National-level energy use, rebound and economic growth: Insights from useful work and exergy analysis

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below.

Two chapters contain jointly authored papers which have been published:

- Chapter 2: Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010 Brockway P.E., Barrett J.R., Foxon T.J. & Steinberger J.K. (2014) Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010. Environ. Sci. Technol. 48, pp.9874−9881. Available at DOI: 10.1021/es501217t
- Chapter 3: Understanding China's past and future energy demand: an energy efficiency and decomposition analysis Brockway P.E., Steinberger J.K., Barrett J.R. & Foxon T.J. (2015) Understanding China's past and future energy demand: an exergy efficiency and decomposition analysis. Applied Energy 155, pp.892–903. Available at DOI: 10.1016/j.apenergy.2015.05.082

Contributions to those papers were as follows:

- Analysis: I led the analysis in both papers. I built stand-alone analytical models to perform exergy analysis for the UK, US and China. Input data was sourced from publically available datasets. Review of the modelling and feedback was received from my three supervisors, and also collaborative colleagues at IST, Lisbon – in particular Tiago Domingos and Andre Serrenho. I based my input mapping framework on Andre Serrenho's IEA-based approach. I also received the background datasets from Benjamin Warr for their 1900-2000 UK and US exergy analysis
- Writing the paper: In both papers I was lead author of the paper. Guided by comments from my supervisors, I developed the structure of the article, received further comments from them at each revision stage, and incorporated comments accordingly. The final journal papers were finished based on comments received at review stage.

The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

PhD in Alternative Format

The PhD Thesis is based on alternative format guidelines available at this link:

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Four journal papers were written as part of the thesis, and are presented in sequence as the following joint-authored publications:

Chapter	Journal paper
Chapter 2: Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010	Brockway P.E., Barrett J.R., Foxon T.J. & Steinberger J.K. (2014) Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010. Environ. Sci. Technol. 48, pp.9874−9881. Available at DOI: 10.1021/es501217t
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Chapter 4: Energy-augmented nested CES aggregate production functions: aspects of their econometric estimation	Brockway P.E., Heun M.K., Santos J., & Barrett J.R. (2016) Energy-augmented nested CES aggregate production functions: aspects of their econometric estimation. *Energy Economics*, Submitted
Chapter 5: A new approach to estimating total economy-wide energy rebound: An exergy efficiency based study of the UK, US and China	Brockway P.E., Saunders H., Heun M.K., Sorrell S.R., Foxon T.J., Steinberger J.K., & Barrett J.R. (2016) A new approach to estimating total economy-wide energy rebound: An exergy efficiency based study of the UK, US and China. *Energies* (planned submission).

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Abstract

The global climate challenge is keeping below a 2°C global temperature rise (versus pre-industrial levels) to avoid runaway climate change. Urgent policy-based action is required to reduce global fossil fuel use and CO_2 emissions, without breaking the economy. This policy conflict highlights the fact that energy-CO_2 and energy-economy interactions are at opposite ends of the energy conversion chain: at one end fossil fuels are extracted, at the other it is exchanged (via monetary transaction) for energy services. The study of the whole energy conversion chain seems desirable, to provide a broad evidence base for policies aimed at meeting both energy and economic priorities. Such study requires an exergy analysis approach, examining exergy as 'usable energy' from extraction (primary exergy) to 'useful work' (when it is lost in exchange for energy services). However, such national-level exergy analysis is currently an underused approach.

In response, I use a useful work accounting and exergy analysis approach to study energy use, rebound and economic growth for the UK, US and China. Several key findings and insights emerge. First, gains in national-level energy (exergy) efficiencies for the UK and US have slowed or stalled, due to efficiency dilution: the increasing use of lower efficiency processes. Second, the asymptotic national exergy efficiency limit is around 15%, suggesting current energy efficiency policies may not work effectively at the economy-wide scale. Third, my primary energy forecast in 2030 for China - the world's largest energy consumer (and CO_2 emitter) - was 20% higher than mainstream projections. Fourth, using an exergy-based approach, the UK and US exhibit partial energy rebound, but China's energy rebound was higher (close to, or above backfire). If rebound is significant, this weakens the effect of current energy efficiency policies, and has implications for our understanding the role of energy efficiency in economic growth.

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List of Abbreviations and Acronyms

ADF	Augmented Dickey Fuller
AES	Allen Elasticity of Substitution
APF	Aggregate Production Function
BAT	Best Available Technology
BIEE	British Institute of Energy Economics
BOF	Basic Oxygen Furnace
BP	British Petroleum
CCCEP	Climate Change Economics and Policy
C-D	Cobb-Douglas
CES	Constant Elasticity of Substitution
CET	seasonal Central England Temperature
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equivalent
CPE	Cross-Price Elasticity
CSP	Cost Share Principle
DECC	Department of Energy and Climate Change
DSGE	Dynamic Stochastic General Equilibrium
E	Primary Energy
EAF	Electric Arc Furnace
EC	European Commission
EEA	Extended Exergy Analysis
EEF	UK Engineering Employers' Federation
EJ	Exajoules
EPSRC	Engineering and Physical Sciences Research Council
EROI	Energy Return On energy Invested
ESEE	European Society of Ecological Economics
ESRC	Economic and Social Research Council
FAOSTAT	Food and Agricultural Organisation of the United Nations
GCS	Gross Capital Stock

GDP	Gross Domestic Product
GE	Gross Energy
GEMBA	Global Energy Modelling: a Biophysical Approach
GHG	Green House Gas
GJ	Gigajoules
GVA	Gross Value Added
HES	Hicks Elasticity of Substitution
HTH	High Temperature Heat
HVDC	High Voltage Direct Current
IDA	Index Decomposition Analysis
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
ISSB	International Steel Statistics Bureau
IST	Instituto Superio Technico
IT	Information Technology
K	Capital
L	Labour
LMDI	Log Mean Divisia Index
LTH	Low Temperature Heat
MARKAL	MARKet Allocation multi-time period linear optimisation model
ME	Metabolisable Energy
MES	Morishima Elasticity of Substitution
MIT	Massachusetts Institute of Technology
MJ	Megajoules
MTH	Medium Temperature Heat
mpg	Miles per gallon
Mtoe	Million tonnes of oil equivalent
NCS	Net Capital Stock
NOAA	National Oceanic and Atmospheric Administration

ODEX	ODYSEE-MURE Energy Efficiency Index
OECD	Organisation for Economic Co-operation and Development
OHF	Open Hearth Furnace
OLS	Ordinary Least Squares
ONS	UK Office of National Statistics
PIM	Perpetual Inventory Method
PPP	Purchasing Power Parity
PRIMES	Price Inducing Model of the Energy System
PWT	Penn World Tables
REXS	Resource EXergy Service database
SRI	Sustainability Research Institute
SSE	Sum of Squared Errors
TFP	Total Factor Productivity
TJ	Terajoules
TPES	Total Primary Energy Supply
U	Useful Work
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
UKERC	UK Energy Research Council
US	United States
USDoE	United States Department of Energy
USEIA	United States Energy Information Administration
UW	Useful Work
UWA	Useful Work Accounting
WEO	World Energy Outlook
Y	Economic output

Chapter 1
Introduction

Energy demand reduction through energy efficiency form a significant part of global climate reduction policies. Energy economics – the study of the supply and use of energy, combined with economics – provides insights that directly inform such energy efficiency policies. However, relying too heavily on conventional energy economics analysis may be a misplaced faith: since it provides only limited – or at least one-sided - evidence on key issues such as national-level energy efficiency and energy rebound.

Useful work accounting (UWA) is an alternative energy accounting method, which estimates the exergy content of energy carriers during stages of energy conversion until exchanged for energy services. Exergy is defined as "available energy" (Reistad, 1975) or "available work" (Carnahan et al., 1975), meaning it is a thermodynamic measure of energy quality - in terms of a carrier's potential to perform 'work' (e.g. provision of heat, light or mechanical work). By estimating the exergy content of energy carriers at the start of energy conversion (i.e. at primary energy stage) and at the end - when as 'useful work' (Cook, 1971) it measures the "heat or work usefully transferred by a device or system" (Carnahan et al., 1975, p.27), thermodynamic energy (exergy) efficiency can be estimated, giving valuable energy use insights. When combined with economics, the research field of exergy economics is formed - one which offers the potential to widen the evidence base to inform energy and emissions policies.

