical influences, but also a wide range of social influences. Consequently:

“the description of alternatives through technologies or markets only is overly simplistic, since the appropriate unit of analysis is not the single actor using the technology, but instead the community or other larger unit making the decisions which enable individuals within it to use more or less energy to satisfy their needs”. (Brand-Correa and Steinberger, 2017, p. 49)

By way of example, they point to collective energy supply systems (such as public transport network) that create economies of scale when compared to highly individualised systems. As a result, there may be the potential to decouple energy use from wellbeing – which others have defined as the ultimate purpose of economic activity (following Georgescu-Roegen, 1971 and, Power, 2004) – and therefore reduce our collective dependency on energy use.

6.3 Energy and the Rebound Effect

The rebound effect describes how attempts to reduce energy consumption in one area increase energy consumption in others. A useful example of this

is found in Figure 10, where consumers are being encouraged to save energy by buying energy saving lightbulbs, then use the points they earn from these purchases to take more flights (a highly energy intensive activity). Rebound can be partial, where the additional energy used is less than the energy saved. Or it can be total, where the additional energy used is greater than or equal to energy saved. Total rebound is known as backfire (Chitnis et al., 2013).



Figure 10: Example of a rebound mechanism
 From Chitnis et al., 2013

While there is a consensus on the existence of the rebound effect, the sources and size of it are disputed (Greening et al., 2000). Some studies argue that the rebound effect can wipe out more than 100 percent of any improvement in the energy efficiency gains which would result in a higher energy consumption (Freire-Gonzalez, 2011). Although there is some empirical literature that attempts to test the significance of this phenomenon and its magnitude (see for example Barker et al., 2007; Greening and Green, 1998), this quantification often relies on oversimplifying rebound the dynamics (and interrelated) adaptive response of different economic agents. This is because of the economical, behavioural, cultural and other transformational changes that result from the enhancement of the energy efficiency (Ramos-Martin, 2003).

Rebound effects can be understood in terms of direct and indirect effects (Dimitropoulos and Sorrell, 2006; Chitnis et al., 2014). The direct rebound effect comes from the fact that increasing energy efficiency could reduce the

cost of a given product or service. This could increase consumption of that good or service, thereby increasing energy demand. The indirect rebound effect comes from the fact that an increase in energy efficiency (and resulting price decrease) could change demand for other goods and services. The indirect rebound effect suggests that energy savings coming from higher efficiency and improved technology could result in higher real income. This higher real income then instigates other forms of spending. These spending could be either consumption of other goods and services with energy requirements or investment that could be energy-intensive in nature (Dimitropoulos and Sorrell, 2006; Sorrell, 2007).

The literature also defines economy-wide rebound effects. This effect entails that the efficiency gains of energy savings would transform into a reduction in cost of production which results in price and quantity market adjustments in favour of expanding the energy-intensive sectors (Greening et al., 2000).

There is little evidence from the literature on how rebound effects this might impact economic productivity. There are sparse evidence-base studies that assesses the indirect rebound effect of energy efficiency improvements and the productivity links through channelling this spending into the business cycle either through consumption or investment (Sorrell et al., 2009).

6.4 Summary and Gaps

Changing our energy consumption habits offers a way into reducing some potential links between energy and productivity. If we are less dependent on energy, then we are better able to substitute away from it during shortages or price increases. There are a large number of theoretical perspectives through which we could view the issue of energy consumption. Those based on behavioural and value foundations have been questioned. This suggests that reductions in energy use may benefit from broader scale transformations of social structures. We flag this as an area for further research.

7 | Energy Return on Energy Invested

Researchers for whom energy is a core element of production suggest that a number of socio-physical parameters are key to understanding energy-economy links. One such parameter is Energy Return on Energy Invested (EROI). EROI is the ratio of energy produced to the energy used in the production process. It is a measure of the energy available for the production

of non-energy goods and services. In relation to the economy, it is rarely explored outside of exergy, biophysical, and ecological economics communities, and within these communities is rarely connected to productivity directly.

7.1 EROI Trends

The evidence suggests that EROIs are declining for a wide variety of fuels (Guildford et al., 2011, Hall et al., 2014, Murphy, 2014, Brockway et al., 2019b). This decline is in part because existing fuel sources are becoming harder to access. This can happen within a fuel type. For example, as conventional crude oil reservoirs are depleted, new sources are increasingly located offshore and are harder to find. Consequently, more energy is required in the exploration and extraction phases (Hall and Klitgaard, 2018). Linked to this is the transition from conventional fossil fuels to unconventional fossil fuels. Conventional crude oil has a much higher EROI than shale oil because shale oil is actually organic matter contained within rock that is then processed to become liquid oil. As a result, it has an additional stage of processing compared to conventional crude oil, and this requires more energy (Cleveland and O'Connor, 2011). The decline can also come because of a shift in energy sources. Conventional fossil fuels are estimated to have higher EROI values than renewables, though there is substantial debate over this, particularly with respect to unconventional fossil fuels (Brockway et al., 2019c). As a result, a reduction in fossil fuels in favour of renewables can reduce the EROI of a national energy mix. For example, Brand-Correa et al. (2017) suggest that UK EROI has been declining since 2003 at least partially because of a shift away from high EROI fuels, like Coal, Oil and Gas over this time period.

7.2 Implications of a Declining EROI for Productivity

Falling EROI is likely to be a problem for productivity. A declining EROI means societies have less energy available for production per unit of energy that goes into energy generation. In other words, there is less energy available to do economically useful work (Fagnart and Germain, 2016). This will impact productivity through loss of energy services, economic restructuring and the price mechanism.

A lower EROI will impact productivity by effecting capital if capital and energy are complements. As set out in Channel 1, if capital and energy are complements then a smaller energy surplus will mean less energy can be directed by capital to produce economically valuable activities, assuming,

for now, that the energy supply is constant. This translates to a lower capital productivity. In turn, EROI will also impact labour productivity through capital. As set out in Channel 2, through capital, energy is a key driver of labour productivity. Consequently, a smaller energy surplus suggests that labour productivity will fall.

Attempts to offset a declining EROI are also likely to reduce productivity. A falling EROI can be offset by increasing the quantity of resources devoted to the energy sector (Sers and Victor, 2018). As EROI falls we can increase the total available energy by devoting more and more of our resources to energy production. However, this could itself impact productivity growth rates because it uses up resources that could have been applied elsewhere.

The evidence for this comes from a number of modelling studies. A comprehensive review of models focussing on EROI-Energy dynamics is provided by Rye and Jackson (2018). Here we highlight a few recent studies and their implications.

Input-output models have been used to argue that steady or increasing economic output in the face of declining EROI will reduce productivity of various factors of production (Fagnart and Germain, 2016, Brandt, 2017). These models assume that production of a given quantity of final output requires a given amount of energy surplus. A declining EROI means a declining energy surplus per unit of energy produced. Offsetting a declining EROI while maintaining final output requires producing more energy. In turn this requires the use of various factors of production, implying a direct decline in their productivity. The input-output structure then compounds this productivity loss, because it means that intermediate goods used by the energy sector also require factors of production to be produced. This means that non-energy producing sectors also have to use more of the various factors of production to support the same level of final output for the whole economy.

Similar findings come out of the simulation models of Hall et al., (2008) and Sers and Victor (2018). The stylised fact at the heart of these models is that the act of generating energy produces only limited value. Generation of economic value depends on how this energy is used by the other sectors of the economy. Declining EROI requires increased investment in the energy sector, reducing investment in the non-energy sectors of the economy. In this way if EROI of the overall energy mix declines sufficiently, the energy sector comes to cannibalise the rest of the economy, severely limiting possibilities for productivity growth. This connects to a more fundamental issue with attempts to offset declining EROIs: it may only be possible up to a certain point.

Researchers posit the existence of a minimum EROI value for the maintenance of society. dependent on the methods used, estimates of a minimum EROI for the continuation of society tend to fall in the range of 4-15 (Brockway et al., 2019b, Lambert et al., 2014, Fizaine and Court, 2016, Court, 2019). The theoretical minimum EROI to support complex societies is constrained by the efficiency with which energy is obtained and used by existing societal infrastructures (Court, 2019). Over the past few decades, we have increasingly seen slowdowns in both of these aspects as machines have reached the thermodynamics limits discussed above and as wealthy societies increasingly choose to implement less energy efficient processes such as air conditioning and mobile devices (Court, 2019, Brockway et al., 2014). Although the estimates and methods of estimating minimum EROIs vary, it is worth noting that estimates of current society-wide EROIs place us close to these minimums (Brand-Correa et al., 2017). This should be a major cause for concern. As EROI values approaches these limits, there will be very little excess energy available to support economic activity beyond maintenance of existing societal infrastructure. From a productivity perspective this means no more energy to drive productivity growth.

Declining EROI may also threaten productivity growth through the variety of mechanisms covered in Section 5, if it is linked to higher energy prices. Some energy analysts do expect declining EROI to drive higher prices (King, 2010, Heun and de Wit, 2012, Murphy and Hall, 2011). The core intuition is that as energy sources becomes harder to find, extract and process this requires additional inputs which pushes up the cost of production. This is less clear cut than the direct loss of energy services. Energy prices are determined by a number of factors (such as geo-politics and mark-up decisions) and cannot, therefore, be uniquely be determined by EROI (Jackson, 2019b, Kallis and Sager, 2017, Herendeen, 2015). Nonetheless, some studies do give us reason to believe that EROI could impact on energy prices.

One argument is that the relation between energy prices and EROI is non-linear and long term. That is the impacts of EROI are thought to be more keenly felt as it approaches 1 (i.e. when energy in equals energy out), and to be more discernible over longer time periods rather than short term fluctuations (Heun and de Wit, 2012, Herendeen, 2015, King and Hall, 2011). The key elements of this argument are that 1) EROI itself is a non-linear ratio. The available energy surplus declines only slightly at higher levels and much more sharply below 10. 2) the profitability of an energy firm depends on their selling their surplus energy. As their own energy requirements increase, their surplus energy relative to the energy they consume will fall. This represents a cost increase. To maintain profit margins, they must

increase the price at which they sell their surplus. In a market economy, firms must be profitable to survive. This suggests that, absent short-term fluctuations, EROI will provide a lower bound on the price of energy (King and Hall, 2011).

The upshot of this argument for productivity is that as long as energy generation must remain profitable, EROI will create a price floor. As EROI declines the price floor will rise ever more rapidly, making price increases more likely and potentially creating conditions for the mechanisms (inflation and aggregate demand loss) discussed in Channel 2 to take place.

It is worth noting that there are two key qualifiers to this argument. First, EROI itself is likely to be partially determined by socio-political decisions. For example, the minimum EROI of society is influenced by the decisions about the technologies used to obtain energy and use energy (Court, 2019). Second, the requirement for energy firms to be profit making entities is itself a political choice. Nationalisation of the energy network is part of the current political discussion in the UK (e.g. UK Labour Party, 2019) and could substantially change the financial dynamic described above. It would not, however, impact the direct channels described earlier.

Another line of research suggests that negative productivity effects of declining EROI may come from the restructuring of the energy sector driving changes in investment and interest rates (Sterman, 1982, Fiddaman, 1997, 1998). In an economic transition period, a significant drop in productivity growth is expected due to “the misallocation of capital”: the changing and replacing of existing capital with more energy efficient technologies (Rye and Jackson, 2018). This slowdown in productivity growth is anticipated to have a long and persistent effect as both the energy and non-energy sector is affected by these dynamics. The transition is expected to lead to idle capital and incomplete capacity utilisation, as the result of investment adjusting to new energy prices (Fiddaman, 1998). Likewise, Sterman (1982) argues that the huge investments and resource requirements likely to be needed by the energy sector as it transitions to new technologies could lead to “crowding-out effects”. This could suck up available financial resources and raise interest rates. In this way declining EROI may indirectly impact investment in non-energy sectors.

7.3 Summary and Gaps

In summary EROI is an important policy tool that relates the higher energy cost in exploration and extraction and the increasing relative shortage of conventional fossil fuel sources to the energy prices. Some studies argue

that this relationship is non-linear and more significant at the long run. This relative scarcity of a basic input of the production process is expected to directly impact productivity and reduce both capital and labour productivity given that capital and energy are seen as complements. However, declining EROI is expected to affect productivity growth through other indirect channels as well. Investments in the energy sector in attempt to offset the declining EROI might have “crowding-effect” that implies lower investments in other productive sectors and more capital inflows to energy production. Prices of energy is not just dependent on EROI, there are other geo-political and market factors that affect energy prices. Yet, declining EROI could contribute to an adverse supply shock and increase in the cost of production and contribute to cost-driven inflation spiral and further productivity slow-down.

The literature directly linking EROI and productivity is in its infancy. We recommend further work explicitly developing links between the two concepts. In particular, we note that potential impacts EROI may have on productivity through price are highly contingent on political relationships and encourage work in this area.

8 | Economic Structure

Changes in the structure of production and consumption that occur as economic development progresses are important factors in determining growth of energy demand (Rosenstein-Rodan, 1943; Felipe et al., 2012; Hausmann and Hidalgo, 2010). Economic development here refers to the theory centred around the two-sector model developed by Lewis (1954). In Lewis’s model the expansion of the industrial sector was explained by the re-allocation of surplus labour from the agricultural sector whose productivity could be nearly negligible (Ranis and Fei, 1961). Links between Lewis’s economic development and energy can be explained using neoclassical firm theory. According to firm theory, the derived demand for inputs including energy, depends on the structure of final aggregate output (Berndt and Wood, 1975). This means that the relative demand on inputs changes based on the nature of demand on final goods and the relative importance of each economic sector. More developed economies are characterised by a greater share of the services sector in final output. This economic transition in the sectoral structure along the path of the economic

development affects energy demand and its responsiveness to productivity shocks (Yang et al., 2018).

The industrial sector currently consumes more than 54 percent of the total world delivered energy (International Energy Outlook, 2016). In the literature, there is a strong link between economic structure and energy demand (Hu et al., 2018; Chunbo and David, 2008; Feng et al., 2009). In the early stages of economic growth, the relative contribution of the industrial sector is high compared to agriculture and services and consequently the energy intensity in the economy is relatively high. However, the later stages of economic development reflect expanding share of services and other manufacturing sectors with less dependence on energy therefore global energy demand could fall (International Energy Outlook, 2016). There is empirical evidence that the structural transformation from the extractive and primary sectors to the secondary and tertiary sectors could reduce energy use (Rosenstein-Rodan, 1943; Felipe et al., 2012; Hausmann and Hidalgo, 2010).

However, falling growth rates of energy demand, do not mean that energy consumption will fall. In the latest McKinsey & Company reports, Nyquist (2016) and Sharma et al. (2019) predict that growth in global energy demand will persist, despite the year-on-year growth rate falling by an average of 0.7 percent through 2050.

8.1 Energy use and the Service Sector

Services may offer a path to reduced energy dependency. The energy intensity of the service sectors is typically lower than that of the industrial sectors (Figure 11, Jackson, 2017; Sharma et al. 2019). However, service activities are not energy free. They still rely on energy intensive activities: computers, for instance require material and energy inputs. In the case of service-based economies like the UK, the most energy intensive portions of the service supply chain take place in other countries. Production of services relies on importing energy intensive goods and services (Schipper et al., 1986, Moreau and Vuille, 2018). The energy intensity of the services sector is lower, but it is not zero. Mulder and Groot (2012) find that the changes the sectoral composition of the economy can significantly explain the dynamics of the aggregate demand on energy with the energy intensity levels at the services decreasing at lower levels than the manufacturing sector in 18 developed countries from 1970 to 2005.