However, despite firstly the potential of UWA and broader exergy economics, and secondly its growing prominence (Reistad, 1975; Carnahan et al., 1975; Percebois, 1979) following the 1970s oil crises, it somewhat curiously remains a rarely used - and certainly not mainstream - approach today. This context, combined with current climate policy efforts on energy efficiency, provides a research gap and mandate for my response via this PhD thesis, which is centred on the following research question: *"How can useful work and exergy analysis inform understanding of energy use, rebound and economic growth?"* Three research objectives in turn show how UWA can be used to study historical energy use, forecast future energy demand and estimate total energy rebound. A fourth research objective synthesises the contribution that the technique can make to the study of energy use, rebound and economic growth.

In this Introduction, Section 1.1 provides context of the global energy goal of a low-carbon future, and secondly outlines the two key challenges to be overcome: a rapid low-carbon energy supply transition, and reducing energy demand. Section 1.2 sets out the alternative approach of UWA as part of the exergy economics field. The literature review which follows in Section 1.3 is framed around the four key energy questions, evaluating the responses of both mainstream energy economics and alternative UWA-enabled exergy economics. The research framing then follows in Section 1.4, before finally the research design in Section 1.5.

1.1 The global energy goal: a low-carbon future

1.1.1 The need for rapid reductions in energy emissions

Since fossil-fuel related CO_2 emissions contribute around 80% to annual global greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change (IPCC), 2014), much of the effort in reducing GHG emissions is focussed on energy use. However, the 1997 Kyoto Protocol (United Nations, 1997) and subsequent climate change mitigation policies have had little impact, given the IPCC reported with high confidence that “annual GHG emissions grew on average by 1.0 gigatonne carbon dioxide equivalent ($GtCO_{2eq}$) (2.2%) per year from 2000 to 2010 compared to 0.4 $GtCO_{2eq}$ (1.3 %) per year from 1970 to 2000” (IPCC, 2014, p.5). Figure 1-1 shows the 2000-2010 acceleration in CO_2 emissions (x-axis), together with its effect (y-axis) of an increasing temperature anomaly versus pre-industrial 1861-1880 baseline to just below one degree Celsius (1°C) – half of the 2°C internationally agreed maximum temperature rise, to avoid dangerous climate change (Anderson & Bows, 2011).

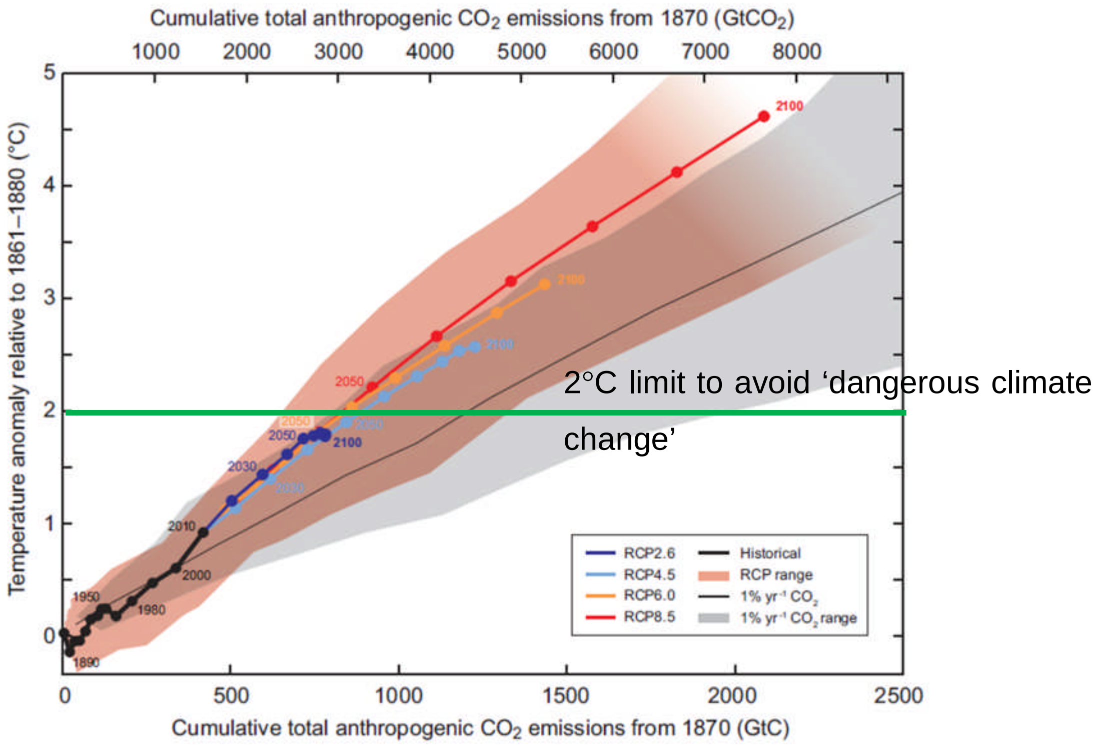
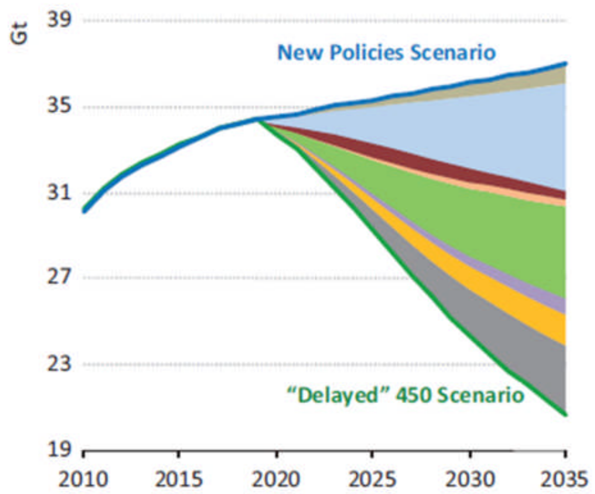


Figure 1-1: Actual CO_2 emissions versus IPCC scenarios (IPCC, 2013)

These temperature effects are being seen globally: since 1880 when records began, 15 of the 16 hottest global years have occurred in the 2000s (the exception was 1998), with 2015 the warmest year on record, beating the mark of 2014[1]. This illustrates how continued large-scale CO_2 emissions are set to have profound temperature effects: Figure 1-1 shows only the most strict emissions pathway - RCP (Representative Concentration Pathway) 2.6 - is forecast to keep below a 2°C temperature rise, with the current emissions pathway (closest to RCP 8.5) suggesting around a 4°C rise by 2100.

All of this translates to the need for a rapid reduction in global energy-related CO_2 emissions. Energy-based decarbonisation pathways from different policy measures can be presented as Pacala-Socolow (2004) type stabilisation 'wedges'. Figure 1-2 shows the example of the International Energy Agency (IEA)'s 450 Scenario - an energy pathway aimed at limiting GHG concentration in the atmosphere to 450 parts per million of CO_2.

[1] https://www.ncdc.noaa.gov/sotc/global/201513



CO_2 Abatement	2025	2035
Demand	5%	5%
End-use efficiency	27%	31%
Power plant efficiency	11%	3%
Fuel and technology switch	2%	2%
Renewables	25%	26%
Biofuels	5%	5%
Nuclear	9%	9%
CCS	15%	20%
Total (Gt CO_2)	6.2	16.4

Figure 1-2: IEA’s 450 Scenario world CO_2 emissions reduction wedges - (IEA, 2013d)

Figure 1-2 shows how carbon mitigation policies are based on two wedge types. The first is that of low carbon energy transition: increasing use of renewables (such as wind, solar, biomass); biofuels; nuclear energy; and carbon capture and storage (CCS) technology. A policy example within this wedge is the European Union (EU) 2009 Renewable Energy Directive (European Parliament, 2009), which mandates 20% of total EU energy use by 2020 is from renewable sources. The second is reducing energy demand, mainly through energy efficiency. The 2012 EU Energy Efficiency Directive (European Parliament, 2012) is an example aiming to reduce EU energy use through energy efficiency by 20% (below a baseline projection) by 2020.

These two wedge types can also be viewed through the Kaya (1989) type identity in equation 1-1:

$$CO_2 = \left(\frac{CO_2}{E_{in}}\right) . \left(\frac{E_{in}}{E_{serv}} . E_{serv}\right) \qquad \textbf{(1-1)}$$

Where

- CO_2 are total CO_2 emissions
- E_{in} is total primary energy (in)
- E_{serv} are total energy services (out)

Thus to reduce CO_2 emissions in equation 1-1, the low carbon energy first wedge reduces carbon intensity $\left(\frac{CO_2}{E_{in}}\right)$ through low carbon energy sources. The second wedge lowers energy demand $\left(\frac{E_{in}}{E_{serv}}.E_{serv}\right)$ by either reducing $(\frac{E_{in}}{E_{serv}})$ via greater energy efficiency (i.e. reduce E_{in} whilst maintaining E_{serv}), or reducing energy service demand (E_{serv}) keeping similar energy efficiency (E_{serv} /E_{in}) ratio.

The challenge of delivering these two wedges are considered now in more detail.

1.1.2 Wedge 1: Rapid transition to low-carbon energy supply

A common view (Smil, 2003; Wilson & Grubler, 2011; Grubler, 2012; Solomon & Krishna, 2011; Bashmakov, 2007; Smil, 2000) is that energy transitions have historically taken decades, as shown in Figure 1-3:

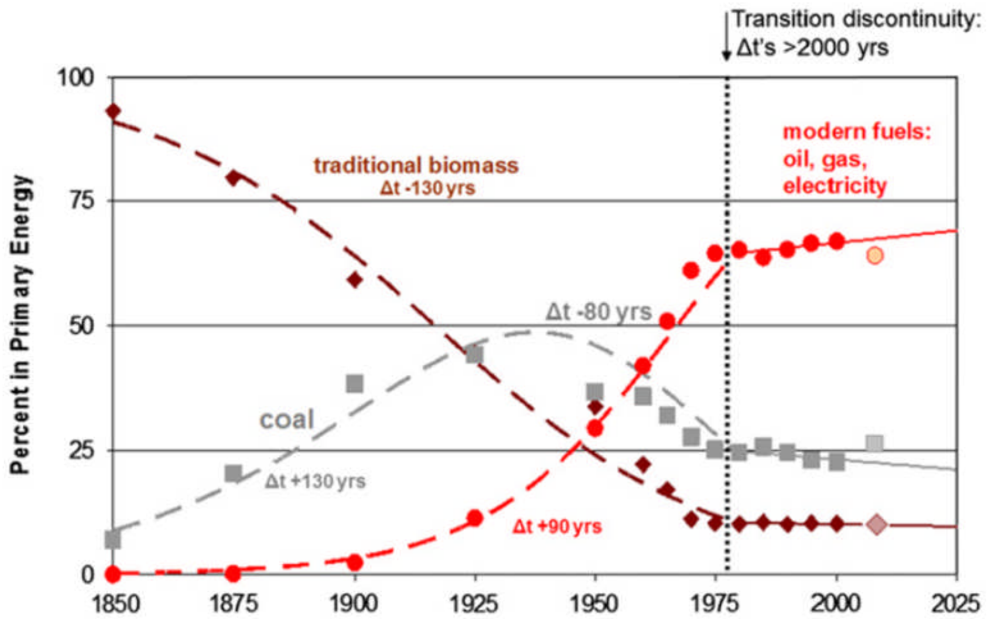


Figure 1-3: Historical energy transitions 1850-2000 (Grubler, 2012)

Currently, modern renewables are estimated to provide around 10% of global final energy use, as shown in Figure 1-4. Therefore, whilst some advocate we are on the verge of new industrial revolution based on low-carbon energy (Stern & Rydge, 2012), the reality is that achieving a near total decarbonisation of global energy supply transition by 2050 to meet a 2°C emissions pathway would be –

by comparison to Figure 1-3 - at a scale and speed of energy transition unprecedented in human history.

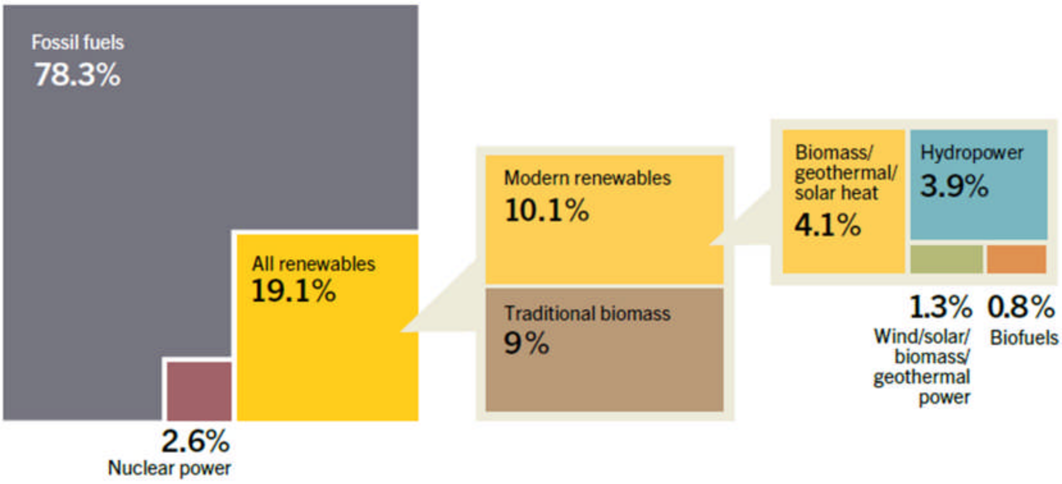


Figure 1-4: Estimated renewable energy share as % of global final energy consumption in 2013 (REN21, 2015)

Technical issues are one part of this low carbon transition challenge. Much effort has been placed into developing renewable energy technologies, and many countries rich in renewable sources are increasing production – for example Denmark now produces over 20% of its electricity from wind (Renewable Energy Policy Network for the 21st Century (REN21), 2015). High Voltage Direct Current (HVDC) power transmission lines are among a group of available smart-grid technologies (IEA, 2012) which are able to interconnect electricity supplies, improving the stability of the energy system. So whilst certain technical issues remain such as storage of intermittent renewables (IEA, 2012), the technical feasibility of wide-scale use of renewables appears not to be the key barrier.

Instead, the key transition challenge lies in a second part: that energy source transition needs to take place within a transformation of broader, whole energy systems. Transforming energy systems involves dealing with interwoven issues including the high number of agents (e.g. Governments, producers, citizens, energy companies), energy infrastructure lock-in (Unruh, 2000), finance constraints (Wiseman et al, 2013) and vested interests (Moe, 2010). For example, electricity based renewables have system issues including grid connections, intermittency and storage, whilst geo-engineering (e.g. CCS) requires integration into energy systems. Understanding and aligning the agents and actors in this network for energy pathways transition is therefore a challenge and whole topic itself (Foxon et al., 2010; Foxon & Steinberger, 2013).

1.1.3 Wedge 2: Reducing energy demand

1.1.3.1 Energy efficiency and energy conservation

Figure 1-2 shows how energy demand reductions are envisaged by energy efficiency improvements, or to a less extent - energy conservation: reduced demand for energy services. In the energy efficiency strand, the aim is to reduce energy use whilst maintaining energy services (e.g. thermal comfort or passenger-kms). The energy conservation strand considers reducing energy services with unaffected device efficiency, by for example lower thermostat temperatures and car speed limits (Herring, 2006). The small role of reducing energy services is explained by Sorrell (2015), who notes that this is hard to achieve since it has to resist strong upward pressures from rising affluence - which itself closely correlates to energy service demand.

Returning to energy efficiency related carbon emissions reduction, it sounds initially straightforward: simply introduce a range of micro-energy efficiency policies to bring higher efficiency energy using devices into use - such as boilers[2] and cars[3], or improve house insulation[4], and energy reductions will follow in the scale originally envisaged by simple engineering calculations. But it is more complex, as at an economy-wide scale, energy efficiency is linked - beyond device level energy efficiency - to broader aspects such as energy prices,

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[2] The EU Ecodesign Directive (Directive 2009/125/EC)[1] sets a legislative framework for the ecodesign requirements for energy-related products (e.g. boilers, lightbulbs, TVs and fridges), which are responsible for around 40% of all EU greenhouse gas emissions. Refer to https://ec.europa.eu/energy/sites/ener/files/documents/list_of_ecodesign_measures.pdf

[3] EU Regulation No 443/2009 sets an average CO_2 emissions target for new passenger cars of 130 grams/kilometre (g/km), with a gradual tightening of this target to 95 g/km from 2021. Refer to http://ec.europa.eu/clima/policies/transport/vehicles/cars/documentation_en.htm

[4] For example in the UK this is achieved via progressive tightening of the Building Regulations: Part L – Conservation of Fuel and Power . Refer to https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/441420/BR_PDF_AD_L2A_2013.pdf

economic output and energy rebound (Ayres et al, 2007). For our purposes I define energy rebound as “the additional energy consumption enabled by energy efficiency increases” (Madlener & Alcott, 2009, p.371).

1.1.3.2 Thermodynamic failings in energy economics: a possible research gap

Such considerations are the realm of energy economics: where the study of the supply and use of energy[5] is combined with mainstream economics, and is distinct from environmental, ecological or resource economics. I set out four key aggregate energy questions in Figure 1-5. By ‘aggregate’ scale, I include sector (e.g. industry, household) and national levels, but not firm level.