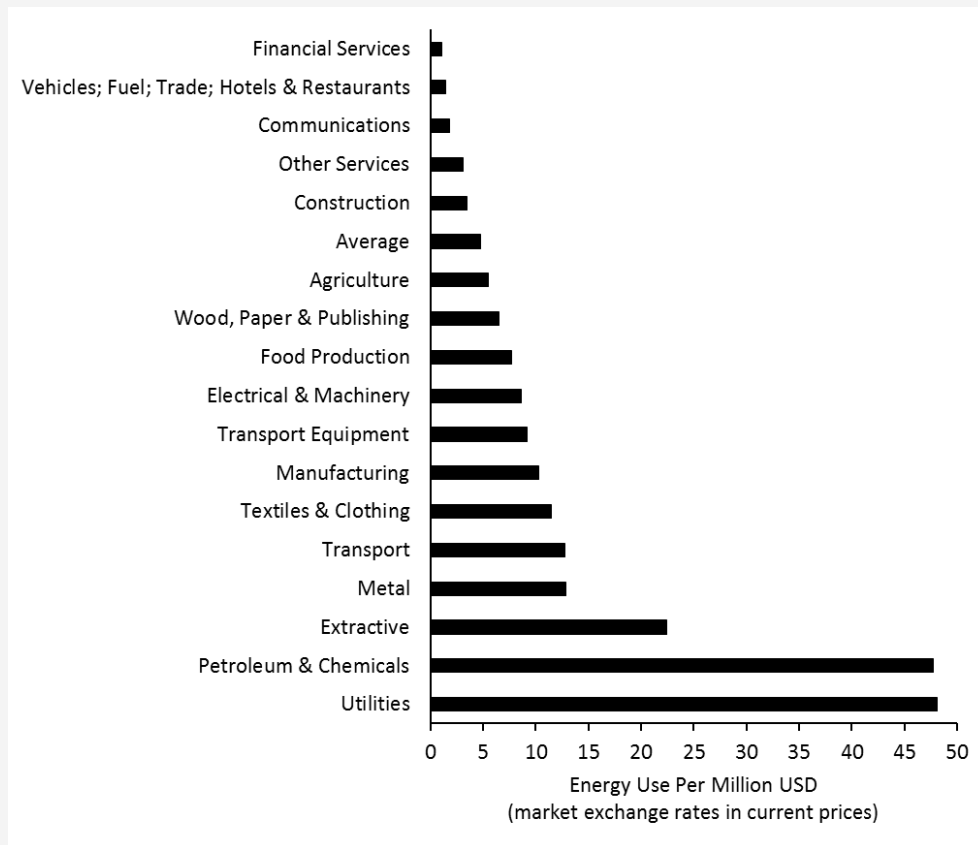


Figure 11: Energy use in different economic sectors in the UK.

Data from (Environmental Footprints, 2019)

Whether changes in sectoral composition lead to reductions in energy use depends on whether sectoral composition can lead to “decoupling”. Decoupling is the idea that we can break the historically observed relationship between energy and economic growth (Jackson and Victor 2019, Stern and Kander, 2012). Medlock III and Soligo (2001) argue that decoupling in the later stage of development is not necessarily the case as the rising incomes generate new demands on energy, and, consequently, the shares of total energy use in the residential and commercial and transport sectors increase. Galli (2012) argue that any attempt to analyse the patterns of energy demand as a function of the stage of the economic development should control for energy intensity that rises then declines after a certain critical point. However, Medlock III and Soligo (2001) found that the even if the sectoral share of energy demand change through the course of the economic growth and industrial energy intensity falls, total energy intensity is significantly slow to drop.

This has an important implication: if consumption of services rises fast enough, it can outstrip the gains that come from reduced energy intensity, leaving the economy and our lifestyles just as vulnerable to economic shocks. We see this in the case of the UK specifically. Hardt et al., (2017) argue that the increase in the share of service goods in final consumption, they argue, was sufficient to overwhelm improvements from changes in structure. This means that we have to consider the scale of production alongside a shift to services as we look to wean ourselves off energy. In France, Mairret and Decellas (2009) find that the growth in the economic growth of the services sector lead to a significant increase in total energy consumption of an average 1.5 percent.

8.2 The Service Sector and Productivity

However, while a services-oriented economic structure might reduce energy demand, it could also slow productivity growth. In 1966, Kaldor argued that the growing service sector was the cause of the UK's low productivity growth. This has become known as the Kaldor-Verdoorn law, a dynamic relation between industrial output growth and productivity growth (Verdoorn, 1949/2002, Rampa, 2002, McCombie and Spreafico, 2017). The basic rationale for the Kaldor-Verdoorn law is that the manufacturing sector is amenable to factors such as economies of scale, but these are only realised when entrepreneurs are investing. In turn this depends on their expectations about output (Lavoie, 2014). The Kaldor-Verdoorn law has been confirmed by a substantial number of empirical studies (McCombie et al., 2002, Knell, 2004, Marconi et al., 2016, Deleidi et al., 2018, Gabrisch, 2019). Similar arguments emerged as explanations for the low labour productivity growth of many wealthy nations after the 2008 financial crises (Barnett et al., 2014, Goodridge et al., 2016, Harris and Moffat, 2017). The full extent to which the service sector may play a role in slowdowns of productivity growth is not settled, but large literatures have grown up around the stylised fact that service sectors have low productivity growth.

Notable among these is Baumol's cost disease (Nordhaus, 2008, Baumol et al., 2012, Hartwig, 2011, 2015), which points out that if wages are linked to productivity growth then rising productivity growth in the industrial sector will push those wages up. To maintain a workforce, service sectors then have to increase their wages faster than their productivity growth rates, pushing up the relative cost of services compared to industry.

It may be possible to improve the ‘productivity’ of service sectors by increasing our use of energy. Artificial intelligence, for example, is increasingly being explored outside of routine -oriented tasks and could conceivably become widespread in the service sectors (Nielsen et al., 2016, Susskind, 2017, Kose and Sakata, 2019). The energy implications of such a transition are understudied. But early estimates are that AI is highly energy intensive (Strubell et al., 2019). Consequently ‘robotisation’ of services could be another example of using energy to make us more labour productive while also making us more dependent on energy. Increased energy dependence could potentially exacerbate the dangers posed by declining EROI and make it harder to avoid catastrophic climate change. Moreover, doing away with people may degrade services themselves.

One of the reasons that services (loosely defined) are thought to be low labour productivity growth sectors is that their human component is inherently desirable (Jackson, 2017). Care work and education, for example may be possible without people. But they will be qualitatively changed. This brings us to the question of what we want from the economy and from productivity.

Productivity in the broadest sense of getting more outputs per unit of input could be measured in many ways. The idea that services are low productivity refers principally to the idea of labour productivity: goods and services provided per hour worked. Yet many other forms of value are provided by the service sector. Workers in these sectors, often report high senses of wellbeing and fulfilment and are motivated by the sense of delivery of a social good (see, for example: Castel et al., 2011, Druckman and Mair, 2019 and the references in the accompanying report (Isham et al 2020) on Wellbeing and Productivity).

As discussed in Section 6, energy can be understood as a way of satisfying our core needs and wants (Brand-Correa and Steinberger, 2017). But how we use it to do this is conditioned by the structures of our social and economic systems. It may not be possible to derive a low energy, high productivity economy if we continue to define productivity as output of goods per unit of labour. However, if we reconceptualise productivity to be about quality of life, services may offer a useful route to achieving this.

8.3 Summary and Gaps

This section discussed how expanding the share of services and other less energy intensive manufacturing might impact productivity growth. Some literature argues such an economic restructuring should weaken the relationship between economic growth and energy demand. This is challenged by other studies who argue that rising incomes generate exponential demand on consumption of services, and, as a result, energy-saving gains the lower energy intensity of services could be overwhelmed by increased demand. Nonetheless, in a different social context, it may be possible to marry these two literatures. An increase in the share of service sector activity could reduce energy dependency, provided demand for these sectors is limited. However, this may reduce productivity growth.

The relationship between the dominance of the services sector and the slow-down in productivity growth is generally undecided. The lower technological intensity of some services and their labour-intensive nature might support this relationship. However, the effect of the modern digitalisation of services and the introduction of artificial intelligence in the services sector (with its intensive energy use) on productivity growth might need more examination. Some literature suggests that the increased share of services sector in the sectoral composition of the economy can have some other aspects of economic prosperity and generation of value, for example service delivery of social goods.

We suggest the following areas for further research:

1. The services-productivity link. On both an empirical and theoretical level, the issue of how services are linked to productivity is undetermined – especially in light of emerging technologies.
2. The services-energy-social value link. As of yet it is unclear just how great a potential the service sector has to reduce our energy dependence. Further work in this area should focus on the social structures that drive demand growth for service sector activities, and the link with broader productivity measures beyond market value.

9 | Climate Change and Productivity

There is a growing body of empirical evidence that the impacts of climate change will reduce a variety of macroeconomic metrics. Almost all empirical

studies of how changes in temperature will impact GDP find a negative relationship (see Figure 2 in Kahn et al., 2019). In a subset of macro-economic studies this negative impact comes about because of an assumed negative link between climate change and capital and labour productivity (reviewed in 9.1).

Any negative impacts that climate change has on productivity can at least partially be attributed to global energy systems. Energy production is a major contributor to climate change. Currently the energy system is dependent on continued use of fossil fuels. This is true both globally, and for the UK (UK Committee on Climate Change, 2019, Mair, 2018). Consequently, use of the current energy system is a major driver of any impacts that climate change may have on productivity.

Relatedly, action to reduce carbon emissions ('climate mitigation') is likely to involve major transformation of the energy system. Jackson (2019c) calculates that in order to remain below 1.5 degrees of warming, the carbon emissions in advanced nations may need to decline by rates as high as 20% per year, dramatically faster than anything that has been achieved over the last half century. However, this will itself only be possible with massive investment in new energy infrastructure, which could drive productivity growth.

9.1 Productivity in Climate-Economy Models

Lamperti et al., (2018) construct an agent-based integrated assessment model to explore climate-economy feedbacks. They allow for climate change induced temperature increases to impact worker labour productivity, and the energy efficiency, capital stock and inventories of firms. Shocks in the model are stochastic and vary in size and on which aspect of production they impact. Shocks in the beginning of the model start small (around 1%) and get bigger through the simulation period (reaching around 5%). Based on the average of 100 runs, Lamperti et al., report that shocks to labour productivity and capital stock generate the greatest economic instability.

Dafermos et al., (2017, 2018) develop a Post-Keynesian Stock-Flow Consistent Model with climate feedbacks. Climate damages are modelled as impacting aggregate demand, and the potential output of the economy by reducing labour and capital productivity. Capital productivity effects are included by incorporating a climate damage term into the depreciation

function. This means that increasing levels of climate change effectively speed up the deterioration of capital goods. Labour productivity effects are similarly modelled by including a climate damage term on the level (not growth rate) of labour productivity. It is important to note that for both labour and capital productivity, Dafermos et al., allow for adaptations to be made which mitigate productivity loss. The size of productivity loss is the net effect of the damage and the adaptation.

Dafermos et al., (2017, 2018) run a number of scenarios to show that proactive green finance packages that expand credit for renewable energy and other ‘clean’ projects can reduce the economic damage of climate change and allow greater economic expansion than conventional financing. However, they argue that green financing is not enough on its own. In all of their scenarios, economic output eventually declines due to climate damages, partially through impacts on capital and labour productivity.

Szewczyk, et al., (2019) bring together 5 different models of the relationship between labour productivity and temperature (in construction and agriculture) and temperature simulations from 5 different climate models (all using a high emissions scenario). They then shock a Computable General Equilibrium model with each of the 25 resulting labour productivity scenarios to estimate the wider economic impacts. Their average labour productivity estimates vary between a 2% reduction and a 21% reduction though this varies substantially across different world regions. They estimate a mean annual GDP loss of 0.6%. Again, this varies substantially by region. Szewczyk, et al., are notable for using a variety of labour productivity-temperature relations, and for using relationships based on empirical datasets. This grounds their model in empirical observation. However, this strength may also be a weakness. Models that rely heavily on empirical data rely on the idea that the past is a good guide to future (Jackson, 2019e). It is not certain that this will be the case with the temperature-labour productivity relation.

Matsumoto (2019) also incorporates temperature-labour productivity dynamics into a coupled climate/CGE model to assess the potential impact of climate change. Like Szewczyk, et al., (2019), Matsumoto finds only small impacts, though, again, these are regionally very diverse. The temperature-labour productivity impacts included in the model are based on empirical relationships derived by (Kjellstrom et al., 2009). These relationships are non-linear, such that higher temperatures have a larger impact on labour

productivity and have a threshold below which there is no impact on temperature. However, Matsumoto uses an adapted form of Kjellstrom et al's relation to ensure that there is always a minimum amount of labour productivity. On the other hand, Kjellstrom et al (2009) who base their work on occupational health and safety standards suggest labour productivity could decline to zero.

Having looked at four recent impact models that use the concept of climate damages and their impact on productivity, we now turn to evaluate the evidence base underlying these mechanisms.

9.2 Labour Productivity and Heat

In a systematic review Levi et al., (2018) identify 36 papers that examine the link between heat-related illness and injuries on worker productivity. It is worth noting that of these almost a third were themselves reviews of the literature, the rest were a combination of simulation models, cross-sectional studies and within-group comparisons. From the papers they study Levi et al, report 3 key mechanisms: 1) extreme heat reduces working hours (reducing output per worker); 2) the effect of temperature is most acute in physically demanding jobs; 3) dehydration associated with higher temperatures is a key driver of worker productivity loss.

The effects of excess heat are already felt by workers in hot climates or jobs that expose them to significant levels of heat. Based on a meta-analysis of 11 experimental studies of individuals who work under conditions of 'heat-stress' (temperatures where the body's mechanisms to control heat fail), they report that 30% of all workers in such conditions report productivity losses. Zander et al., (2015) use an online survey of 1726 adults to investigate self-reported reductions in productivity related to heat in Australia. They classify two types of productivity loss: 7% of their sample had been absent from work for at least 1 day in the previous 12 months. On the other hand, 70 percent reported a drop in the quality of their work for at least 1 day in the previous 12 months. These results are largely corroborated by for a range of other countries and work environments (Table 5).

The reason that workers in hot climates or who engage in physical work are thought to most at risk of heat related productivity loss heat is because the total heat in the body is a function of both the ambient temperature, and heat generated by the body itself (Levi et al., 2018, Shi et al., 2013, Kjellstrom

et al., 2016). The latter is significantly greater during manual work because of the heat generated by greater use of muscles (Kjellstrom et al., 2016). This leads to workers 'self-regulating' their temperature by reducing the intensity with which they work (Miller and Bates, 2007).