1. How should we measure energy efficiency?
2. How large is the energy rebound effect?
3. How does economic output relate to energy use?
4. How much energy will we need in the future?

Figure 1-5: Four key aggregate energy questions

These four questions matter to the topic of ‘energy demand reduction through efficiency’ – which Figure 1-2 projected to be 38% of global CO_2 abatement in 2025 - because if energy efficiency policies are to be successful, such aspects should be included in their design. The first two questions consider the single issues of energy efficiency and rebound. The third question relates to a long standing pre-occupation in energy economics: the study of linkages between energy use and economic growth, and is therefore relevant to the topic of energy demand reduction. The fourth question of future energy demand is complex: interwoven with the previous questions and other macroeconomic aspects such as population and energy prices.

Let us now preface further discussion with two central assertions, which underpin the rationale of a possible research gap:

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[5] Where ‘energy’ is considered as ‘primary’ (e.g. extracted coal, oil, gas) or ‘final’ (e.g. finished fuels such as diesel, electricity).

1. **Thermodynamic failings in energy economics:** Energy economics does not adequately include the second law of thermodynamics which is concerned with energy quality and work. This means the mainstream field has not – and cannot - adequately answer these key macroeconomic questions, inhibiting the effectiveness of polices aimed at reducing energy demand through energy efficiency.
2. **Exergy economics is a viable - but underused - alternative:** UWA exists as the basis for a first and second law approach to better study these questions – when combined with other analytical approaches forms an alternative, exergy economics research field. However, UWA and the broader field of exergy economics has been underused in the context of these key questions.

By thermodynamics, I mean “a branch of physics concerned with heat and temperature and their relation to energy and work”.[6] The most relevant two (of four) thermodynamic laws are the first law: conservation of total system energy, and the second law: where ‘exergy’ (as available energy) degrades with use.

The assertions are illustrated by Figure 1-6. This shows the three issues of economic growth, energy efficiency and rebound. in addition, there are other factors which influence energy demand reduction, such as population, energy prices and resource constraints (Chertow, 2001; Liu & Ang, 2003), but these are beyond the study focus of my PhD, largely on the basis of practicality (needing to draw a boundary round an already large topic).

[6] https://en.wikipedia.org/wiki/Thermodynamics

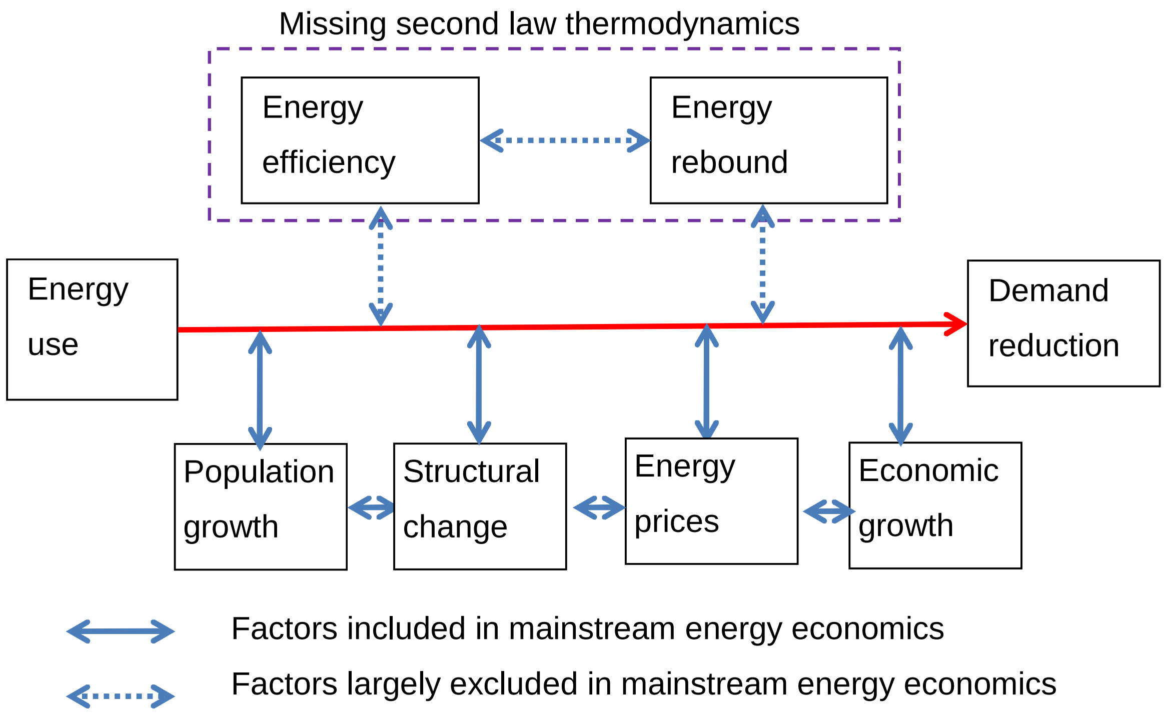

Figure 1-6: Thermodynamic failings in the study economy-wide energy demand reduction through energy efficiency

Figure 1-6 shows how, if the effects of energy efficiency and/or rebound are significant, then the study of energy demand - in terms of assessing historical drivers or future estimates - may be limited without due attention to the study (and measurement) of the effects of linkages of energy efficiency and rebound.

1.2 An exergy-economic approach to studying economy-wide energy efficiency, rebound and economic growth

1.2.1 Concepts and definitions

Energy as a general definition is 'the potential to do work', and is a much more widely used term than exergy. Exergy as a term was introduced by Rant (1956), and has a much tighter thermodynamic meaning. Baehr (1965) stated exergy was "the totally convertible part of the energy", and more formally exergy is measured as "the maximum work that can be provided by a system (or by fuel) as it proceeds (by any path) to a specified final state in thermodynamic equilibrium with the atmosphere” (Carnahan et al., 1975, p.27).

In simple terms, Reistad (1975, p.429) equated exergy to be “available energy”. The important aspect of exergy is that it is includes the second law of thermodynamics, such that energy conversion to higher quality energy vectors (such as electricity) accounts for the entropic cost of increasing disorder. This was a key point of Georgescu-Roegen (1971; 1975; 1979), who as shown in Figure 1-7, noted how the temporary concentration of energy to provide energy services ultimately dissipates into diffuse, low-grade wastes.

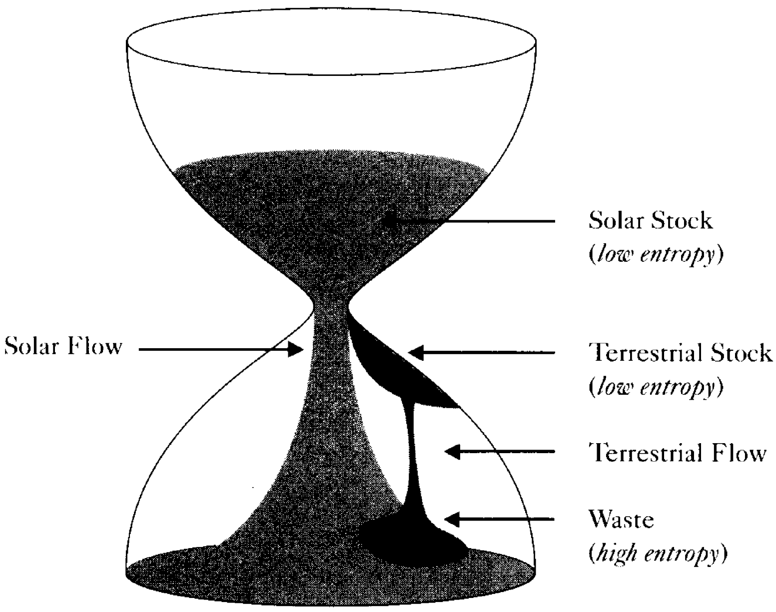

Figure 1-7: Georgescu-Roegen entropy hourglass (Daly, 1996, p.49)

At an economy-wide scale, exergy flows through an economy as shown in Figure 1-8, being reduced at each conversion stage (owing to the second thermodynamic law). At the start, there is primary exergy, which is the ‘available energy’ part of the primary energy source (e.g. coal, oil, gas, biomass). Once transformed into ‘final energy’ (e.g. petrol, electricity), it is used for the intended energy service purpose, such as heat, motion, mechanical work, lighting. It is here that ‘useful work’ is done (a term introduced by Cook, 1971). And this raises a fundamental point: since it situates the energy analysis not at the start of the energy conversion chain, but at the other end: the place of economic transaction where energy is exchanged for energy services.