Table 5: Survey of studies exploring links between temperature and labour productivity

Citation	Type of Work	Location	Methodology	Key Findings
(Nag and Nag, 1992)	Seated, manipulative	N/A	Experimental	Productivity declined as temperature increased from 26 degrees C to 35.8 degrees C.
(Gun and Budd, 1995)	Shearers	Australia	Case Study	Productivity responses to temperature are mediated by behavioural factors
(Niemelä et al., 2002)	Telecommunication Office	Not Stated	Case Study	Labour productivity decreased 5–7%, when the air temperature exceeded 25 °C.
(Seppanen et al., 2006a)	Office	N/A	Meta-Analysis	Productivity peaks at 21.75 degrees c
(Crowe et al., 2009)	Sugar Cane	Costa Rica	Case Study	Workers self-reported declines in productivity with heat
(Delgado Cortez, 2009)	Sugar Cane	Nicaragua	Case Study	Productivity was negatively impacted by dehydration, but this is fixable by an intervention to improve hydration
(Kjellstrom et al., 2009)	All	Global	Simulation	Significant regional variation, but all regions suffer some labour productivity loss due to temperature increases. Notably, 11-27% reductions in labour productivity in South-East Asia, Andean and Central America, and the Caribbean.
(Hsiang, 2010)	Agriculture, Non-Agriculture	Caribbean	Econometric	Labour productivity losses of 2.4% per 1 degree C temperature increase in non-agricultural production. Labour productivity losses of 2.3% per 1 degree C temperature increase in agricultural production.
(Langkulsen et al., 2010)	Pottery, Knife, Power Plant, Construction	Thailand	Cross-Sectional	Workers self-reported productivity losses between 10 and 60% in the pottery and construction industries, but not in the knife or power plant industries.
(Dunne et al., 2013)	All	Global	Simulation	Heat stress has reduced labour capacity by 10% in peak months over recent decades. Labour capacity is projected to be reduced by 20% in peak months under scenarios restricted to 2 degrees of warming by 2050.
(Kershaw and Lash, 2013)	Office	UK	Simulation	Productivity is negatively impacted by extremes of temperature

Citation	Type of Work	Location	Methodology	Key Findings
(Kjellstrom et al., 2013)	Mainly outdoor	South-East Asia	Simulation	For heavy work, 30-40% of worktime is lost in the shade, 60-70% in the sun. Projections for 2050 suggest that for heavy work, 50-60% of afternoon worktime in the sun could be lost, heavy work in the sun could lose 80% of afternoon worktime; moderate work could see 50% reductions in work time.
(Sahu et al., 2013)	Rice Harvesting	India	Cross-sectional	Measured productivity (rice bundles collected) declined by about 5% for every degree of temperature increase.
(Hajizadeh et al., 2014)	Brick Production	Iran	Cross-sectional	Productivity is inversely correlated with temperature
(Sett and Sahu, 2014)	Brickfield	India	Cross-sectional	Linear decline in productivity as air temperature exceed 34.9 degrees C
(Zivin and Neidell, 2014)	All	US	Econometric	At extremes of temperature, labour productivity in high risk (e.g. outdoor) industries is significantly impacted. Only moderate impacts are observed in low risk (e.g. indoor) industries.
(Altinsoy and Yildirim, 2015)	Manual work/Outdoor Labour	Turkey	Simulation	Labour productivity in manual and outdoor (e.g. agriculture and construction) could fall by up to 52 % during the summer months between 2070-2100
(Burke et al., 2015)	Agriculture, Non-Agriculture	Global	Econometric	Labour productivity in all forms of work is sensitive to extremes of temperature. Agriculture is more sensitive.
(Zander et al., 2015)	Various	Australia	Cross-sectional	7% of workers reported at least one day of absence from work due to heat stress in the last year. 70 percent reported a drop in the quality of their work for at least 1 day in the previous 12 months
(Venugopal et al., 2016)	Various (principally manual work)	India	Cross-sectional	57% of workers self-reported productivity loss due to heat. This was more pronounced amongst outdoor workers.
(Krishnamurthy et al., 2017)	Steel	Southern India	Cross-sectional	Workers self-reported productivity loss due to heat exposure
(Lamb and Kwok, 2016)	Offices	New Zealand	Longditudinal	No relation between thermal comfort and work performance
(Lao et al., 2016)	Council	Australia	Case Study	Workers report that heat reduces their productivity
(Yi and Chan, 2017)	Construction	Hong Kong	Case Study	0.33% reduction in work time for a 1 degree temperature increase.
(Quiller et al., 2017)	Orchards	USA	Cross-Sectional	Little to no effect when workplace factors accounted for.

Citation	Type of Work	Location	Methodology	Key Findings
(Ioannou et al., 2017)	Grape picking	USA	Case Study	Increases in temperature were significantly related to lost labour time
(Setyawan et al., 2018)	Textiles	Indonesia	Case Study	Productivity is inversely correlated with temperature
(Lundgren-Kownacki et al., 2018)	Brick Kilns	India	Case Study	16% of workers report being absent from work due to heat, 48% report losing productivity due to heat
(Pogačar et al., 2018)	Manufacturing	Slovenia	Case Study	Managers' report heat stress reducing productivity
(Zhang et al., 2018)	Manufacturing	China	Econometric	Total Factor Productivity has an inverted U relationship with temperature.
(Chang et al., 2019)	Telecommunication Office	China	Econometric	At normal temperature ranges, productivity was not impacted.
(Kahn et al., 2019)	All	Global	Econometric	Productivity is negatively impacted by deviation from historical temperature norms
(Orlov et al., 2019)	Agriculture, Construction	Europe	Case Study	In the heat waves of 2003, 2010 and 2015, Europe saw average economic losses of \$59-90 per worker in agriculture and \$41-72 per worker in construction
(Zander and Mathew, 2019)	Various	Malaysia	Cross-sectional	Workers reported to have reduced work capacity on a median of 29 days in a year. On these days they felt that their work capacity was at least halved.

Across all the studies reviewed, there is a generally accepted relationship that extremes of heat are negatively associated with productivity, but the evidence supporting this is less robust for indoor workers in temperate climates. Of the 33 studies surveyed in Table 5, six specifically consider office workers and three explicitly consider temperate regions. Another 6 are macro level studies with no specific sectoral or geographical focus. Of these Zivin and Chang (2014) report smaller effects for indoor workers, while Lamb and Kwok (2016) and Chang et al., (2019) find no relation between temperature and work performance for office workers. This is attributed to the ability to control an indoor climate. On the other hand, three studies report that any change in temperature deviation from the ideal or norm is negative (Kahn et al., 2019, Kershaw and Lash, 2013, Seppanen et al., 2006b). The most recent of these, Kahn et al., (2019) construct and test a theoretical model linking changes in labour productivity growth to deviations in local temperatures. They calibrate the model using data from 1960-2014 and find that any deviation from local temperatures negatively affects labour

productivity growth, regardless of the income level or temperature base of the country under consideration.

Although there is a general consensus that temperature impacts productivity, several authors stress that this is not a straight-forward relationship. One proposed reason for this is the role that context plays in mediating exposure to heat and the capacity for adaptation. Gun et al., (1995) note that responses to heat capacity are often determined by personal or behavioural factors. In their study of sheep-shearers, in Australia they report that the weight and alcohol intake are important factors in mediating the effects of heat stress. Likewise, based on a review of the literature, Heal and Park (2016) suggest that although the short run effects of heat exposure on productivity are well established there is little evidence on how long run adaptations may be used to mitigate these effects. It is worth noting, however, that some researchers are sceptical of our ability to adapt. Kjellstrom et al (2016) argue that some forms of work will be very difficult to adapt with current technologies. For example, they point out that work outdoors or in large indoor environments will be hard to air condition. Day et al., (2019) are more optimistic suggesting that we have access to a wide range of options beyond air conditioning. They suggest optimisation of working hours to avoid peak temperatures, and for climate change induced heat to be accounted for in urban planning and building design.

9.3 Capital Productivity and Climate Change

The direct effects on capital productivity from climate change are in general less well studied than those on labour productivity. However, several mechanisms have been proposed. A number of authors suggest that capital stock may be directly damaged or destroyed by extreme weather events or by being left unused (Fankhauser et al., 1999, Dietz and Stern, 2015, Rezai et al., 2018).

The stranded assets thesis concerns how we manage the large amounts of capital currently tied up in the fossil fuel industry during a transition to a low carbon economy (Carbon Tracker, 2019, Jackson, 2019d). In order to avoid catastrophic climate change we must very rapidly transition away from fossil fuels as our energy base (UK Committee on Climate Change, 2019, Jackson, 2019c). This will leave a large quantity of fossil fuels unburnt, and power plants effectively useless (Carbon Tracker, 2015). Estimates in the literature vary based on the level of temperature increase they consider, as

well as the probability of achieving this (Jackson, 2019d). One recent study suggests that 10- 20% of the operating capacity of fossil fuel power stations must be stranded to remain below 3 degrees of warming (Pfeiffer et al., 2018). Carbon Tracker (2015) estimate 2 trillion US dollars' worth of investments that are at risk of stranding in the transition to a low carbon economy.

It is unclear just how stranding of these assets will impact productivity. There are relatively few economic modelling studies of the impacts of asset stranding (see Jackson 2019d for a notable exception). However, such a large quantity of unused assets clearly has the potential for substantial macroeconomic impacts. We can see, for example, how abandoning of fossil fuel plants could represent under-utilisation of capital, thereby reducing productivity, and also how attempts by firms to recoup lost capital could inflate energy prices. Further work is urgently needed in this area.

9.4 Increasing investment in Renewable Energy and Kaldor-Verdoorn effects.

Over the past two decades, energy trade has increased more than any other product with an average annual growth rate of 12 percent and fuel exports were more than eight times in ten years since 1995 (WTO, 2015). It is expected that a transition towards a larger share of renewables in the structure of the energy mix would generate a significant change in the energy linkages with the economic activity at the global and national level (IEA, 2016). Consequently, a transition to renewable energy generation could reduce recessionary impacts of energy prices and knock-on effects on productivity.

The other side of the stranded assets thesis is that a transition to a low carbon economy requires substantial investment in new infrastructure. Pollin (2015), for instance, presents a 20 year investment program bringing investment in renewable energy from 0.2-0.3% of Global GDP to 1.7-1.8% of Global GDP. The OECD (2011), suggests that the investments required to reduce global emissions by 2050 is around \$46 trillion. For context the IEA (2019) estimate that in 2018 global investment in energy supply and efficiency was around \$2 trillion. For the UK, the UK Committee on Climate Change (2019) estimates that to achieve net-zero carbon emissions by 2050, will require an annual investment in the energy sector to rise to £20 billion by 2050. Such a large-scale economic program is likely to effect productivity. It is possible that this wave of investment in new capital could boost

productivity growth via the Kaldor-Verdoorn mechanism introduced in Section 8.2.

An expansion of investment of capital-intensive energy infrastructure could, if the Kaldor-Verdoorn law holds, be expected to drive productivity growth. The Kaldor-Verdoorn mechanism rests on the idea that industrial production has specific qualities that make it amenable to productivity growth. Therefore, if investment in renewable technology stimulates industrial technology, and the Kaldor-Verdoorn law holds, productivity should grow. However, while correlations between industrial output growth and labour productivity have been confirmed by a substantial number of empirical studies (McCombie et al., 2002, Knell, 2004, Marconi et al., 2016, Deleidi et al., 2018, Gabrisch, 2019) such studies are not able to conclusively prove the direction of causality.

9.5 Innovation for a low-carbon economy and productivity

To achieve a low carbon economy, we require not just the massive expansion of renewables discussed in Section 9.4, but also innovations that improve energy efficiency, and storage. It is possible that the development of these new technologies could boost productivity growth by representing new opportunities for innovation.

Innovation has a long pedigree as a driver of productivity and economic growth. Adam Smith (1776) discusses with the ways that the division of labour creates conditions for innovating within a work process and made this key to his theory of growth. Arrow (1971), building on Smith, placed productivity gains from ‘learning by doing’ at the core of his growth model. Learning by doing Schumpeter’s growth theory famously relies on the notion of creative destruction and long period cycles of innovation (Aghion et al., 2013). Endogenous growth theory brings these ideas into mainstream frameworks focusing in particular on Research and Development (R&D) (Romer, 1986, 1994).

Aghion et al., (2019) argue that the transition to a low carbon economy could bring substantial innovations. They argue that low carbon technologies represent a greater potential for learning by doing because they are newer: incumbent fossil fuel technologies have exhausted their low hanging fruit opportunities with respect to productivity gains. They also suggest that there is the potential for spillover effects from direct innovations in low

carbon technology to productivity gains in other sectors. Dechezleprêtre et al., (2014) find that patents for ‘clean’ technologies receive on average 43% more citations than those for ‘dirty’ patents. On this basis they argue that potential knowledge spillovers from clean technologies are comparable to those of information technology – often considered a ‘general purpose technology’. However, some authors are cautious as to the potential of low carbon technologies to drive productivity growth. Foxon (2017) argues historical energy transitions became general purpose technologies through a complex set of circumstances. In particular, he argues that first energy systems had to prove their usefulness and economic viability to a wide variety of actors, something that low carbon technology may do but has not done yet. Foxon also argues that previous energy systems became general purpose technologies because of the way they developed with a wide variety of broader institutions and infrastructures that could take advantage of them. Whether this will happen with low carbon technology remains to be seen.

An additional question remains around how we might achieve innovation for a low carbon economy. An influential theory in mainstream economics is induced innovation. The theory of induced innovation posits that an increase in the price of one factor of production relative to another should induce innovations to decrease its demand (Hicks, 1932). So, rising energy prices should prompt energy efficiency gains. Using U.S. patent data from 1970 to 1994, Popp (2002) argues that energy prices are a substantial driver of energy efficiency. However, recent studies have shown that R&D spending in the energy sector in major industrialised countries is not necessarily associated with significant changes in energy efficiency or carbon reduction (McDonald, Schrattenholzer, 2001; Sagar and Holdren, 2002; Sagar and van der Zwaan, 2006). In part this has been attributed to the complexity of the energy sector.

The energy sector is likely to be vulnerable to path dependencies. Path dependency is the idea that future changes in a system are dependent on decisions made in the past. The accumulation of past investment decisions that are expensive and hard to change can ‘lock in’ a particular development path (Aghion et al., 2019, Grubler, 2004). This is particularly problematic in the energy sector because of its heavy reliance on long lived technologies (King, 2010). In an influential modelling study, Acemoglu et al., (2012) argues that decoupling productivity growth from ‘dirty’ energy will require government intervention in the form of a research subsidies and carbon

taxes. Aghion et al., (2019) argue that this is because in Acemeglu et al.'s model 'dirty' technology has a larger installed base at the start of the model run. Consequently, there is an existing network and infrastructure in place to use the dirty technology. This creates immediate economic incentives for profit maximising researchers to invest in better ways to use dirty technologies which can only be broken through government intervention.

9.6 Productivity as a driver of Climate Change

Productivity growth has itself been argued to be a major driver of greenhouse gas emissions. This is for a number of reasons, including the social dynamics that mean increasing productivity growth requires greater levels of production in order to maintain employment, which in turn drives energy use, and that productivity growth is often predicated on fossil energy use (Mair, 2019, Jackson and Victor, 2011, Ferguson, 2016).

One way to understand this analysis is through a macro-economic interpretation of the rebound effect (introduced in Section 6.3) As Jevon's pointed out in his 1865 book *The Coal Question*, there is the potential for a substantial 'rebound' effect through the kind of efficiency gains assumed by induced innovation. Induced innovation theory rests on the premise that as prices rise, this creates incentives to use energy more efficiently. The other side of this coin is that increased efficiency reduces costs, creating incentives to increase energy use.

Macro level studies also report rebound or rebound like effects (Sorrell, 2014, Allan et al., 2007, Hanley et al., 2009, Dimitropoulos, 2007). Sakai et al. (2019), for example report that energy efficiency has been a key driver of economic growth, which in turn creates more income and demand for goods, which requires energy use. The issue of rebound also comes up in the EROI literature where Murphy et al., refer to it as the 'growth paradox'.

The risk from significant rebound effects is that energy efficiency measures actually lead to increased energy dependency and making it harder to reduce our use of fossil fuels. This is evidenced by studies that report complementary relationships between renewable energy use and fossil fuel use (Omri and Nguyen, 2014, Kumar et al., 2015). This suggests that without substantive changes to our social structure induced energy efficiency measures will be insufficient to avoid the EROI or Climate Change, with their attendant impacts on productivity.

A full treatment of the potential relation between productivity growth and climate change is beyond the scope of this review. But we point to work in the ecological economics, feminist economics and post/degrowth communities which argues that we may need to rethink the basis of the economy, and learn to live with fewer, or no productivity gains to avoid catastrophic climate change (Jackson, 2019a, Raworth, 2017, Mair, 2019, Power, 2004, Ferguson, 2016, Kallis et al., 2012, Nørgård, 2013, Kallis and March, 2015, Mair et al., 2018, Nelson and Power, 2018).

It may seem extreme to suggest that we reduce productivity growth in order to avoid climate change. However, the risks of extreme climate change scenarios are uncertain, but potentially catastrophic. Modern human civilisation, settled societies, agriculture, and capitalism all evolved during a period of climatic stability known as the Holocene. Climate change risks pushing the climate out of this period of climatic stability by warming the climate to temperatures that humans as a species have never lived with (Burke et al., 2018). Ecological economists point out that we simply have no way of knowing whether an economy that developed under one set of climatic conditions can operate under a different set (Raworth, 2017, Mair, 2019).

From this perspective, climate change poses an existential threat to society as we know it. Consequently, if productivity is lost due to mitigation, this may be a price worth paying. Especially as the literature overwhelmingly points to a loss of productivity due to climate impacts. If we can transform the economy to be stable without productivity growth as conventionally measured, the literature suggests that there could even be positive social outcomes as well as environmentally beneficial ones (Jackson 2017).

9.7 Summary and Gaps

The energy system is a key driver of climate change. Researchers have suggested that productivity growth could be impacted by climate change. Several recent climate-economy models suggest climate impacts on productivity could be an important way in which the economy is impacted by climate change, though the estimated size of the effect depends on the model used.

There is a substantial evidence base around one proposed way that climate change would reduce labour productivity. Reviewing studies on heat effects

on workers we found broad agreement that this was likely to happen. However, the evidence base is stronger for manual workers and those already in hot climates.