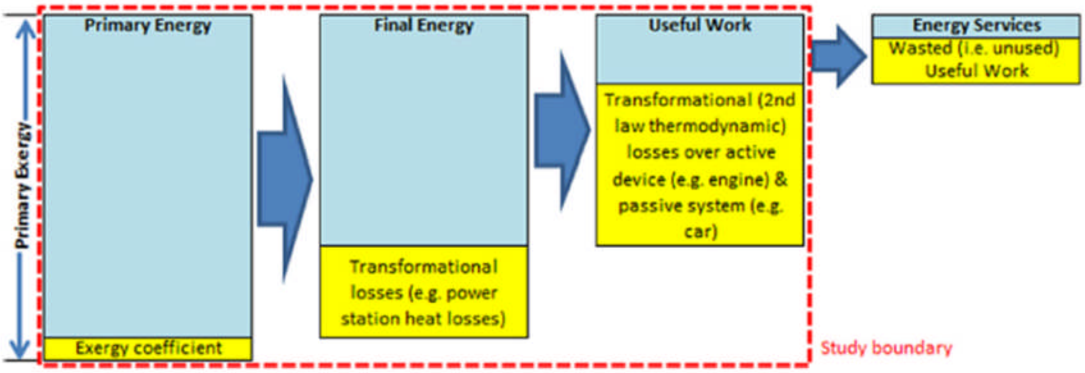

Figure 1-8: Conceptual diagram of primary energy to useful work (Brockway et al., 2015)

Carnahan et al (1975) provided the first systematic national-level study of exergy and useful work for energy analysis, defining useful work as "the minimum available work [exergy input, $B_{\min}$] required to perform the task" (ibid, p.37), where 'tasks' are energy end uses that provide energy services, such as low-temperature heat, lighting, or car transport. This leads to their definition (ibid, p.35) of task-level exergy efficiency (ε_{task}) in equation 1-2:

$$\varepsilon_{task} = \frac{useful\ work\ (output)}{primary\ exergy\ (input)} = \frac{U_{task}}{E_{task}} \quad \text{(1-2)}$$
$$= \frac{minimum\ exergy\ input\ to\ achieve\ task\ work\ transfer\ (B_{\min})}{\max reversiable\ work\ done\ as\ system\ reaches\ equilibrium\ (W_{\max})}$$

Thus for the whole economy, which comprises n tasks, we can therefore calculate total (aggregate) exergy efficiency (ε_{tot}) by dividing the sum of useful work by sum of primary exergy for each task-level. This thermodynamic definition of economy-wide energy (exergy) efficiency is also given in equation 1-3:

$$\varepsilon_{tot} = \frac{Total\ useful\ work\ (output)}{Total\ primary\ exergy\ (input)} = \frac{\sum_1^n U_{task}}{\sum_1^n E_{task}} \quad \text{(1-3)}$$

To distinguish primary exergy from primary energy, primary exergy for common fuels, are approximated to the lower heating values, as shown in Table 1-1. This results – for fossil fuels – in an exergy conversion factor of typically 1.04-1.08

from primary energy to primary exergy, based on ratios given by Kotas (1985) and Szargut et al (1988).

Table 1-1: Typical exergy conversion values for selected fuels (Gasparatos et al, 2009)

Fuels	LHVs[a]	Exergy factors[b]
Coal	26.0 GJ/tonne	1.06
Petroleum products	43.6 GJ/tonne	1.06
Natural gas	35.6 MJ/m^3	1.04
Coke	29.8 GJ/tonne	1.05
Coke oven gas	16.2 MJ/m^3	1.04
Electricity	–	1
Fuelwood (20% humidity)	10.0 GJ/tonne	1.11
Landfill and sewage gas	21.0 MJ/m^3	1.13
Waste	–	1.11

For renewable and nuclear generated electricity, exergy conversion coefficients (from primary exergy to final electricity) are typically based on estimates of the conversion device efficiency, as shown in Table 1-2.

Table 1-2: Typical exergy coefficients for renewable and nuclear based electricity (Warr et al., 2010)

Energy technology	Exergy inflow coefficient
Hydroelectric (natural storage)	0.75–0.90
Hydroelectric (pumped storage)	0.3
Geothermal	0.35
Solar (PV)	0.07
Solar (thermal)	0.1
Aeolian	0.15
Solid biomass	0.33
Nuclear	0.33

The selection of renewable factors are not without controversy – as discussed in Section 1.3.1.2. Notwithstanding this, for most industrialised countries - since most energy inputs are fossil-fuel based - total primary exergy to primary exergy ratio is close to unity (~1.04).

1.2.2 Economy-wide studies

Economy-wide exergy analysis has progressed on two fronts, as discussed in depth by Brockway et al (2014; 2015) which form Chapter 2 and 3 of this thesis. First, is societal extended-exergy analysis (EEA), which is akin to a mass-balance analysis, where all material and energy inputs to society are mapped through an economy as exergy equivalent stocks and flows, as shown in Figure 1-9. Prominent authors include Wall (1987; 1990), Sciubba (2001; 2011), Rosen and Dincer (2001; 2003) and Chen et al (2014).

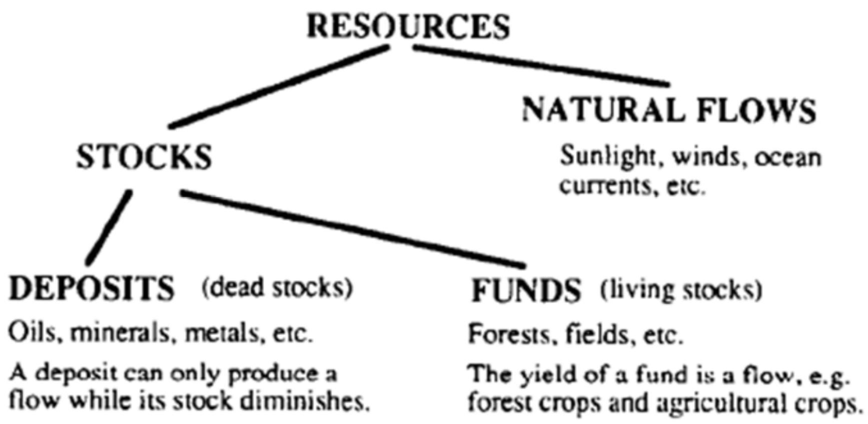

Figure 1-9: EEA based natural resource boundary (Wall, 1990)

By considering all resources into an economy, EEA is therefore closely aligned to the broadest ideas of ecological economics. However, a second group of researchers focus more narrowly on exergy flows involved with “energy carriers for energy use” (Ertesvag, 2001, p.254), since energy use comprises the great majority of EEA studies in exergy terms and is asserted by some as an important factor of economic production. Therefore its specific study is relevant to energy economics, and important empirical studies include Reistad (1975), Kümmel et al (1985), Nakicenovic et al (1996), Hammond and Stapleton (2001), Ayres and Warr (2005), Cullen and Allwood (2010b) and Serrenho et al (2016).

Typical outputs are estimates of economy-wide useful work and primary exergy values, leading via equation 1-1 to estimates of aggregate (or economy-wide) exergy efficiency. Figure 1-10 provides a sample output, which shows increasing aggregate exergy efficiency for four countries: from 3-4% in 1900, to 12-18% in

2000. It also reveals other insights: such as how aggregate efficiencies grew fastest between 1940 and1970.

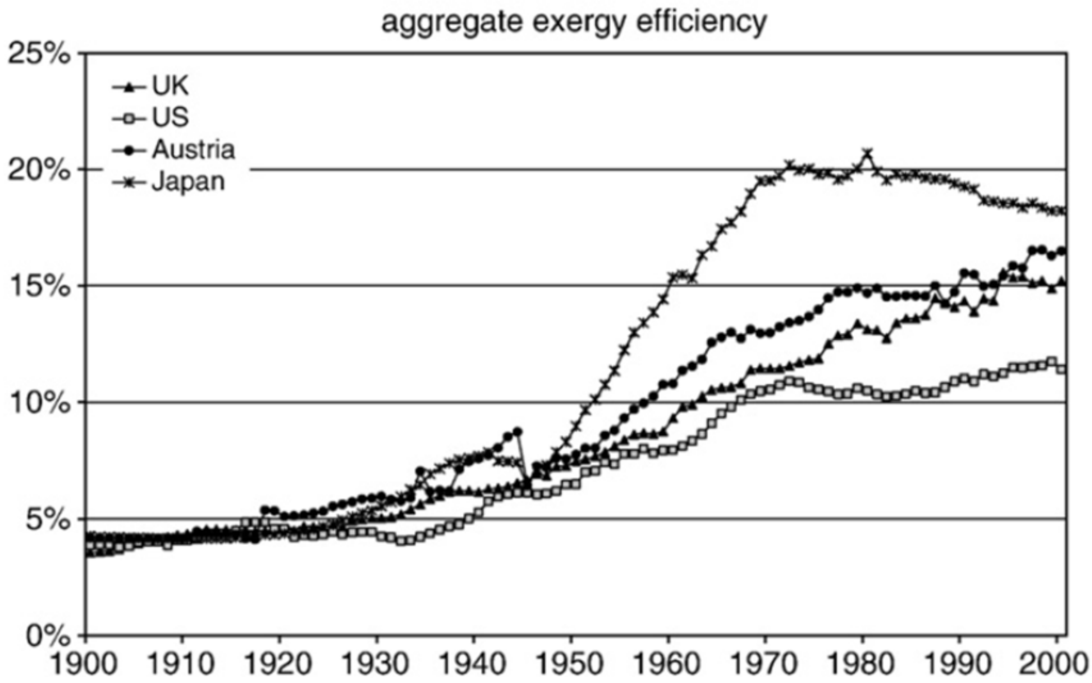

Figure 1-10: 'Energy carrier for energy use' based outputs (Warr et al., 2010)

It is this second group that is relevant to studying the economy-wide energy economic questions (highlighted in Section 1.1.3), since it focusses on the thermodynamic work done by energy carriers, which as noted earlier is the principle part of global GHG emissions. Therefore this second approach forms the methodological basis for my thesis.

Within this group, Ayres and Warr and co-authors (Ayres & Warr, 2005; Ayres, 2001; Warr & Ayres, 2006; Ayres & Warr, 2010) have been the most prolific exponents of the exergy analysis approach in relation to energy use and economics.

1.2.3 Claimed advantages of UWA and exergy economics

Numerous advantages are claimed of UWA and its use in exergy economics, compared to traditional energy economic analysis. First it provides a thermodynamic measure of energy quality – which Stern (2010) equates to 'energy productivity', i.e. a measure of the effect of energy use on economic production. Therefore UWA is a measure of energy quality since it accounts for how much exergy (as available energy) is lost at each stage in energy conversion through to the 'useful work' stage. In that sense it offers an alternative to other measures of aggregate level energy quality such as fuel type or price based differentiation (Stern, 2010; Ang & Zhou, 2012; Stern, 2012) or net energy (Gagnon et al, 2009; Dale 2012).

Second, 'exergy' efficiencies calculated on a first and second law basis enable a more stable comparison between technologies, as demonstrated by Figure 1-11, which shows misleading (and thermodynamically impossible) first law (energy) efficiencies for electric heaters and heat pumps.

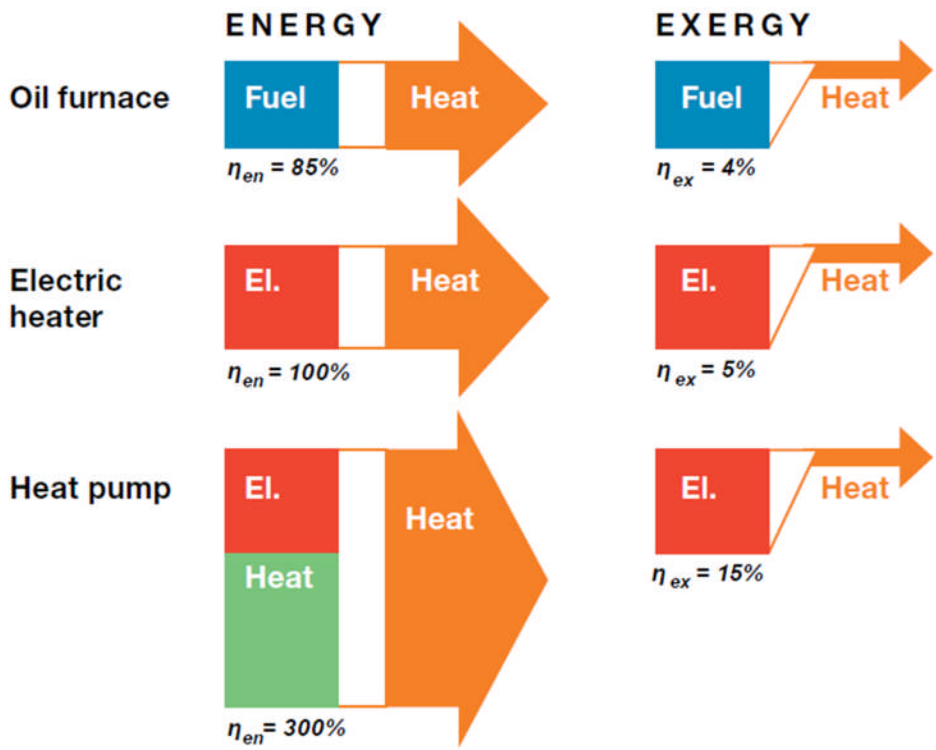

Figure 1-11: Energy versus exergy efficiency for typical heating systems (Science Europe, 2015)

A third claimed advantage is that UWA analysis provides not only "a measure of how nearly the efficiency of a process approaches the ideal… [but also] it quantifies the locations, types and magnitudes of wastes and losses" (Kanoglu et al, 2009, p.984). Hammond (2004) illustrates in Figure 1-12 the gap between energy efficiency theory (economic and technical potential) and thermodynamic reality. Later, Cullen and co-authors (Cullen & Allwood, 2010a; Allwood et al., 2010; Ma et al., 2012) give additional insight via their studies into active and passive stages of exergy use to energy services.

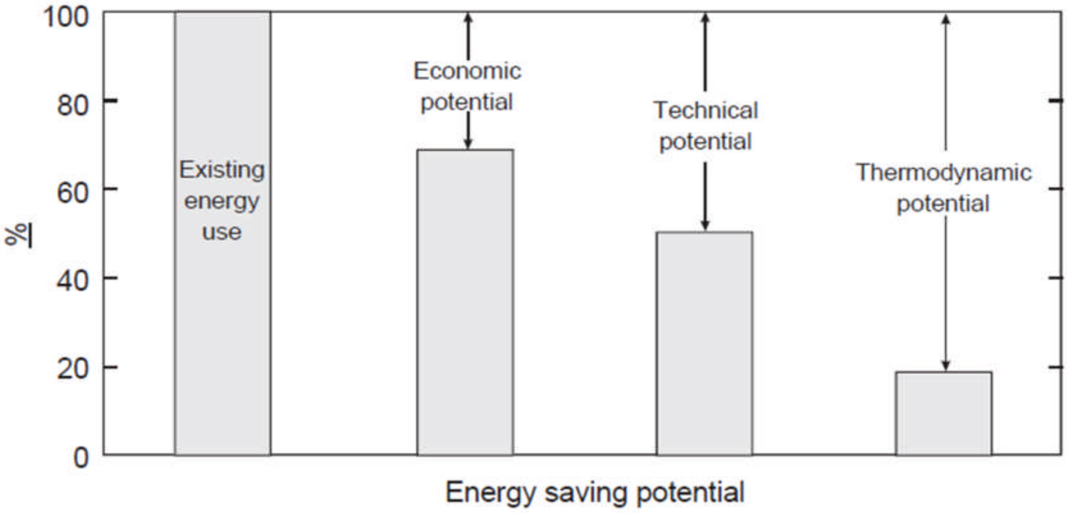

Figure 1-12: The energy efficiency gap between theory and practice (Hammond, 2004)

Fourth, if UWA provides a firmer energy analysis footing, then greater insights into energy use and economics may follow, via application to exergy economics. This is not a new suggestion, and a very similar argument to that of Georgescu-Roegen - the "father of the thermodynamics of economics" (Rosen and Dincer, 2003, p.1636) - who made an immense theoretical contribution to this field[7], particularly in the 1970s (Georgescu-Roegen, 1971; 1975; 1979). At the same time, Percebois (1979, p.148) suggested that useful energy (useful work) intensity – rather than primary energy intensity – "allows us to analyse structural change in energy supply and situates our analysis at the level of satisfied needs". Later Ayres and Warr (2005) applied their UWA results to economic growth, and

[7] Cleveland and Ruth (1997, p.204) suggest his key contribution was to "incorporate biophysical principles into … models of standard economics [and thus] pointed towards the economic importance of the laws of conversation of mass and energy, and the entropy law"

suggested that useful work explained more of economic growth (than primary energy) as a factor of production.