There is less evidence on the ways that capital may be affected by climate change. However, researchers have offered a number of possible mechanisms including direct damage from extreme weather and abandonment. Better evidenced is the risk of ‘asset stranding’ if we move to a low carbon economy. However, the macro-economic implications of stranding remain relatively unexplored

There is a possibility that renewable and low carbon technologies could boost productivity growth. This could happen through a dynamic investment channel: increased spending on capital intensive energy systems could boost productivity growth through Kaldor-Verdoorn effects. Likewise, it has been suggested that low carbon technologies offer opportunities for learning by doing.

Finally, we pointed to the literature suggesting that productivity growth is itself a driver of climate change. This can be understood as a macro-economic rebound effect: as we become more productive, this incentivises us to use more energy. There is a large literature that is critical of the notion of productivity, partially on these grounds.

We suggest the following areas for further research:

1. Systematic comparison of the theoretical assumptions of different climate-economy models with respect to productivity. CGE models appear to find small impacts via productivity, while others find much more substantial impacts.
2. Research into the specific mechanisms by which energy capital may influence productivity. There is little empirical work on the ways that capital may be impacted by climate change or mitigation efforts.

Transformational strategies to avoid climate change. A substantial body of work suggests that productivity growth may be driving climate change. Consequently, structural transformation may be required to avoid it.

10 | Conclusions

In this report we have aimed to map and synthesised perspectives on the energy-productivity relation from a wide range of disciplines. Researchers have proposed a range of links between energy and productivity. However, the evidence base supporting (or not) these mechanisms is at best incomplete, and empirical results are rarely conclusive.

In section 2 we introduced key theoretical elements of productivity measurement. Although energy measures of productivity are used, their use is rare compared to capital and labour. Likewise, productivity research focuses almost exclusively on market measures of output. We suggested that productivity research would benefit from a broader scope, engaging more fully with energy metrics of productivity, and broader output measures.

In Section 3 we reviewed the literature exploring the long run relationship between energy and productivity. Over the long run there is a relationship between energy and labour productivity growth. However, there is little agreement on the causes of this relationship.

Many of the mechanisms that could explain a relationship between energy and productivity rely on an assumption about whether energy and capital are complements or substitutes. We explored this in Section 4, setting out the theoretical bases for these claims, and then reviewing the empirical evidence. There is no solid empirical basis for any particular relationship between energy and capital. The empirical data is inconclusive and conflicting, despite having a striking homogeneity in its methods. The problems start at a fundamental point in the operationalisation of production theory – notably in capital datasets. We recommend a re-examination of empirical methods used in this area of productivity research.

There is a large literature looking at links between energy prices and productivity (Section 5). We reviewed 4 proposed channels within this literature: the potential inflationary effects of energy price rises, effects via expectations, adjustment costs, and the marginal productivity of labour. Again, we suggest that there are difficulties in proving any of these channels or their relative sizes empirically.

If the channels identified via capital and price do hold, then it may be necessary to reduce our dependence on energy (Section 6). In this way we will reduce our exposure to energy shocks. Marginal changes appear to be

unlikely to sufficient, however, and we recommend future research explores the potential for transformational changes in our energy consumption.

In Section 7 we turned to the quality of energy measured by Energy Return on Energy Invested (EROI). The literature suggests that EROI values are declining for a wide range of fuels. This could directly affect productivity because it means we have to use more energy to obtain the energy we need just to maintain current production. Has also been suggested that EROI may be a long run determinant of price, in which case EROI may also impact productivity through price channels. However, this latter is less clear in part because the link between EROI and price is contingent on the political context of energy supply systems. We recommend further work on EROI-productivity links, particularly how they are mediated by socio-political systems.

Economic structure is a major driver of energy consumption and may influence productivity growth. This is particularly pertinent as shifting to a service-based economy has been proposed as a way to reduce our dependence on energy. However, this is disputed on the grounds that increases in demand for services have the potential to drive up overall demand, and therefore energy use, even though services have low energy intensities. It is also possible that a shift to service-based economies could reduce productivity growth. We recommend future work focus on the twin challenges of just how services and productivity are linked, and on the social structures that drive demand growth in service sector activities, and the link with social value.

Finally, we explored the links between energy and climate change. The literature is largely in agreement that climate change, driven by our energy system, is likely to damage productivity – though how much this will damage the broader economy is disputed. However, the effects that our response to climate change will have on productivity is less clear. It could lead to substantial productivity loss via stranded assets or could lead to productivity growth through investment and innovation. This is a key area for further work. There is also a substantial body of work that points to productivity growth as a key driver to climate change, and argues for a rethinking of productivity growth altogether. We suggest further work in this area, to ensure that we are able to meet the potentially existential threat of climate change.

References

- Abbott, M. (2018) 'Productivity: a history of its measurement', *History of Economic Thought and Policy*, 1, pp. 57-80.
- Abrahamse, W., Steg, L., Vlek, C. and Rothengatter, T. (2005) 'A review of intervention studies aimed at household energy conservation', *Journal of Environmental Psychology*, 25(3), pp. 273–291.
- Abramovitz, M. (1956) *Resource and Output Trends in the United States Since 1870*. Available at: <http://www.nber.org/books/abra56-1> (Accessed: 01/10 2019).
- Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D. (2012) 'The Environment and Directed Technical Change', *American Economic Review*, 102(1), pp. 131–66.
- Aghion, P., A, U. and Howitt, P. (2013) What do we learn from Schumpeterian growth theory? Working paper, Department of Economics, Harvard University. Available at: <http://nrs.harvard.edu/urn-3:HUL.InstRepos:27755233> (Accessed: 10/10 2018).
- Aghion, P., Hepburn, C., Teytelboym, A. and Zenghelis, D. (2019) 'Path dependence, innovation and the economics of climate change', in Fouquet, R. (ed.) *Handbook on Green Growth*: Edward Elgar Publishing.
- Allan, G., Hanley, N., McGregor, P., Swales, K. and Turner, K. (2007) 'The impact of increased efficiency in the industrial use of energy: A computable general equilibrium analysis for the United Kingdom', *Energy Economics*, 29(4), pp. 779-798.
- Allen, R. (2009) *The British Industrial Revolution in Global Perspective*. USA: Cambridge University Press, p. 331.
- Altinsoy, H. and Yildirim, H. A. (2015) 'Labor productivity losses over western Turkey in the twenty-first century as a result of alteration in WBGT', *International journal of biometeorology*, 59(4), pp. 463-471.
- Applebaum, E. and Kohli, U. (1997) 'Import price uncertainty and the distribution of income', *The Review of Economics and Statistics*, 79(4), pp. 620-630.
- Arnberg, S. and Bjorner, T. (2007) 'Substitution between energy, capital, and labor within industrial companies: a micro panel data analysis', *Resource and Energy Economics*, 29, pp. 122–136.
- Arrow, K. J. (1971) 'The economic implications of learning by doing', *Readings in the Theory of Growth*: Springer, pp. 131-149.
- Asensio, O. I. and Delmas, M. A. (2015) 'Nonprice incentives and energy conservation', *Proceedings of the National Academy of Sciences*, 112(6), pp. E510-E515.

- Atkeson, A. and Kehoe, P. J. (1999) 'Models of energy use: Putty-putty versus putty-clay', *American Economic Review*, 89(4), pp. 1028-1043.
- Atkinson, S. and Halvorsen, R. (1984) 'Parametric Efficiency Tests, Economies of Scale, and Input Demand in U.S. Electric Power Generation', *International Economic Review*, 25(3), pp. 647-662.
- Ayres, R. and Voudouris, V. (2014) 'The economic growth enigma: Capital, labour and useful energy?', *Energy Policy*, 64, pp. 16-28.
- Ayres, R. and Warr, B. (2005) 'Accounting for growth: the role of physical work', *Structural Change and Economic Dynamics*, 16, pp. 181-209.
- Ayres, R., van den Bergh, J., Lindenberger, D. and Warr, B. (2013) 'The underestimated contribution of energy to economic growth', *Structural Change and Economic Dynamics*, 27, pp. 79-88.
- Baily, M. (1981) 'Productivity and the Services of Capital and Labor', *Brookings Papers on Economic Activity*, (1), pp. 1-65.
- Balke, N. S., Brown, S. P. and Yücel, M. K. (2002) 'Oil price shocks and the US economy: Where does the asymmetry originate?', *The Energy Journal*, pp. 27-52.
- Bank of England (2019) Data. Available at: <https://www.bankofengland.co.uk/statistics/research-datasets> (Accessed: 12/11 2019).
- Barker, T., Ekins, P., & Foxon, T. (2007). The macro-economic rebound effect and the UK economy. *Energy Policy*, 35(10), 4935-4946.
- Barnett, A., Batten, S., Chiu, A., Franklin, J. and Sebastiá-Barriel, M. (2014) 'The UK productivity puzzle', *Bank of England Quarterly Bulletin*, Q2, pp. 114-128.
- Baumeister, C. and Kilian, L. (2016) 'Lower oil prices and the US economy: Is this time different?', *Brookings Papers on Economic Activity*, 2016(2), pp. 287-357.
- Baumeister, C. and Peersman, G. (2013.) 'Time-varying effects of oil supply shocks on the US economy', *American Economic Journal: Macroeconomics*, 5(4), pp. 1-28.
- Baumeister, C., Kilian, L. and Zhou, X. (2017) Is the Discretionary Income Effect of Oil Price Shocks a Hoax? Available at: <https://www.bankofcanada.ca/wp-content/uploads/2017/11/swp2017-50.pdf> (Accessed: 12/10 2019).
- Baumol, W., de Ferranti, D., Malach, M., Pablos-Mendez, A., Tabish, H. and Wu, L. (2012) *The Cost Disease: Why Computers get Cheaper and Health Care Doesn't*.
- BEIS (2017) *Building Our Industrial Strategy: Green Paper* (Accessed: 06/01 2018).
- BEIS (2018) *Industrial Strategy: Building a Britain Fit for the Future*. Available at:

- https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf (Accessed: 29/04 2018).
- Berg, M., Hartley, B. and Richters, O. (2015) 'A stock-flow consistent input-output model with applications to energy price shocks, interest rates, and heat emissions', *New Journal of Physics*.
- Bernanke, B. S. (1983) 'Irreversibility, uncertainty, and cyclical investment', *The Quarterly Journal of Economics*, 98(1), pp. 85-106.
- Bernanke, B. S., Gertler, M., Watson, M., Sims, C. A. and Friedman, B. M. (1997) 'Systematic monetary policy and the effects of oil price shocks', *Brookings papers on economic activity*, 1997(1), pp. 91-157.
- Berndt, E. and Khaled, M. (1979) 'Parametric Productivity Measurement and Choice Among Flexible Functional Forms', *Journal of Political Economy*, 87(6), pp. 1220-1245.
- Berndt, E. and Wood, D. (1975) 'Technology, Prices, and the Derived Demand for Energy', *The Review of Economics and Statistics*, 57(3), pp. 259-268.
- Berndt, E. and Wood, D. (1979) 'Engineering and Econometric Interpretations of Energy-Capital Complementarity', *The American Economic Review*, 69(3), pp. 342-354.
- Berndt, E. and Wood, D. (1986) 'Energy Price Shocks and Productivity Growth in US and UK Manufacturing', *Oxford Review of Economic Policy*, 2(3), pp. 1-31.
- Bjorndal, T., Gordon, D. and Singh, B. (1988) 'Economies of scale in the Norwegian fish-meal industry: implications for policy decisions', *Applied Economics*, 20(1), pp. 1321-1332.
- Blanchard, O. and Gali, J. (2008) 'The macroeconomic effects of oil price shocks: why are the 2000's so different from the 1970's?', in Gali, J. & Gertler, M. (eds.) *International Dimensions of Monetary Policy*: University of Chicago Press.
- Bloom, N. (2009) 'The impact of uncertainty shocks', *Econometrica*, 77(3), pp. 623-685.
- Boehnert, J, S. Mair and C Landa-Avila (2019). Mapping Method Report—Exploring the Links between Energy, Wellbeing and Productivity. Online at: www.cusp.ac.uk/themes/powering-productivity.
- Bohi, D. (1991) 'On the macroeconomic effects of energy price shocks', *Resources and Energy*, 13(2), pp. 145-162.
- Brand-Correa, L. and Steinberger, J. (2017) 'A Framework for Decoupling Human Need Satisfaction from Energy Use', *Ecological Economics*, 141, pp. 43-52.
- Brand-Correa, L., Brockway, P., Copeland, C., Foxon, T., Owen, A. and Taylor, P. (2017) 'Developing an Input-Output Based Method to Estimate a National-Level Energy Return on Investment (EROI)', *Energies*, 10(4).

- Brandt, A. (2017) 'How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI)', *BioPhysical Economics and Resource Quality*, 2(2).
- Broadberry, S., Guan, H. and Li, D. (2018) 'China, Europe, and the Great Divergence: A Study in Historical National Accounting, 980–1850', *The Journal of Economic History*, 78(4), pp. 955–1000.
- Broadstock, D., Hunt, L. and Sorrell, S. (2007) Review of evidence for the rebound effect. Technical report 3: elasticity of substitution studies.: UKERC. Available at: <http://www.ukerc.ac.uk/publications/ukerc-review-of-evidence-for-the-rebound-effect-technical-report-3-elasticity-of-substitution-studies.html> (Accessed: 03/10 2019).
- Brockway, P. E., Owen, A., Brand-Correa, L. I. and Hardt, L. (2019b) 'Estimation of global final stage energy return-on-investment for fossil fuels with comparison to renewable energy sources', *Nature Energy*, 4(7), pp. 612–621.
- Brockway, P., Barrett, J., Foxon, T. and Steinberger, J. (2014) 'Divergence of trends in US and UK aggregate exergy efficiencies 1960–2010.', *Environmental science & technology*, 48(16), pp. 9874–9881.
- Brockway, P., Heun, M., Santos, J. and Barrett, J. (2017) 'Energy-Extended CES Aggregate Production: Current Aspects of Their Specification and Econometric Estimation', *Energies*, 10(202).
- Brockway, P., Owen, A., Brand-Correa, L. and Hardt, L. (2019c) 'Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. ', *Nature Energy*, 4(7), pp. 612–621.
- Brockway, P., Sorrell, S., Foxon, T. and Miller, J. (2019a) 'Exergy economics - New insights into energy consumption and economic growth', in Jenkins, K. & Hopkins, D. (eds.) *Transitions in Energy Efficiency and Demand: The Emergence, Diffusion and Impact of Low-Carbon Innovation*, pp. 23.
- Brown, S. and Yücel, M. (2002) 'Energy prices and aggregate economic activity: an interpretative survey', *The Quarterly Review of Economics and Finance*, 42(2), pp. 193–208.
- Burke, K., Williams, J., Chandler, M., Haywood, A., Luntf, D. and Otto-Bliesner, B. (2018) 'Pliocene and Eocene provide best analogs for nearfuture climates', *Proceedings of the National Academy of Sciences*, 115(52), pp. 13288–13293.
- Burke, M., Hsiang, S. M. and Miguel, E. (2015) 'Global non-linear effect of temperature on economic production', *Nature*, 527(7577), pp. 235.
- Burney, N. and Al-Matrouk, F. (1996) 'Energy conservation in electricity generation: A case study of the electricity and water industry in Kuwait. *Energy Economics*', *Energy Economics*, 18(1-2), pp. 69–79.