Last, such quantitative energy economic advantages translate into policy benefits. Koroneos et al., (2011, p.2475) suggests exergy studies “can play an important role in the establishment of efficiency standards of the energy use in various economy sectors”, whilst Dincer (2002, p.149) writes “the role of exergy in energy policy making activities is crucial.” Support for exergy analysis as a means to define economy-wide energy efficiency is also found outside academia such as the American Physical Society (2008) and Science Europe (2015).

1.3 Literature review

This literature review is framed around the four macroeconomic questions in Figure 1-5. It surveys common approaches to each question and considers to what extent each have been answered through mainstream (energy economics) approaches, and what the alternative UWA-enabled exergy economics response has contributed. The focus is aimed at providing sufficient breadth to test the suggested research gap, leading to the assessment of whether the proposed study is valid. Following the confirmation of research framing and design (Sections 1.4 and 1.5), literature reviews of greater depth are contained within each Chapter 2-5 – where each form a journal paper.

1.3.1 Qu. 1 How should we measure aggregate energy efficiency?

Two points relating to the definition of energy efficiency provide a necessary backdrop to the review of approaches taken regarding measurement. The first is suggested by Ayres et al (2011, p.10634), who notes that energy efficiency is often used “without a formal definition, as if the term really needed none. Unfortunately, that is not the case”. Their point is that energy efficiency cannot be measured without a definition, meaning in turn that without measurement we cannot ascertain the effectiveness of energy efficiency policies or practices. Second, where definitions are used, they are based only on a broad ‘first law’ definition, which follows the type shown by Patterson (1996) in equation 1-4. This definition mimics that applied by others, such as the UK Government’s 2012

Energy Efficiency Strategy (Department of Energy & Climate Change (DECC), 2012, p.6), which states “energy efficiency is a measure of energy used for delivering a given service”.

$$\text{Energy efficiency} = \frac{\text{useful output}}{\text{energy input}} \tag{1-4}$$

Such a broad definition creates a problem regarding measurement, since the ‘useful output’ numerator is open to wide interpretation. This result is that without a tight, formal definition, a variety of common approaches are taken, as set out in the next section.

1.3.1.1 Mainstream energy economic approaches

Four different approaches to measuring and reporting economy-wide energy efficiency have emerged in common use. The first method is to calculate monetary-based energy intensity (GJ/$) - as energy input (GJ) divided by economic output ($) – as a measure of energy efficiency. However, these monetary intensities (and their reverse: energy productivity ($/GJ)), have been criticised since they contain other information, such as trends in population or structural effects (Patterson, 1996; Ang, 2006). Decomposition techniques - which split energy use changes into activity, structure or intensity effects (Ang, 1994; Ang & Pandiyan, 1997) – provide additional information. This metric is typically reported for industrial sectors or overall national-level (Renshaw, 1981; Liddle, 2012).

The second method is the use of physical-based intensities. For industry sectors, physical outputs are in tonnes, yielding GJ/tonnes as an indicator (Ross & Feng, 1991; Eichhammer & Mannsbart, 1997). Physical units differ in other sectors: for example floor area in residential sector gives GJ/m^2 (Amecke et al., 2013), or passenger-kms in transport sector yields GJ/passenger-km (Can et al., 2010). The IEA (Table 3.1, IEA, 2013a) summarise well the various indicators taken as energy efficiency by sector. However, as indicators vary between sectors (m^2 versus tonnes), they cannot be combined at national-scale with this method.

A third method - based on combining monetary and physical approaches - has emerged since the 1990s. It overcome the issues that 1. monetary indicators cannot be applied at all sectors (e.g. household), whilst 2. physical intensities cannot be summated at a national-level. In this hybrid method, energy efficiency intensities are first calculated at a granular level, as either monetary (GJ/$) or physical (GJ/tonnes), depending what is most appropriate for that sector. Next, the values are benchmarked against a given year (e.g. 100 in year 2000), and then combined based on their weighted energy use to produce a value for overall indexed energy intensity. An example is the ODEX indicator (Enerdata, 2010), used in the EU ODYSSEE project[8], as shown in Figure 1-13:

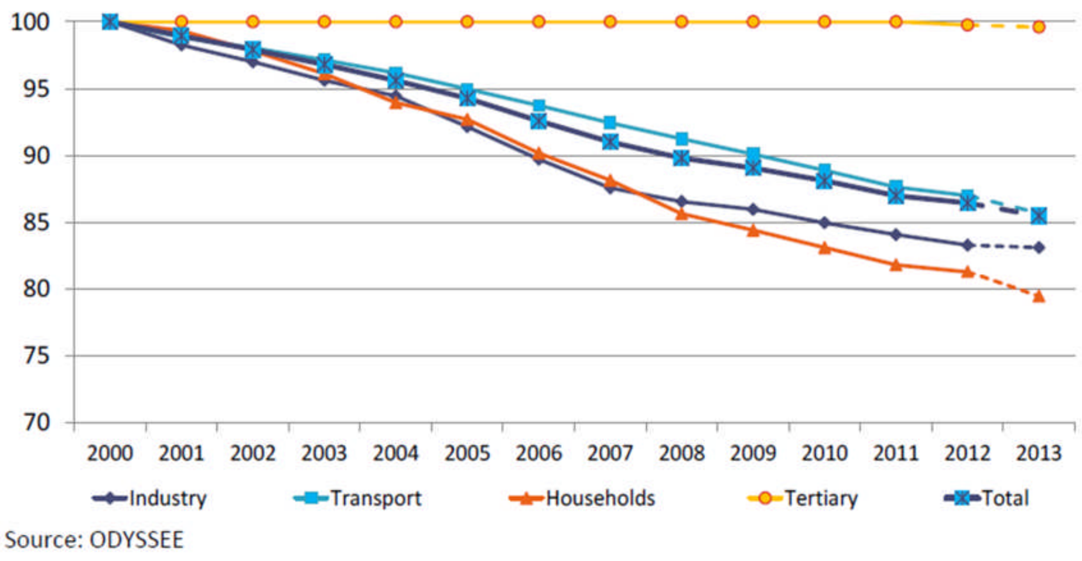

Figure 1-13: Energy efficiency progress in the EU (ODEX) (ODYSSEE-MURE, 2015)

The fourth, less common method, is to estimate thermodynamic 'first law' efficiency, i.e. energy out / energy in. This can be reported at device-level, for example the Seasonal Efficiency of Domestic Boilers in the UK (SEDBUK) boiler efficiencies[9]. It can also be estimated at a national-level, as shown in Figure 1-14:

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[8] ODYSSEE web site (www.odyssee-indicators.org).

[9] http://www.homeheatingguide.co.uk/sedbuk-rating.html

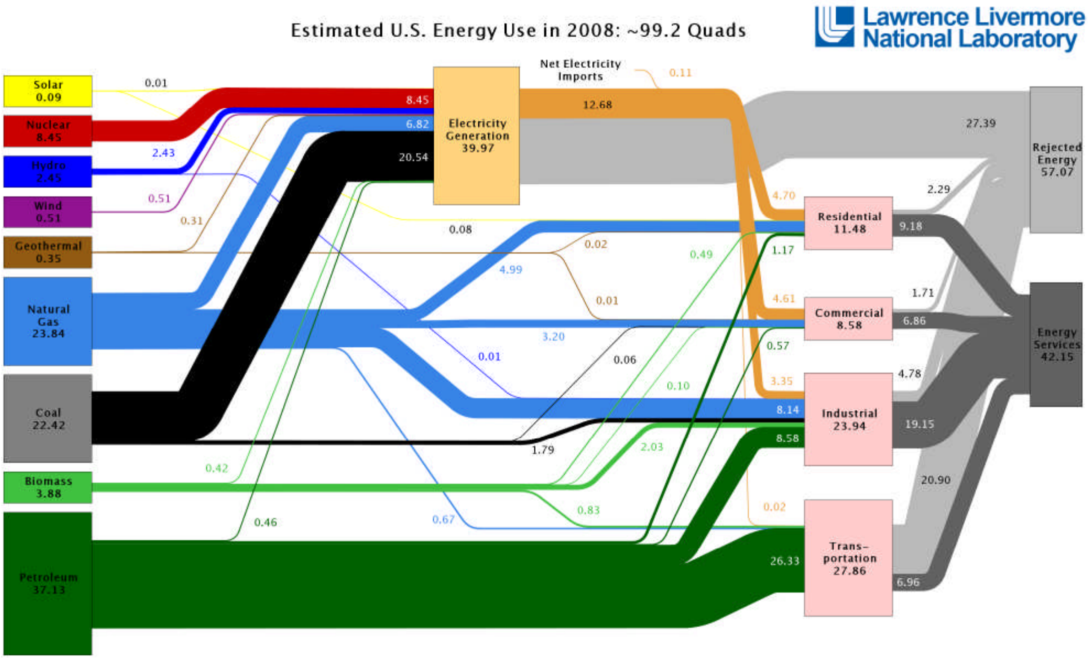

Figure 1-14: US Energy use – first law efficiency (Ayres et al., 2011)[10]

However, Patterson (1996, p.378) contends that “a significant problem with first-law energy efficiencies is that they do not take account of the energy quality of the inputs and the useful outputs.” Ayres et al (2011) agrees, suggesting that the estimate of US efficiency given in Figure 1-14 is misleading when compared to including a ‘second law’ (exergy) efficiency approach (as discussed in Section 1.3.1.2).