- Carbon Tracker (2015) Carbon Tracker, 2015, The \$2 trillion stranded assets danger zone: How fossil fuel firms risk destroying investor returns. Available at: <https://www.carbontracker.org/reports/stranded-assets-danger-zone/> (Accessed: 21/10 2019).
- Carbon Tracker (2019) Stranded Assets
- Carnahan, W., Ford, K., Rochlin, G., Socolow, R., Hartley, D. and Hardesty, D. (1975) Technical Aspects of the More Efficient Utilization of Energy: Chapter 2—Second law efficiency: The Role of the Second Law of Thermodynamics in Assessing the Efficiency of Energy Use. Available at: <https://aip.scitation.org/doi/abs/10.1063/1.30306> (Accessed: 08/10 2019).
- Casler, S. (1997) 'Applied production theory: explicit, flexible, and general functional forms', *Applied Economics*, 29, pp. 1483-1492.
- Castel, D., Lemoine, C. and Durand-Levigne, A. (2011) 'Working in Co-operatives and the Social Economy: Effects on Job Satisfaction and the Meaning of Work.', *Perspectives Interdisciplinaires Sur Le Travail et La Sante*, 13(2).
- Castree, N. (2003) 'Commodifying what nature?', *Progress in human geography*, 27(3), pp. 273-297.
- Chang, K. (1994) 'Capital-Energy Substitution and Multilevel CES Production Function', *Energy Economics*, 16(1), pp. 22-26.
- Chang, T. Y., Graff Zivin, J., Gross, T. and Neidell, M. (2019) 'The effect of pollution on worker productivity: evidence from call center workers in China', *American Economic Journal: Applied Economics*, 11(1), pp. 151-72.
- Chitnis, M., Sorrell, S., Druckman, A., Firth, S. K. and Jackson, T. (2013) 'Turning lights into flights: Estimating direct and indirect rebound effects for UK households', *Energy Policy*, 55(0), pp. 234-250.
- Chitnis, M., Sorrell, S., Druckman, A., Firth, S. and Jackson, T. (2014) 'Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups', *Ecological Economics*, 106, pp. 12-32.
- Christensen, L. and Greene, W. (1976) 'Economies of Scale in U.S. Electric Power Generation', *Journal of Political Economy*, 84(4), pp. 655-676.
- Christensen, L., Jorgenson, D. and Lau, L. (1973) 'Transcendental Logarithmic Production Frontiers
- Chung, J. (1987) 'On the Estimation of Factor Substitution in the Translog Model', *The Review of Economics and Statistics*, 69(3), pp. 409-417.
- Clark, J. (1908) *The Distribution of Wealth: A Theory of Wages, Interest and Profits*. Available at: <https://oll.libertyfund.org/titles/clark-the-distribution-of-wealth-a-theory-of-wages-interest-and-profits> (Accessed: 03/09 2019).

- Clark, T. and Terry, S. (2010) 'Time Variation in the Inflation Passthrough of Energy Prices', *Journal of Money, Credit and Banking*, 42(7), pp. 1419-1433.
- Cleveland, C. and O'Connor, P. (2011) 'Energy Return on Investment (EROI) of Oil Shale', *Sustainability*, 3(11), pp. 2307-2322.
- Cortwright, J. (2008) Driven to the brink: how the gas price spike popped the housing bubble and devalued the suburbs. Available at: https://community-wealth.org/sites/clone.community-wealth.org/files/downloads/paper-cortwright_0.pdf (Accessed: 22/10 2019).
- Costantini, V., Crespi, F. and Paglialunga, E. (2019) 'Capital–energy substitutability in manufacturing sectors: methodological and policy implications', *Eurasian Business Review*, 9, pp. 157-182.
- Court, V. (2019) 'An Estimation of Different Minimum Exergy Return Ratios Required for Society', *BioPhysical Economics and Resource Quality*, 4(11), pp. 1-13.
- Crafts, N. (2009) 'Solow and Growth Accounting: A Perspective from Quantitative Economic History', *History of Political Economy*, 41(Suppl 1), pp. 200-220.
- Crowe, J., van Wendel de Joode, B. and Wesseling, C. (2009) 'A pilot field evaluation on heat stress in sugarcane workers in Costa Rica: What to do next?', *Global Health Action*, 2(1), pp. 2062.
- Cullen, J. M. and Allwood, J. M. (2010) 'Theoretical efficiency limits for energy conversion devices', *Energy*, 35(5), pp. 2059-2069.
- Cunado, J. and De Gracia, F. P. (2005) 'Oil prices, economic activity and inflation: evidence for some Asian countries', *The Quarterly Review of Economics and Finance*, 45(1), pp. 65-83.
- Dafermos, Y., Nikolaidi, M. and Galanis, G. (2017) 'A stock-flow-fund ecological macroeconomic model', *Ecological Economics*, 131, pp. 191-207.
- Dafermos, Y., Nikolaidi, M. and Galanis, G. (2018) 'Climate change, financial stability and monetary policy', *Ecological Economics*, 152, pp. 219-234.
- Dahl, C. and Erdogan, M. (2000) 'Energy and interfactor substitution in Turkey. ', *OPEC Review*, 24(1), pp. 1-22.
- Daly, H. (1968) 'On Economics as a Life Science', *Journal of Political Economy*, 76(3), pp. 392-406.
- Darby, S. (2006) 'Social learning and public policy: Lessons from an energy-conscious village', *Energy policy*, 34(17), pp. 2929-2940.
- Dargay, J. (1983) 'The Demand for Energy in Swedish Manufacturing Industries', *The Scandinavian Journal of Economics*, 85(1), pp. 37-51.

- Davis, S. J. and Haltiwanger, J. (2001) 'Sectoral job creation and destruction responses to oil price changes', *Journal of monetary economics*, 48(3), pp. 465-512.
- Day, E., Fankhauser, S., Kingsmill, N., Costa, H. and Mavrogianni, A. (2019) 'Upholding labour productivity under climate change: an assessment of adaptation options', *Climate policy*, 19(3), pp. 367-385.
- De Stercke, S. (2014) *Dynamics of Energy Systems: A Useful Perspective*. IIASA Interim Report. Available at: <http://pure.iiasa.ac.at/id/eprint/11254/> (Accessed: 08/06 2018).
- de Vries, P. (2010) 'The California School and Beyond: How to Study the Great Divergence? ', *History Compass*, 8(7), pp. 730-751.
- de Vries, P. 2001. Are coal and colonies really crucial? Kenneth Pomeranz and the great divergence. JSTOR.
- Debeir, J., Deleage, J. and Hemery, D. (1991) *In the Servitude of Power: Energy and Civilization Through the Ages*. Translated by: Barzman, J. London: Zed Books.
- Dechezleprêtre, A., Martin, R. and Mohnen, M. (2014) 'Knowledge spillovers from clean and dirty technologies'.
- Deleidi, M., Meloni, W. and Stirati, A. (2018) Structural change, labour productivity and the Kaldor-Verdoorn law: evidence from European countries. Available at: [http://dipeco.uniroma3.it/db/docs/WP%20239\(1\).pdf](http://dipeco.uniroma3.it/db/docs/WP%20239(1).pdf) (Accessed: 01/11 2019).
- Delgado Cortez, O. (2009) 'Heat stress assessment among workers in a Nicaraguan sugarcane farm', *Global health action*, 2(1), pp. 2069.
- Dengler, C. and Strunk, B. (2017) 'The Monetized Economy Versus Care and the Environment: Degrowth Perspectives On Reconciling an Antagonism', *Feminist Economics*, 24(3), pp. 160-183.
- Denny, M., May, J. D. and Pinto, C. (1978) 'The demand for energy in Canadian manufacturing: Prologue to an energy policy', *Canadian Journal of Economics*, pp. 300-313.
- Dietz, S. and Stern, N. (2015) 'Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions', *The Economic Journal*, 125(583), pp. 574-620.
- Diewert, E. (2018) 'Productivity Measurement in the Public Sector', in Griffell-Tatje, E., Lovell, C. & Sickles, R. (eds.) *The Oxford Handbook of Productivity Analysis*. New York: Oxford University Press, pp. 241-285.
- Dimitropoulos, J., & Sorrell, S. (2006, June). The rebound effect: microeconomic definitions, extensions and limitations. In *Proceedings of the 29th IAEE international conference*, Potsdam, Germany.

- Dimitropoulos, J. (2007) 'Energy productivity improvements and the rebound effect: An overview of the state of knowledge', *Energy Policy*, 35(12), pp. 6354-6363.
- Dixit, A. K., Dixit, R. K. and Pindyck, R. S. (1994) *Investment under uncertainty*. Princeton university press.
- Docherty, I. and Waite, D. (2018) *Productivity Insights Network Evidence Review 03: Infrastructure*. Available at: https://productivityinsightsnetwork.co.uk/app/uploads/2018/07/Evidence-Review_Infrastructure-1.pdf (Accessed: 05/10 2018).
- Doms, M. and Dunne, T. (1998) 'Capital adjustment patterns in manufacturing plants', *Review of economic dynamics*, 1(2), pp. 409-429.
- Doyal, L. and Gough, I. (1991) *A theory of human need*. Macmillan International Higher Education.
- Druckman, A. and Jackson, T. (2008) *The Surrey Environmental Lifestyle Mapping (SELMA) Framework: Development and Key results to Date*. Available at: http://www3.surrey.ac.uk/resolve/Docs/WorkingPapers/RESOLVE_WP_08-08.pdf.
- Druckman, A. and Mair, S. (2019) *Wellbeing, Care and Robots —Prospects for good work in the health and social care sector*, CUSP Working Paper No. 21. Guildford: University of Surrey. Available at: <https://www.cusp.ac.uk/themes/s2/wellbeing-care-robots/> (Accessed: 18/9 2019).
- Dunne, J. P., Stouffer, R. J. and John, J. G. (2013) 'Reductions in labour capacity from heat stress under climate warming', *Nature Climate Change*, 3(6), pp. 563.
- Dwyer, W., Leeming, F., Cobern, M., Porter, B. and Jackson, J. (1993) 'Critical review of behavioural interventions to preserve the environment: Research since 1980', *Environment and Behaviour*, 25, pp. 485-505.
- Economic Growth', *The Energy Journal*, 33(3), pp. 125-152.
- Edelstein, P. and Kilian, L. (2009) 'How sensitive are consumer expenditures to retail energy prices? ', *Journal of Monetary Economics*, 56(6), pp. 766-779.
- Environmental Footprints (2019) data. Available at: <https://environmentalfootprints.org/explorer> (Accessed: 9/10 2019).
- European Commission, IMF, OECD, UN and World Bank (2008) *System of National Accounts*. Available at: <http://unstats.un.org/unsd/nationalaccount/docs/SNA2008.pdf> (Accessed: 17/11/2015).
- Fagnart, J. and Germain, M. (2016) 'Net energy ratio, EROEI and the macroeconomy', *Structural Change and Economic Dynamics*, 37, pp. 121-126.

- Fan, Y., Liao, H. and Wei, Y.-M. (2007) 'Can market oriented economic reforms contribute to energy efficiency improvement? Evidence from China', *Energy Policy*, 35(4), pp. 2287-2295.
- Fankhauser, S., Smith, J. B. and Tol, R. S. (1999) 'Weathering climate change: some simple rules to guide adaptation decisions', *Ecological economics*, 30(1), pp. 67-78.
- Ferderer, J. P. (1996) 'Oil price volatility and the macroeconomy', *Journal of macroeconomics*, 18(1), pp. 1-26.
- Ferguson, P. (2016) 'Productivity growth as a barrier to a sustainability transition', *Environmental Innovation and Societal Transitions*, 20, pp. 86-88.
- Fiddaman, T. (1997) Feedback complexity in integrated climate-economy models. PhD, Massachusetts Institute of Technology.
- Fiddaman, T. 'A feedback-rich climate-economy model', 16th International Conference of the Systems Dynamics Society, Quebec.
- Financial Markets. Available at: <https://www.carbontracker.org/terms/stranded-assets/> (Accessed: 17/06 2019).
- Finn, M. (2000) 'Perfect Competition and the Effects of Energy Price Increases on Economic Activity', *Journal of Money, Credit and Banking*, 32(3), pp. 400-416.
- Fiorito, G. and van den Bergh, J. (2016) 'Capital-energy substitution in manufacturing for seven OECD countries: learning about potential effects of climate policy and peak oil', *Energy Efficiency*, 9, pp. 49-65.
- Firfiray, S., Larraza-Kintina, M. and Gomez-Mejia, L. (2018) 'The Labor Productivity of Family Firms: A Socio-Emotional Wealth Perspective', in Griffell-Tatje, E., Iovell, C. & Sickles, R. (eds.) *The Oxford Handbook of Productivity Analysis*. New York: Oxford University Press, pp. 387-491.
- Fizaine, F. and Court, V. (2016) 'Energy expenditure, economic growth, and the minimum EROI of society. ', *Energy Policy*, 95, pp. 172-186.
- Foster, K. (2016) 'Productivity and Prosperity: A Historical Sociology of Productivist Thought'.
- Foxon, T. (2017) *Energy and Economic Growth: Why we need a new pathway to prosperity*. Earthscan from Routledge.
- Franklin, M. (2018) A simple guide to multi-factor productivity. Online: Office for National Statistics. Available at: <https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/methodologies/asimpleguidetomultifactorproductivity> (Accessed: 15/8 2019).
- Franklin, M. (2019) Multi-factor productivity estimates: Experimental estimates January to March 2019: UK Office for National Statistics.

- Available at:
<https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/multifactorproductivityestimates/experimentalestimatesjanuarytomarch2019#industry-breakdown> (Accessed: 17/08 2019).
- Freire-González, J. (2011). Methods to empirically estimate direct and indirect rebound effect of energy-saving technological changes in households. *Ecological modelling*, 223(1), 32-40.
- Fronzel, M. (2002) 'Empirical assessment of energy-price policies: the case for cross-price elasticities', *Energy Policy*, 32(8), pp. 989–1000.
- Fronzel, M. and Schmidt, C. (2002) 'The Capital-Energy Controversy: An Artifact of Cost Shares?', *The Energy Journal*, 23(4), pp. 53-79.
- Gabrisch, H. (2019) The productivity puzzle and the Kaldor-Verdoorn law: the case of Central and Eastern Europe. Available at: https://www.nbp.pl/publikacje/materialy_i_studia/318_en.pdf (Accessed: 01/11 2019).
- Galli, A., Kitzes, J., Niccolucci, V., Wackernagel, M., Wada, Y. and Marchettini, N. (2012) 'Assessing the global environmental consequences of economic growth through the ecological footprint: a focus on China and India', *Ecological Indicators*, 17, pp. 99-107.
- Gärling, T., Eek, D., Loukopoulos, P., Fujii, S., Johansson-Stenman, O., Kitamura, R., Pendyala, R. and Vilhelmson, B. (2002) 'A conceptual analysis of the impact of travel demand management on private car use', *Transport Policy*, 9(1), pp. 59-70.
- Garofalo, G. and Malhotra, D. (1984) 'INPUT SUBSTITUTION IN THE MANUFACTURING SECTOR DURING THE 1970's: A REGIONAL ANALYSIS', *Journal of Regional Science*, 24(1), pp. 51-62.
- Garofalo, G. and Malhotra, D. (1990) 'The demand for inputs in the traditional manufacturing region', *Applied Economics*, 22(7), pp. 961-972.
- Geller, E. (2002) 'The challenge of increasing pro-environmental behaviour', in Bechtel, R. & Churchman, A. (eds.) *Handbook of Environmental Psychology*. New York: Wiley, pp. 525–540.
- Georgescu-Roegen, N. (1971) *The Entropy Law and the Economic Process*. Cambridge MA: Harvard University Press.
- Georgescu-Roegen, N. (1979) 'Energy analysis and economic valuation', *Southern Economic Journal*, 45(4), pp. 1023-1058.
- Gilbert, R. J. and Mork, K. A. (1986) 'Efficient pricing during oil supply disruptions', *The Energy Journal*, 7(2), pp. 51-68.
- Giljum, S., Dittrich, M., Lieber, M. and Lutter, S. (2014) 'Global patterns of material flows and their socio-economic and environmental

- implications: a MFA study on all countries world-wide from 1980 to 2009', *Resources*, 3(1), pp. 319-339.
- Gollop, F. M. and Swinand, G. P. (1998) 'From total factor to total resource productivity: an application to agriculture', *American Journal of Agricultural Economics*, 80(3), pp. 577-583.
- Goodridge, P., Haskel, J. and Wallis, G. (2016) 'Accounting for the UK Productivity Puzzle: A Decomposition and Predictions', *Economica*, In Press.
- Goodwin, B. and Brester, G. (1995) 'Structural Change in Factor Demand Relationships in the U.S. Food and Kindred Products Industry', *American Journal of Agricultural Economics*, 77(1), pp. 69-79
- Gopalakrishnan, C. (1987) 'Energy-Nonenergy Input Substitution in Western U.S. Agriculture: Some Findings', *The Energy Journal*, 8(1), pp. 133-145.
- Gopalakrishnan, C., Gholam, K. and Rajendra, S. (1989) 'Energy-non-energy input substitution in US agriculture: some findings', *Applied Economics*, 21(5), pp. 673-680.
- Gordon, R. J. (2017) *The rise and fall of American growth: The US standard of living since the civil war*. Princeton University Press.
- Greening, L. A., Greene, D. L., & Difiglio, C. (2000). Energy efficiency and consumption—the rebound effect—a survey. *Energy Policy*, 28(6-7), 389-401.
- Griffell-Tatje, E., Lovell, C. and Sickles, R. (2018a) 'Overview of Productivity Analysis: History Issues and Perspectives', in Griffell-Tatje, E., Lovell, C. & Sickles, R. (eds.) *The Oxford Handbook of Productivity Analysis*. New York: Oxford University Press, pp. 3-73.
- Griffell-Tatje, E., Lovell, C. and Sickles, R. (2018b) *The Oxford Handbook of Productivity Analysis*. New York: Oxford University Press.
- Griffin, J. M. and Gregory, P. R. (1976) 'An intercountry translog model of energy substitution responses', *The American Economic Review*, 66(5), pp. 845-857.
- Grubler, A. (2004) 'Transitions in energy use', *Encyclopedia of Energy*, 6, pp. 163-177.
- Grubler, A., Johansson, T., Mundaca, L., Nakicenovic, N., Pachauri, S., Riahi, K., Rogner, H. and Strupeit, L. (2012) 'Energy Primer', in Johansson, T.B., Patwardhan, A.P., Nakićenović, N. & Gomez-Echeverri, L. (eds.) *Global energy assessment: toward a sustainable future*. Cambridge, UK and New York, NY, USA: Cambridge University Press and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 99-150.
- Guildford, M., Hall, C., O'Connor, P. and Cleveland, C. (2011) 'A New Long-Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production', *Sustainability*, 3(10), pp. 1866-1887.

- Gun, R. and Budd, G. M. (1995) 'Effects of thermal, personal and behavioural factors on the physiological strain, thermal comfort and productivity of Australian shearers in hot weather', *Ergonomics*, 38(7), pp. 1368-1384.
- Hajizadeh, R., Golbabaie, F., Monazzam, M., Farhang-Dehghan, S. and Ezadi-Navan, E. (2014) 'Productivity loss from occupational exposure to heat stress: A case study in Brick Workshops/Qom-Iran', *International Journal of Occupational Hygiene*, 6(3), pp. 143-148.
- Hall, C. and Klitgaard, K. (2012) *Energy and the Wealth of Nations: Understanding the Biophysical Economy*. New York: Springer.
- Hall, C. and Klitgaard, K. (2018) 'Peak Oil, EROI, Investments, and Our Financial Future.', *Energy and the Wealth of Nations*. Cham: Springer, pp. 405-422.
- Hall, C., Lambert, J. and Balogh, S. (2014) 'EROI of different fuels and the implications for society', *Energy Policy*, 64, pp. 141-152.
- Haller, S. A. and Hyland, M. (2014) 'Capital–energy substitution: Evidence from a panel of Irish manufacturing firms', *Energy Economics*, 45, pp. 501-510.
- Halvorsen, R. and Smith, T. R. (1986) 'Substitution Possibilities for unpriced natural resources: Restricted cost functions for the Canadian metal mining industry', *The Review of Economics and Statistics*, pp. 398-405.
- Hamilton, J. (1983) 'Oil and the macroeconomy since World War II', *Journal of political economy*, 91(2), pp. 228-248.
- Hamilton, J. (1988) 'A Neoclassical Model of Unemployment and the Business Cycle', *Journal of Political Economy*, 96(3), pp. 593-617.
- Hamilton, J. (1996) 'This is what happened to the oil price-macroeconomy relationship', *Journal of Monetary Economics*, 38(2), pp. 215-220.
- Hamilton, J. (2003) 'What is an oil shock?', *Journal of Econometrics*, 113(2), pp. 363-398.
- Hamilton, J. (2009) *Causes and Consequences of the Oil Shock of 2007-08*: NBER. Available at: <https://www.nber.org/papers/w15002> (Accessed: 05/10 2019).
- Hamilton, J. D. and Herrera, A. M. (2004) 'Comment: oil shocks and aggregate macroeconomic behavior: the role of monetary policy', *Journal of Money, credit and Banking*, pp. 265-286.
- Hanley, N., McGregor, P. G., Swales, J. K. and Turner, K. (2009) 'Do increases in energy efficiency improve environmental quality and sustainability?', *Ecological Economics*, 68(3), pp. 692-709.
- Hardt, L., Barrett, J., Brockway, P., Foxon, T. J., Heun, M. K., Owen, A. and Taylor, P. G. (2017) 'Outsourcing or efficiency? Investigating the decline in final energy consumption in the UK productive sectors', *Energy Procedia*, 142, pp. 2409-2414.

- Harris, A., McAvinchey, I. D. and Yannopoulos, A. (1993) 'The demand for labour, capital, fuels and electricity: a sectoral model of the United Kingdom economy', *Journal of Economic Studies*, 20(3).
- Harris, R. and Moffat, J. (2017) 'The UK productivity puzzle, 2008 2012 : evidence using plant-level estimates of total factor productivity.', *Oxford Economic Papers*, 69(3), pp. 529-549.
- Hartwig, J. (2011) 'Testing the Baumol-Nordhaus Model with EU KLEMS Data', *Review of Income and Wealth*, 57(3), pp. 471-488.
- Hartwig, J. (2015) 'Structural change, aggregate demand and employment dynamics in the OECD, 1970–2010', *Structural Change and Economic Dynamics*, 34, pp. 36-45.
- Hassler, J., Krusell, P. and Olovsson, C. (2012) Energy-saving technical change: National Bureau of Economic Research.
- Heal, G. and Park, J. (2016) 'Reflections—temperature stress and the direct impact of climate change: a review of an emerging literature', *Review of Environmental Economics and Policy*, 10(2), pp. 347-362.
- Henningsen, A., Henningsen, G. and van der Werf, E. (2018) 'Capital-labour-energy substitution in a nested CES framework: A replication and update of Kemfert (1998)', *Energy Economics*.
- Herendeen, R. (2015) 'Connecting net energy with the price of energy and other goods and services', *Ecological Economics*, 109, pp. 142–149.
- Herrera, A. M., Lagalo, L. G. and Wada, T. (2015) 'Asymmetries in the response of economic activity to oil price increases and decreases?', *Journal of International Money and Finance*, 50, pp. 108-133.
- Herrera, A., Karakiy, M. and Rangarajuz, S. (2019) 'Oil Price Shocks and U.S. Economic Activity', *Energy Policy*, 129, pp. 89–99.
- Heun, M. K. and de Wit, M. (2012) 'Energy return on (energy) invested (EROI), oil prices, and energy transitions', *Energy Policy*, 40, pp. 147-158.
- Heun, M., Owen, A. and Brockway, P. (2018) 'A physical supply-use table framework for energy analysis on the energy conversion chain', *Applied Energy*, 226, pp. 1134–1162.
- Heun, M., Santos, J., Brockway, P., Pruim, R., Domingos, T. and Sakai, M. (2017) 'From Theory to Econometrics to Energy Policy: Cautionary Tales for Policymaking Using Aggregate Production Functions', *Energies*, 10(203).
- Hicks, J. (1932) *The theory of wages*. New York: Macmillan.
- House, C. L. (2014) 'Fixed costs and long-lived investments', *Journal of Monetary Economics*, 68, pp. 86-100.
- Hsiang, S. M. (2010) 'Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America', *Proceedings of the National Academy of sciences*, 107(35), pp. 15367-15372.

- Huang, K. S. (1991) 'Factor demands in the US food-manufacturing industry', *American Journal of Agricultural Economics*, 73(3), pp. 615-620.
- Hulten, C. (2001) Total factor productivity: a short biography. Online: NBER. Available at: <https://www.nber.org/chapters/c10122.pdf> (Accessed: 01/10/2019 2019).
- Hunt, L. C. (1984) 'Energy and capital: substitutes or complements? Some results for the UK industrial sector', *Applied Economics*, 16(5), pp. 783-789.
- Hunt, L. C. (1986) 'Energy and capital: substitutes or complements? A note on the importance of testing for non-neutral technical progress', *Applied Economics*, 18(7), pp. 729-735.
- IEA (2016) Renewable Energy Benefits: Measuring the Economics. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency.
- IEA (2019) World Energy Investment. Available at: <https://webstore.iea.org/world-energy-investment-2019> (Accessed: 29/10 2019).
- Ioannou, L. G., Tsoutsoubi, L., Samoutis, G., Bogataj, L. K., Kenny, G. P., Nybo, L., Kjellstrom, T. and Flouris, A. D. (2017) 'Time-motion analysis as a novel approach for evaluating the impact of environmental heat exposure on labor loss in agriculture workers', *Temperature*, 4(3), pp. 330-340.
- Iqbal, M. (1986) 'Substitution of labour, capital and energy in the manufacturing sector of Pakistan', *Empirical Economics*, 11(2), pp. 81-95.
- Isham, A., Mair, S. and Jackson, T. (2020) Wellbeing and productivity: a review of the literature. CUSP Working Paper No 22. Available at: <https://www.cusp.ac.uk/powering-productivity/>.
- Jackson, A. (2019d) A stock-flow consistent framework for the analysis of stranded assets and the transition to a low carbon economy, Doctoral thesis, University of Surrey (Accessed: 18/06 2019).
- Jackson, T. (1996) *Material Concerns: Pollution, Profit and Quality of Life*. Routledge.
- Jackson, T. (2005) Motivating sustainable consumption: a review of evidence on consumer behaviour and behavioural change. Sustainable Development Research Network. Available at: http://www.sd-research.org.uk/wp-content/uploads/motivatingfinal_000.pdf.
- Jackson, T. (2017) *Prosperity Without Growth: Foundations for the Economy of Tomorrow*. 2nd edn. London and New York: Routledge.
- Jackson, T. (2019a) 'The Post-growth Challenge: Secular Stagnation, Inequality and the Limits to Growth', *Ecological Economics*, 156, pp. 236-246.

- Jackson, T. (2019b) The Post-Growth Challenge—Secular Stagnation, Inequality and the Limits to Growth, CUSP Working Paper No 12. Available at: <https://www.cusp.ac.uk/themes/aetw/wp12> (Accessed: 22/05 2019).
- Jackson, T. (2019c) Zero Carbon Sooner: The case for an early zero carbon target for the UK. Available at: <https://www.cusp.ac.uk/themes/aetw/zero-carbon-sooner/> (Accessed: 26/07 2019).
- Jackson, T. (2019e) “All Models are Wrong” —The challenge of modelling ‘deep decarbonisation’. Available at: <https://www.cusp.ac.uk/themes/s2/all-models-are-wrong/> (Accessed: 05/11 2019).
- Jackson, T. and Victor, P.A. (2019) Unravelling the claims for (and against) green growth. *Science* 366 (6468), 950-951.
- Jackson, T. and Victor, P.A. (2011) 'Productivity and work in the 'green economy': Some theoretical reflections and empirical tests', *Environmental Innovation and Societal Transitions*, 1(1), pp. 101-108.
- Jan van de Ven, D. and Fouquet, R. (2017) 'Historical energy price shocks and their changing effects on the economy', *Energy Economics*, 62, pp. 204-216.
- Jarvis, A. (2018) 'Energy Returns and The Long-run Growth of Global Industrial Society', *Ecological Economics*, 146, pp. 722-729.
- Jevons, W. S. (1865) 'The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines', in Flux, A.W. (ed.). New York: Augustus M. Kelly.
- Johannsson, K. (2017) Developing improved estimates of quality adjusted labour inputs using the Annual Survey of Hours and Earnings: a progress report. Available at: <https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/developingimprovedestimatesofqualityadjustedlabourinputsusingtheannualsurveyofhoursandearnings/aprogressreport> (Accessed: 10/10 2019).
- Jones, D., Leiby, P. and Paik, I. (2004) 'Oil price shocks and the macroeconomy: what has been learned since 1996', *The Energy Journal*, pp. 1-32.
- Jorgenson, D. (1982) 'Energy prices and productivity growth.', *The Impact of Rising Oil Prices on the World Economy*. London.: Palgrave Macmillan, pp. 25-39.
- Jorgenson, D. (2018) 'The World KLEMS Initiative', in Griffell-Tatje, E., Lovell, C. & Sickles, R. (eds.) *The Oxford Handbook of Productivity Analysis*, pp. 663-668.

- Kahn, M., Mohaddes, K., Ng, R., Pesaran, H., Raissi, M. and Yang, J. (2019) Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis: NBER. Available at: <https://www.nber.org/papers/w26167> (Accessed: 25/10 2019).
- Kaldor, N. (1966) Causes of the Slow Rate of Economic Growth of the United Kingdom: An Inaugural Lecture. Great Britain: University of Cambridge Press.
- Kallis, G. and March, H. (2015) 'Imaginarities of Hope: The Utopianism of Degrowth', *Annals of the Association of American Geographers*, 105(2), pp. 360-368.
- Kallis, G. and Sager, J. (2017) 'Oil and the economy: A systematic review of the literature for ecological economists', *Ecological Economics*, 131, pp. 561-571.
- Kallis, G., Kerschner, C. and Martinez-Alier, J. (2012) 'The Economics of Degrowth', *Ecological Economics*, 84, pp. 172-180.
- Kant, S. and Nautiyal, J. (1997) 'Production structure, factor substitution, technical change, and total factor productivity in the Canadian logging industry', *Canadian journal of forest research*, 27(5), pp. 701-710.
- Karaki, M. B. (2018) 'Oil Prices and State Unemployment Rates', *Energy Journal*, 39(3).
- Keen, S., Ayres, R. and Standish, R. (2019) 'A Note on the Role of Energy in Production', *Ecological Economics*, 157, pp. 40-46.
- Kemfert, C. (1998) 'Estimated substitution elasticities of a nested CES production function approach for Germany', *Energy Economics*, 20(3), pp. 249-264.
- Kemfert, C. and Welsch, H. (2000) 'Energy-capital-labor substitution and the economic effects of CO2 abatement: Evidence for Germany', *Journal of Policy Modeling*, 22(6), pp. 641-660.
- Kerschner, C., Prell, C., Feng, K. and Hubacek, K. (2013) 'Economic vulnerability to peak oil', *Global environmental change*, 23(6), pp. 1424-1433.
- Kershaw, T. and Lash, D. (2013) 'Investigating the productivity of office workers to quantify the effectiveness of climate change adaptation measures', *Building and Environment*, 69, pp. 35-43.
- Kilian, L. and Vigfusson, R. J. (2011) 'Are the responses of the US economy asymmetric in energy price increases and decreases?', *Quantitative Economics*, 2(3), pp. 419-453.
- Kim, M. (1988) 'The structure of technology with endogenous capital utilization', *International Economic Review*, pp. 111-130.
- King, C. (2010) 'Energy intensity ratios as net energy measures of United States energy production and expenditures', *Environmental Research Letters*, 5(4).

- King, C. and Hall, C. (2011) 'Relating financial and energy return on investment', *Sustainability*, 3(10), pp. 1810–1832.
- Kjellstrom, T., Briggs, D., Freyberg, C., Lemke, B., Otto, M. and Hyatt, O. (2016) 'Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts', *Annual review of public health*, 37, pp. 97-112.
- Kjellstrom, T., Kovats, R., Lloyd, S., Holt, T. and Tol, R. (2009) 'The direct impact of climate change on regional labor productivity', *Archives of Environmental & Occupational Health*, 64(4), pp. 217-227.
- Kjellstrom, T., Lemke, B. and Otto, M. (2013) 'Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980–2011 and future estimates to 2050', *Industrial health*, 51(1), pp. 56-67.
- Klein, Y. L. (1988) 'An econometric model of the joint production and consumption of residential space heat', *Southern Economic Journal*, pp. 351-359.
- Knell, M. (2004) 'Structure Change and the Kaldor-Verdoorn law in the 1990s', *Revue d'économie industrielle* 105, pp. 71-83.
- Koetse, M. J., De Groot, H. L. and Florax, R. J. (2008) 'Capital-energy substitution and shifts in factor demand: A meta-analysis', *Energy Economics*, 30(5), pp. 2236-2251.
- Kokkelenberg, E. and Bischoff, C. (1986) 'Expectations and factor demand', *The Review of Economics and Statistics*, pp. 423-431.
- Kose, T. and Sakata, I. (2019) 'Identifying technology convergence in the field of robotics research', *Technological Forecasting and Social Change*, 146, pp. 751-766.
- Krishnamurthy, M., Ramalingam, P., Perumal, K., Kamalakannan, L. P., Chinnadurai, J., Shanmugam, R., Srinivasan, K. and Venugopal, V. (2017) 'Occupational heat stress impacts on health and productivity in a steel industry in southern India', *Safety and health at work*, 8(1), pp. 99-104.
- Kumar, S., Fujii, H. and Managi, S. (2015) 'Substitute or complement? Assessing renewable and nonrenewable energy in OECD countries', *Applied Economics*, 47(14), pp. 1438-1459.
- Kuper, G. H. and Van Soest, D. P. (2003) 'Path-dependency and input substitution: implications for energy policy modelling', *Energy Economics*, 25(4), pp. 397-407.
- Kuper, G. H. and van Soest, D. P. (2006) 'Does oil price uncertainty affect energy use?', *The Energy Journal*, pp. 55-78.
- Kurz, H. and Salvadori, N. (1995) *Theory of Production: A Long Period Analysis*. Cambridge University Press.
- Kurz, H. D. (2006) 'The agents of production are the commodities themselves: on the classical theory of production, distribution and value', *Structural Change and Economic Dynamics*, 17(1), pp. 1-26.

- Kydland, F. E. and Prescott, E. C. (1982) 'Time to build and aggregate fluctuations', *Econometrica: Journal of the Econometric Society*, pp. 1345-1370.
- Labandeira, X., Labeaga, J. and López-Otero, X. (2017) 'A meta-analysis on the price elasticity of energy demand', *Energy Policy*, 102, pp. 549-568.
- Lamb, S. and Kwok, K. C. (2016) 'A longitudinal investigation of work environment stressors on the performance and wellbeing of office workers', *Applied Ergonomics*, 52, pp. 104-111.
- Lambert, J., Hall, C., Balogh, S., Gupta, A. and Arnold, M. (2014) 'Energy, EROI and quality of life', *Energy Policy*, 64, pp. 153–167.
- Lamperti, F., Dosi, G., Napoletano, M., Roventini, A. and Sapio, A. (2018) 'Faraway, so close: coupled climate and economic dynamics in an agent-based integrated assessment model. ', *Ecological Economics*, 150, pp. 315-339.
- Langkulsen, U., Vichit-Vadakan, N. and Taptagaporn, S. (2010) 'Health impact of climate change on occupational health and productivity in Thailand', *Global health action*, 3(1), pp. 5607.
- Lao, J., Hansen, A., Nitschke, M., Hanson-Easey, S. and Pisaniello, D. (2016) 'Working smart: An exploration of council workers' experiences and perceptions of heat in Adelaide, South Australia', *Safety science*, 82, pp. 228-235.
- Lavoie, M. (2014) *Post-Keynesian Economics: New Foundations*. Cheltenham: Edward Elgar.
- Levi, M., Kjellstrom, T. and Baldasseroni A (2018) ' Impact of climate change on occupational health and productivity: a systematic literature review focusing on workplace heat', *Medlav*, 109(3), pp. 163-79.
- Lewis, W. A. (1954). *Economic development with unlimited supplies of labour*. *The Manchester School*, 22(2), 139-191.
- Li, J. (2009) *Production Structure, Input Substitution, and Total Factor Productivity Growth in the Softwood Lumber Industries in US and Canadian Regions*. Available at: <https://tspace.library.utoronto.ca/handle/1807/18812> (Accessed: 10/11 2019).
- Lin, B. and Li, J. (2014) 'The rebound effect for heavy industry: empirical evidence from China', *Energy Policy*, 74, pp. 589-599.
- Lin, B. and Liu, K. (2017) 'Energy substitution effect on China's heavy industry: Perspectives of a translog production function and ridge regression', *Sustainability*, 9(11), pp. 1892.
- Logar, I. and van den Bergh, J. (2013) 'The impact of peak oil on tourism in Spain: An input–output analysis of price, demand and economy-wide effects', *Energy*, 54, pp. 155–166.

- Lundgren-Kownacki, K., Kjellberg, S. M., Gooch, P., Dabaieh, M., Anandh, L. and Venugopal, V. (2018) 'Climate change-induced heat risks for migrant populations working at brick kilns in India: a transdisciplinary approach', *International journal of biometeorology*, 62(3), pp. 347-358.
- Ma, H., Oxley, L. and Gibson, J. (2009) 'Substitution possibilities and determinants of energy intensity for China', *Energy Policy*, 37(5), pp. 1793-1804.
- Magnus, J. R. (1979) 'Substitution between energy and non-energy inputs in the Netherlands 1950-1976', *International Economic Review*, 20(2), pp. 465-484.
- Mair, S. (2018) *Capital, Capitalism, and Climate in Adam Smith's Growth Theory: 'Political Economy of Capitalism'*; University of Geneva. Available at: https://www.researchgate.net/publication/331248942_Capital_Capitalism_and_Climate_in_Adam_Smith's_Growth_Theory (Accessed: 21/02 2019).
- Mair, S. (2019) *Climate Change and Capitalism: A Political Marxist View*. Online: New Socialist. Available at: <https://newsocialist.org.uk/climate-capitalism-political-marxism/> (Accessed: 16/7 2019).
- Mair, S., Druckman, A. and Jackson, T. (2018) *The Future Of Work: Lessons from the History of Utopian Thought*. CUSP Working Paper Series. Online: CUSP. Available at: <https://www.cusp.ac.uk/themes/aetw/wp13/> (Accessed: 18/07 2018).
- Mairet, N. and Decellas, F. (2009) 'Determinants of energy demand in the French service sector: A decomposition analysis', *Energy Policy*, 37(7), pp. 2734-2744.
- Malm, A. (2016) *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*. US: Verso.
- Marconi, N., Reis, C. and Araújo, E. (2016) 'Manufacturing and economic development: The actuality of Kaldor's first and second laws', *Structural Change and Economic Dynamics*, 37, pp. 75-89.
- Martiskainen, M. (2007) 'Affecting consumer behaviour on energy demand'.
- Marx, K. (1873/2013) *Capital: A Critical Analysis of Capitalist Production*. Translated by: Vol 1: Moore, S.a.A., E & Vol 2: Unterman, E. 2nd edn.: Wordsworth, p. 1136.
- Maslow, A. (1943) 'A Theory of Human Motivation', *Psychological Review*, 50, pp. 370-396.
- Matsumoto, K. i. (2019) 'Climate change impacts on socioeconomic activities through labor productivity changes considering interactions between socioeconomic and climate systems', *Journal of Cleaner Production*, 216, pp. 528-541.

- Matutinović, I. (2009) 'Oil and the political economy of energy', *Energy Policy*, 37(11), pp. 4251-4258.
- Max-Neef, M. (1992) *Human scale development: conception, application and further reflections*.
- McCann, P. (2018) *Productivity Perspectives Synthesis: Productivity Insights Network*. Available at: <https://productivityinsightsnetwork.co.uk/app/uploads/2018/11/Productivity-Perspectives-Synthesis-updated-21.11.18.pdf> (Accessed: 13/03 2019).
- McCloskey, D. (2010) *The Bourgeois Dignity: Why Economics Can't Explain the Modern World*. University of Chicago Press.
- McCombie, J. and Spreafico, M. (2017) 'Kaldor's 'Technical Progress Function' and Verdoorn's Law Revisited', *Cambridge Journal of Economics*, 40, pp. 1117-1136.
- McCombie, J., Pugno, M. and Soro, B. (2002) *Productivity Growth and Economic Performance: Essays on Verdoorn's Law*. Hampshire: Palgrave Macmillan, p. 281.
- McElroy, M. B. (1987) 'Additive general error models for production, cost, and derived demand or share systems', *Journal of Political Economy*, 95(4), pp. 737-757.
- McNown, R. F., Pourgerami, A. and Hirschhausen, C. R. (1991) 'Input substitution in manufacturing for three LDCs: translog estimates and policy implications', *Applied Economics*, 23(1), pp. 209-218.
- Medina, J. and Vega-Cervera, J. A. (2001) 'Energy and the non-energy inputs substitution: evidence for Italy, Portugal and Spain', *Applied Energy*, 68(2), pp. 203-214.
- Medlock III, K. B. and Soligo, R. (2001) 'Economic development and end-use energy demand', *The Energy Journal*, pp. 77-105.
- Miller, E. (1990) 'Can a Perpetual Inventory Capital Stock be Used for Production Function Parameter Estimation?', *Review of Income and Wealth*, 36(1), pp. 67-82.
- Miller, J., Foxon, T. and Sorrell, S. (2016) 'Exergy accounting: A quantitative comparison of methods and implications for energy-economy analysis', *Energies*, 9(11), pp. 947.
- Miller, V. S. and Bates, G. P. (2007) 'The thermal work limit is a simple reliable heat index for the protection of workers in thermally stressful environments', *Annals of occupational hygiene*, 51(6), pp. 553-561.
- Mohaddes, K. and Pesaran, M. (2016) *Oil Prices and the Global Economy: Is It Different This Time Around?* Available at: <https://www.imf.org/external/pubs/ft/wp/2016/wp16210.pdf>.

- Moreau, V. and Vuille, F. (2018) 'Decoupling energy use and economic growth: Counter evidence from structural effects and embodied energy in trade', *Applied energy*, 215, pp. 54-62.
- Mork, K. (1989) 'Oil and the macroeconomy when prices go up and down: An extension of Hamilton's results', *Journal of Political Economy*, 91, pp. 740-744.
- Mulder, P. and De Groot, H. L. (2012) 'Structural change and convergence of energy intensity across OECD countries, 1970–2005', *Energy Economics*, 34(6), pp. 1910-1921.
- Murphy, D. (2014) 'The implications of the declining energy return on investment of oil production', *Philosophical Transactions of the Royal Society of London A*, 372, pp. 20130126.
- Murphy, D. and Hall, C. (2011) 'Energy return on investment, peak oil, and the end of economic growth', *Annals of the New York Academy of Sciences*, 1219(1), pp. 52-72.
- Nag, A. and Nag, P. K. (1992) 'Heat stress of women doing manipulative work', *American Industrial Hygiene Association Journal*, 53(12), pp. 751-756.
- Nelson, J. (1995) 'Feminism and Economics', *Journal of Economic Perspectives*, 9(2), pp. 131-148.
- Nelson, J. and Power, M. (2018) 'Ecology, Sustainability, and Care: developments in the Field.', *Feminist Economics*, 24(3), pp. 80-88.
- Nguyen, S. V. and Streitwieser, M. L. (1997) Capital-energy substitution revisited: new evidence from micro data. Center for Economic Studies, US Department of Commerce, Bureau of the Census.
- Nielsen, J., Andersen, K. and Sigh, A. (2016) 'Robots conquering local government services: A case study of eldercare in Denmark', *Information Polity*, 21(2), pp. 139-151.
- Niemelä, R., Hannula, M., Rautio, S., Reijula, K. and Railio, J. (2002) 'The effect of air temperature on labour productivity in call centres—a case study', *Energy and Buildings*, 34(8), pp. 759-764.
- Nordhaus, W. (2008) 'Baumol's diseases: a macroeconomic perspective', *The BE Journal of Macroeconomics*, 8(1).
- Nørgård, J. S. (2013) 'Happy degrowth through more amateur economy', *Journal of Cleaner Production*, 38(0), pp. 61-70.
- Norsworthy, J., Harper, M. and Kunze, K. (1979) 'The Slowdown in Productivity Growth: Analysis of Some Contributing Factors', *Brookings Papers on Economic Activity*, 2, pp. 387-421.
- OECD (2001) Primary Energy. Available at: <https://stats.oecd.org/glossary/detail.asp?ID=2112> (Accessed: 05/10 2019).

- OECD (2009) Measuring Capital: OECD Manual. Available at: https://www.oecd-ilibrary.org/economics/measuring-capital-oecd-manual-2009_9789264068476-en (Accessed: 25/11 2019).
- OECD (2012) OECD-STAN Database. Available at: <http://www.oecd.org/sti/ind/stanstructuralanalysisdatabase.htm> (Accessed: 10/10 2019).
- OECD (2015) Capital Productivity. Available at: https://www.oecd-ilibrary.org/industry-and-services/oecd-compendium-of-productivity-indicators-2015/capital-productivity_pdtvy-2015-9-en (Accessed: 01/12 2019).
- OECD 2011. OECD Green Growth Studies: Energy. Online: OECD.
- Okagawa, A. and Ban, K. (2008) 'Estimation of substitution elasticities for CGE models', Discussion Papers in Economics and Business, 16.
- Olson, D. O. and Jonish, J. (1985) 'The Robustness of Translog Elasticity of Substitution Estimates and the Capital Energy Complementarity Controversy', Quarterly Journal of Business and Economics, pp. 21-35.
- O'Mahony, M. and Timmer, M. (2009) 'Output, Input and Productivity Measures at the Industry Level: The Eu Klems Database', The Economic Journal, 119(538), pp. F374-F403.
- Omri, A. and Nguyen, D. K. (2014) 'On the determinants of renewable energy consumption: International evidence', Energy, 72, pp. 554-560.
- ONS (2016) National accounts. Available at: <https://www.ons.gov.uk/economy/nationalaccounts/uksectoraccounts/methodologies/nationalaccounts> (Accessed: 09/10 2019).
- Orlov, A., Sillmann, J., Aaheim, A., Aunan, K. and de Bruin, K. (2019) 'Economic Losses of Heat-Induced Reductions in Outdoor Worker Productivity: A Case Study of Europe', Economics of Disasters and Climate Change, 3(3), pp. 191-211.
- O'Sullivan, M. (2017) 'A Confusion of Capital in the United States', in Hudson, P. & Tribe, K. (eds.) The Contradictions of Capital in the Twenty-First Century: The Piketty Opportunity: Agenda Publishing.
- Otojanov, R. and Fouquet, R. (2018) Factor prices and induced technical change in the Industrial Revolution. Available at: <http://webpace.qmul.ac.uk/pmartins/CGRWP92.pdf> (Accessed: 18/10 2019).
- Özatalay, S., Grubaugh, S. and Long, T. V. (1979) 'Energy substitution and national energy policy', The American Economic Review, 69(2), pp. 369-371.
- Pablo-Romero, M. d. P. and Sánchez-Braza, A. (2015) 'Productive energy use and economic growth: Energy, physical and human capital relationships', Energy Economics, 49, pp. 420-429.

- Parthasarathi, P. (2011) *Why Europe Grew Rich and Asia Did Not*. USA: Cambridge University Press, p. 365.
- Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. and Caldecott, B. (2018) 'Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement', *Environmental Research Letters*, 13(5), pp. 054019.
- Pindyck, R. S. and Rotemberg, J. J. (1983) 'Dynamic factor demands and the effects of energy price shocks', *The American Economic Review*, 73(5), pp. 1066-1079.
- Pirgmaier, E. (2019) 'The value of value theory for ecological economics', *Ecological Economics*, Forthcoming.
- Pogačar, T., Casanueva, A., Kozjek, K., Ciuha, U., Mekjavić, I. B., Bogataj, L. K. and Črepinšek, Z. (2018) 'The effect of hot days on occupational heat stress in the manufacturing industry: implications for workers' well-being and productivity', *International journal of biometeorology*, 62(7), pp. 1251-1264.
- Pollak, R. A. and Wales, T. J. (1987) 'Specification and estimation of nonseparable two-stage technologies: The Leontief CES and the Cobb-Douglas CES', *Journal of Political Economy*, 95(2), pp. 311-333.
- Pollin, R. (2015) *Greening the Global Economy*. USA: MIT Press.
- Pomeranz, K. (2000) *The great divergence: China, Europe, and the making of the modern world economy*. Princeton University Press.
- Popp, D. (2002) 'Induced innovation and energy prices', *American economic review*, 92(1), pp. 160-180.
- Power, M. (2004) 'Social Provisioning as a Starting Point for Feminist Economics', *Feminist Economics*, 10(3), pp. 3-19.
- Published by: The MIT Press
- Punzi, M. (2019) 'The impact of energy price uncertainty on macroeconomic variables', *Energy Policy*, 129, pp. 1306-1319.
- Quiller, G., Krenz, J., Ebi, K., Hess, J. J., Fenske, R. A., Sampson, P. D., Pan, M. and Spector, J. T. (2017) 'Heat exposure and productivity in orchards: Implications for climate change research', *Archives of environmental & occupational health*, 72(6), pp. 313-316.
- Rafiq, S. (2014) 'What Do Energy Prices Tell Us About UK Inflation?', *Economica*, 81, pp. 293-310.
- Raj, B. and Veall, M. R. (1998) 'The energy-capital complementarity debate: an example of a bootstrapped sensitivity analysis', *Environmetrics: The official journal of the International Environmetrics Society*, 9(1), pp. 81-92.
- Ramey, V. (2017) 'Comments on "Lower Oil Prices and the US Economy: Is This Time Different?" by Christiane Baumeister and Lutz Kilian', forthcoming, *Brookings Papers on Economic Activity*.

- Ramey, V. A. and Vine, D. J. (2011) 'Oil, automobiles, and the US economy: How much have things really changed?', NBER Macroeconomics Annual, 25(1), pp. 333-368.
- Ramos-Martin, J. (2003). Empiricism in ecological economics: a perspective from complex systems theory. *Ecological Economics*, 46(3), 387-398.
- Rampa, G. (2002) 'Verdoorn's Law: Some Notes on Output Measurement and the Role of Demand', in McCombie, J., Pugno, M. & Soro, B. (eds.) *Productivity Growth and Economic Performance: Essays on Verdoorn's Law*. Hampshire: Palgrave Macmillan, pp. 219-238.
- Ranis, G., & Fei, J. C. (1961). A theory of economic development. *The American economic review*, 51(4), 533-565.
- Raworth, K. (2017) *Doughnut Economics: 7 Ways to Think Like a 21st Century Economist*. London: Random House Business Books.
- Rentschler, J., Bleischwitz, R. and Flachenecker, F. (2018) 'On imperfect competition and market distortions: the causes of corporate under-investment in energy and material efficiency', *International Economics and Economic Policy*, 15(1), pp. 159–183.
- Rezai, A., Taylor, L. and Foley, D. (2018) 'Economic Growth, Income Distribution, and Climate Change', *Ecological Economics*, 146, pp. 164-172.
- Robinson, J. (1953) 'The production function and the theory of capital', *The Review of Economic Studies*, 21(2), pp. 81-106.
- Romer, P. (1986) 'Increasing Returns and Long-Run Growth', *Journal of Political Economy*, 94(5), pp. 1002-1037.
- Romer, P. (1994) 'The Origins of Endogenous Growth', *Journal of Economic Perspectives*, 8(1), pp. 3-22.
- Rotemberg, J. and Woodford, M. (1996) *Imperfect Competition and the Effects of Energy Price Increases on Economic Activity*. Available at: <https://www.nber.org/papers/w5634> (Accessed: 02/10 2019).
- Roy, J., Sanstad, A. H., Sathaye, J. A. and Khaddaria, R. (2006) 'Substitution and price elasticity estimates using inter-country pooled data in a translog cost model', *Energy economics*, 28(5-6), pp. 706-719.
- Rye, C. D. and Jackson, T. (2018) 'A review of EROEI-dynamics energy-transition models', *Energy Policy*, 122, pp. 260-272.
- Sahu, S., Sett, M. and Kjellstrom, T. (2013) 'Heat exposure, cardiovascular stress and work productivity in rice harvesters in India: implications for a climate change future', *Industrial health*.
- Sakai, M., Brockway, P., Barrett, J. and Taylor, P. (2019) 'Thermodynamic Efficiency Gains and their Role as a Key 'Engine of Economic Growth'', *Energies*, 12(1), pp. 110.
- Samuelson, P. A. (1948) 'Consumption theory in terms of revealed preference', *Economica*, 15(60), pp. 243-253.

- Sandel, M. (2012) *The Moral Limits of Markets*. UK: Penguin.
- Sanne, C. (2002) 'Willing consumers—or locked-in? Policies for a sustainable consumption', *Ecological Economics*, 42(1), pp. 273-287.
- Santos, J., Domingos, T., Sousa, T. and Aubyn, M. (2018) 'Useful Exergy Is Key in Obtaining Plausible Aggregate Production Functions and Recognizing the Role of Energy in Economic Growth: Portugal 1960–2009', *Ecological Economics* 148, pp. 103-120.
- Saunders, C. and Dalziel, P. (2017) 'Twenty-Five Years of Counting for Nothing: Waring's Critique of National Accounts', *Feminist Economics*, 23(2), pp. 200-218.
- Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H. and Schaffartzik, A. (2018) 'Global material flows and resource productivity: forty years of evidence', *Journal of Industrial Ecology*, 22(4), pp. 827-838.
- Schipper, L., Meyers, S. and Ketoff, A. N. (1986) 'Energy use in the service sector: An international perspective', *Energy policy*, 14(3), pp. 201-218.
- Schumpeter, J. (1954/2006) *History of Economic Analysis*. Online: Taylor and Francis, p. 1283.
- Seidman, L. (1989) 'Complements and Substitutes: The Importance of Minding p's and q's', *Southern Economic Journal*, 56(1), pp. 183-190.
- Seppanen, O., Fisk, W. and Lei, Q. (2006a) 'Effect of temperature on task performance in office environment', Technical Report. Lawrence Berkeley National Laboratory.
- Seppanen, O., Fisk, W. and Lei, Q. (2006b) Effect of temperature on task performance in office environment: Lawrence Berkeley National Laboratory. Available at: <http://escholarship.org/uc/item/45g4n3rv> (Accessed: 01/12/2011).
- Serletis, A. and Kumbhakar, S. C. (1990) 'KLEM substitutability: a dynamic flexible demand system', *Applied Economics*, 22(2), pp. 275-283.
- Sers, M. and Victor, P. (2018) 'The Energy-Emissions Trap', *Ecological Economics*, 151, pp. 10-21.
- Sett, M. and Sahu, S. (2014) 'Effects of occupational heat exposure on female brick workers in West Bengal, India', *Global health action*, 7(1), pp. 21923.
- Setyawan, H., Qodrijati, I., Widjanarti, M., Rinawati, S., Atmojo, T., Fajariyani, R., Wardhani, T. and Utomo, E. 'The impact of hot work climate on textile industry productivity'. IOP Conference Series: Earth and Environmental Science: IOP Publishing, 012053.
- Shi, X., Zhu, N. and Zheng, G. (2013) 'The combined effect of temperature, relative humidity and work intensity on human strain in hot and humid environments', *Building and Environment*, 69, pp. 72-80.

- Shove, E. and Walker, G. (2014) 'What Is Energy For? Social Practice and Energy Demand', *Theory, Culture & Society*, 31(5), pp. 41–58.
- Smil, V. (2017) *Energy and Civilization: A History*. USA: MIT Press.
- Smith, A. (1776) *An Inquiry into the Nature and Causes of The Wealth of Nations*: Marxists Internet Archive. Available at: <https://www.marxists.org/reference/archive/smith-adam/works/wealth-of-nations/> (Accessed: 21/03 2018).
- Smyth, R., Narayan, P. K. and Shi, H. (2011) 'Substitution between energy and classical factor inputs in the Chinese steel sector', *Applied energy*, 88(1), pp. 361-367.
- Solow, R. (1957) 'Technical Change and the Aggregate Production Function', *The Review of Economics and Statistics*, 39(3), pp. 312-320.
- Sorrell, S. (2014) 'Energy Substitution, Technical Change and Rebound Effects', *Energies*, 7, pp. 2850-2873.
- Sorrell, S. (2015) 'Reducing energy demand: A review of issues, challenges and approaches', *Renewable and Sustainable Energy Reviews*, 47, pp. 74-82.
- Source: *The Review of Economics and Statistics*, Vol. 55, No. 1 (Feb., 1973), pp. 28-45
- Stable URL: <https://www.jstor.org/stable/1927992>.
- Steinberger, J. K. and Krausmann, F. 2011. *Material and energy productivity*. ACS Publications.
- Sterman, J. (1982) *The energy transition and the economy: a system dynamics approach*. PhD, Massachusetts Institute of Technology.
- Stern, D. (2011) 'Elasticities of substitution and complementarity. ', *Journal of Productivity Analysis*, 36(1), pp. 79-89.
- Stern, N. and Kander, A. (2012) 'The Role of Energy in the Industrial Revolution and Modern
- Stresing, R., Lindenberger, D. and Kümmel, R. (2008) 'Cointegration of output, capital, labor, and energy', *The European Physical Journal B*, 66(2), pp. 279–287.
- Strubell, E., Ganesh, A. and McCallum, A. (2019) *Energy and Policy Considerations for Deep Learning in NLP*. Available at: <https://arxiv.org/abs/1906.02243> (Accessed: 17/06 2019).
- Struckmeyer, C. S. (1987) 'The putty-clay perspective on the capital-energy complementarity debate', *The Review of Economics and Statistics*, pp. 320-326.
- Stuber, G. (2001) *The Changing Effects of Energy- Price Shocks on Economic Activity and Inflation*: Bank of Canada. Available at: <https://www.bankofcanada.ca/wp-content/uploads/2010/06/stubere.pdf> (Accessed: 10/10 2019).

- Susskind, D. (2017) Re-Thinking the Capabilities of Machines in Economics. Available at: <https://www.economics.ox.ac.uk/departments-of-economics-discussion-paper-series/re-thinking-the-capabilities-of-machines-in-economics> (Accessed: 02/03 2018).
- Szewczyk, W., Gosling, S. and Zaherpour, J. (2019) 'Economic implications of future heat stress on labour productivity'.
- Szilagyiova, S. (2014) An investigation of the two way relationship between commodities and the UK economy in an environment of inflation targeting. Doctoral, University of Huddersfield [Online] Available at: <http://eprints.hud.ac.uk/id/eprint/23483/> (Accessed: 02/03 2018).
- Thomas, J. K. (2002) 'Is lumpy investment relevant for the business cycle?', *Journal of political Economy*, 110(3), pp. 508-534.
- Thompson, H. (2006) 'The applied theory of energy substitution in production', *Energy Economics*, 28(4), pp. 410-425.
- Tobin, J. (1980) 'Stabilization policy ten years after', *Brookings Papers on Economic Activity* 1, pp. 19-71.
- Tovar, M. A. and Iglesias, E. M. (2013) 'Capital-energy relationships: an analysis when disaggregating by industry and different types of capital', *The Energy Journal*, pp. 129-150.
- Truett, L. J. and Truett, D. B. (2001) 'The Spanish automotive industry: scale economies and input relationships', *Applied Economics*, 33(12), pp. 1503-1513.
- Turnovsk, M., Folie, M. and Ulph, A. (1982) 'Factor substitutability in Australian manufacturing with emphasis on energy inputs', *Economic Record*, 58(1), pp. 61-72.
- UK Committee on Climate Change (2019) Net Zero: The UK's contribution to stopping global warming. Available at: <https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf> (Accessed: 02/05 2019).
- UK Labour Party (2019) Bringing Energy Home: Labour's proposal for publicly owned energy networks. Available at: <https://www.labour.org.uk/wp-content/uploads/2019/03/Bringing-Energy-Home-2019.pdf> (Accessed: 28/10 2019).
- Valadkhani, A., Babacan, A. and Dabir-Alai, P. (2014) 'The impacts of rising energy prices on non-energy sectors in Australia', *Economic Analysis and Policy*, 44(4), pp. 386-395.
- Van der Werf, E. (2008) 'Production functions for climate policy modeling: An empirical analysis', *Energy economics*, 30(6), pp. 2964-2979.
- Vega-Cervera, J. and Medina, J. (2000) 'Energy as a productive input: the underlying technology for Portugal and Spain', *Energy*, 25(8), pp. 757-775.

- Venugopal, V., Chinnadurai, J., Lucas, R. and Kjellstrom, T. (2016) 'Occupational heat stress profiles in selected workplaces in India', *International journal of environmental research and public health*, 13(1), pp. 89.
- Veracierto, M. L. (2002) 'Plant-level irreversible investment and equilibrium business cycles', *American Economic Review*, 92(1), pp. 181-197.
- Verdoorn, P. (1949/2002) 'Factors that Determine the Growth of Labour Productivity', in McCombie, J., Pugno, M. & Soro, B. (eds.) *Productivity Growth and Economic Performance: Essays on Verdoorn's Law*. Hampshire: Palgrave Macmillan, pp. 28-36.
- Victor, P. (2019) *Managing Without Growth: Slower by Design not Disaster*. 2nd edn. Cheltenham: Edward Elgar, p. 413.
- Wang, F., Jiang, Y., Zhang, W. and Yang, F. (2019) 'Elasticity of factor substitution and driving factors of energy intensity in China's industry', *Energy & Environment*, 30(3), pp. 385-407.
- Wang, X. and Lin, B. (2017) 'Factor and fuel substitution in China's iron & steel industry: evidence and policy implications', *Journal of cleaner production*, 141, pp. 751-759.
- Warde, P. (2007) *Energy consumption in England and Wales 1560–2000*. Rome, Italy: Consiglio.
- Warr, B., Schandl, H. and Ayres, R. (2008) 'Long term trends in resource exergy consumption and useful work supplies in the UK, 1900 to 2000', *Ecological Economics*, 68(1-2), pp. 126-140.
- Welsch, H. and Ochsen, C. (2005) 'The determinants of aggregate energy use in West Germany: factor substitution, technological change, and trade', *Energy Economics*, 27(1), pp. 93-111.
- Westoby, R. and McGuire, A. (1984) 'Factor substitution and complementarity in energy: a case study of the UK electricity industry', *Applied Economics*, 16(1), pp. 111-118.
- WHO (2016) Disease burden and mortality estimates. Available at: https://www.who.int/healthinfo/global_burden_disease/estimates/en/index1.html (Accessed: 11/09 2019).
- Wiedmann, T., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J. and Kanemoto, K. (2015) 'The material footprint of nations', *Proceedings of the National Academy of Sciences*, 112(20), pp. 6271-6276.
- Williams, M. and Laumas, P. (1981) 'The relation between energy and non-energy inputs in India's manufacturing industries', *The Journal of Industrial Economics*, pp. 113-122.
- Wirl, F. (1991) 'Energy demand and consumer price expectations: An empirical investigation of the consequences from the recent oil price collapse', *Resources and Energy*, 13(3), pp. 241-262.

- Wrigley, E. (2010) *Energy and the English Industrial Revolution*. USA: Cambridge University Press, p. 272.
- Wrigley, E. (2013) 'Energy and the English Industrial Revolution', *Philosophical Transactions of the Royal Society of London A*, 371(20110568).
- Wrigley, E. (2016) *The Path to Sustained Growth: England's Transition from and Organic Economy to an Industrial Revolution*. United Kingdom: Cambridge University Press.
- WTO (2015) *International Trade Statistics 2015*. Geneva, Switzerland.: World Trade Organization.
- Wurlod, J. and Noailly, J. (2018) 'The impact of green innovation on energy intensity: An empirical analysis for 14 industrial sectors in OECD countries', *Energy Economics*, 71, pp. 47-61.
- Yi, W. and Chan, A. (2017) 'Effects of heat stress on construction labor productivity in Hong Kong: a case study of rebar workers', *International journal of environmental research and public health*, 14(9), pp. 1055.
- Zander, K. K. and Mathew, S. (2019) 'Estimating economic losses from perceived heat stress in urban Malaysia', *Ecological economics*, 159, pp. 84-90.
- Zander, K. K., Botzen, W. J., Oppermann, E., Kjellstrom, T. and Garnett, S. T. (2015) 'Heat stress causes substantial labour productivity loss in Australia', *Nature Climate Change*, 5(7), pp. 647.
- Zha, D. and Zhou, D. (2014) 'The elasticity of substitution and the way of nesting CES production function with emphasis on energy input', *Applied energy*, 130, pp. 793-798.
- Zhang, P., Deschenes, O., Meng, K. and Zhang, J. (2018) 'Temperature effects on productivity and factor reallocation: Evidence from a half million Chinese manufacturing plants', *Journal of Environmental Economics and Management*, 88, pp. 1-17.
- Zivin, J. and Neidell, M. (2014) 'Temperature and the allocation of time: Implications for climate change', *Journal of Labor Economics*, 32(1), pp. 1-26.