From the four methods, several features stand out. First, without a strict definition of energy efficiency, a variety of approaches are taken to its measurement. Second, monetary, physical and hybrid methods calculate intensities (energy in / useful output) – the inverse of efficiencies (useful output / energy input) - and hence are described as energy efficiency indicators, acting as proxies for thermodynamic energy efficiency. Third, the research question and data availability influences whether a top-down (monetary); bottom-up (physical, thermodynamic); or hybrid (monetary-physical) method is chosen, as shown in Figure 1-15:

10 Original source: Lawrence Livermore National Laboratory (LLNL). Available at: https://flowcharts.llnl.gov/energy.html

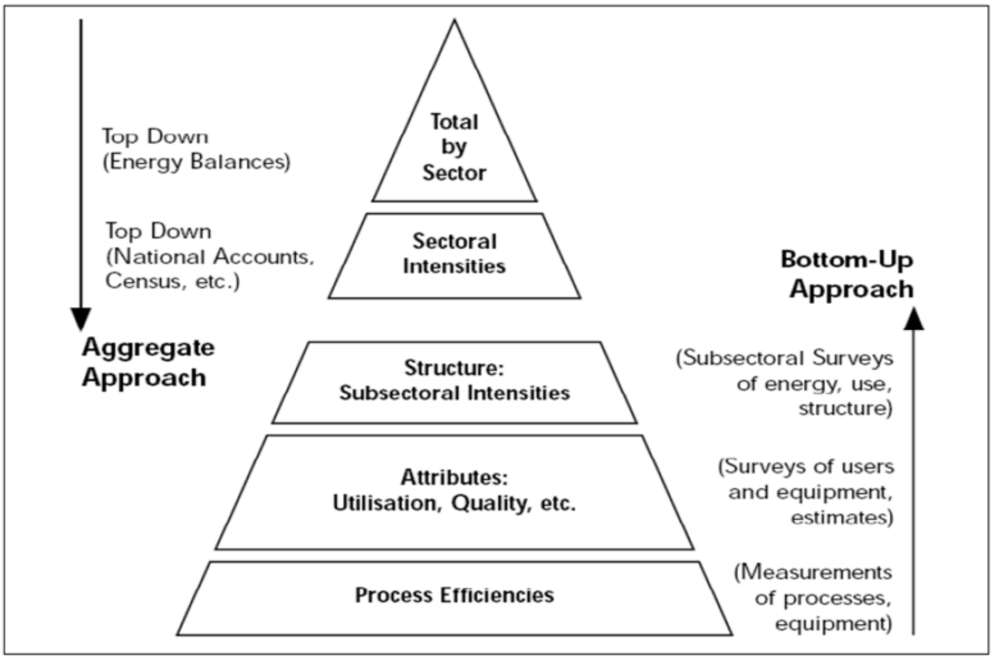

Figure 1-15: Energy efficiency indicators pyramid (Can et al., 2010)

From a policy perspective, energy efficiency policies target reductions to energy use below a baseline projection. An example is the EU's 2012 Energy Efficiency Directive, which aims for a 20% reduction of primary energy use relative to their 2007PRIMES market optimisation model's[11] baseline projection for 2020. A second example is DECC's 2012 Energy Efficiency Strategy (Department of Energy & Climate Change (DECC), 2012), which targets per capita final energy use reductions versus MARKAL baseline projections, as Figure 1-16 shows:

[11] http://www.energyplan.eu/othertools/national/primes/

Figure 1-16: UK final energy consumption per capita scenarios (DECC, 2012)

1.3.1.2 Alternative UWA-enabled exergy-economic approach

A thermodynamic first and second law approach offers a route to overcome these limitations, by measuring energy efficiency in exergy terms. The broad definition in equation 1-4 can be narrowed through a first and second law (exergy) lens by equating useful output to useful work, and energy inputs to primary exergy, giving aggregate exergy efficiency in equation 1-5:

$$Exergy\ Efficiency = \frac{\text{Sum of useful work } (\Sigma U)}{\text{Sum of primary exergy } (\Sigma E)} \qquad \textbf{(1-5)}$$

Reistad (1975) provided the first country-level exergy analysis, for US in 1970 – reporting an aggregate exergy efficiency of 21%. Later, Wall estimated exergy efficiencies for Sweden (Wall, 1987) and Japan (Wall, 1990). Ertesvag (2001) compared exergy efficiencies studies for various countries, and found aggregate exergy efficiencies to have a wide spread: 13-30%. More recently Ayres and Warr (Ayres & Warr, 2005; Warr et al., 2010) have estimated aggregate efficiencies for the US, UK and Japan which have been between 14-18%. Nakicenovic et al (1996) provided a first global exergy efficiency estimate of 10%. The application of energy efficiency beyond quantification has been limited:

though Williams et al (2008) importantly introduce the topic of efficiency dilution for Japan. (See Chapters 2 and 3).

Individual economic sectors have also been examined (Hammond, 2007; Ayres et al., 2011; Kondo, 2009), and demonstrate how manufacturing processes have higher exergy efficiencies than the residential sector, as would be expected. Rosen's examination of global industry efficiencies (Rosen, 2013) suggests a first law (energy) efficiency of 51% and a first and second law (exergy) efficiency of 30%. He then suggests how exergy analysis, despite lower reported efficiencies, gives greater insights than energy analyses by finding "a larger margin for improvement exists from an exergy perspective" (ibid, p.461) This focus on potential improvement in efficiency is kept up by Cullen and Allwood, who estimate since "the overall efficiency of global energy conversion to be only 11 per cent; global demand for energy could be reduced by almost 90 per cent if all energy conversion devices were operated at their theoretical maximum efficiencies" (2010b, p.2054).

Whilst exergy analysis has also been applied to renewable technologies (Dewulf et al., 2008; de Castro et al., 2011), the results can be misleading, as they show exergy conversion efficiencies for fossil fuels (~20%) are typically double that for renewable exergy efficiencies (~10%). Koroneos et al (2003, p.308) suggests this highlights that "their main disadvantage lies in their incapability to take advantage of a big part of the available energy". However, Dukes 'buried sunshine' (Dukes, 2003) proposition shows how such methods may be invalid, since they do not calculate primary exergy content of fossil fuels and renewables on an equivalent basis. To do so, either exergetic losses from incident sunlight (which occurred millions of years ago) to fossilised fuel stage (i.e. buried oil, coal, gas) should be included, or renewables should not be penalised via the device level efficiencies in Table 1-2. As such, the need to develop a consistent approach to fossil fuel and renewables generated electricity remains one of several robustness issues with the calculation of economy-wide exergy efficiency. Sousa et al (2016) consider this and other aspects of consistency including granularity, transport and industrial exergy efficiency, muscle work and non-energy use.

1.3.2 Qu. 2 How large is national-level energy rebound?

In 1865 Jevons (1865) famously wrote “it is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth”. A significant body of work on this topic has followed, and is well summarised by Alcott (2005), and later considered in more depth by Sorrell and co-authors (Sorrell, 2007; Sorrell & Dimitropoulos, 2007a; Broadstock et al., 2007; Sorrell & Dimitropoulos, 2007b). Two schools of thought have emerged since in the last 30-40 years. The first is what Saunders (1992) termed the ‘Khazzoum-Brookes postulate’, named after Khazzoum (1980) and Brookes (1979). These authors believe energy rebound may be significant, and in some cases higher than efficiency savings (backfire), leading to an increase in overall energy use, as Jevons suggested. A second, counter school of thought, led by economists such as Lovins (1988), and continued by authors including Schipper and Grubb (2000) and Gillingham et al (2013), who argue only small rebound effects are observable, and so energy efficiency policies are largely effective.

1.3.2.1 Mainstream energy economic approaches

First, let us assume the three components of energy rebound are direct, indirect and economy-wide, and add up to total rebound, as commonly defined (Greening et al., 2000; Saunders, 2000; Chitnis et al., 2014; Jenkins et al., 2011) and shown in Figure 1-17:

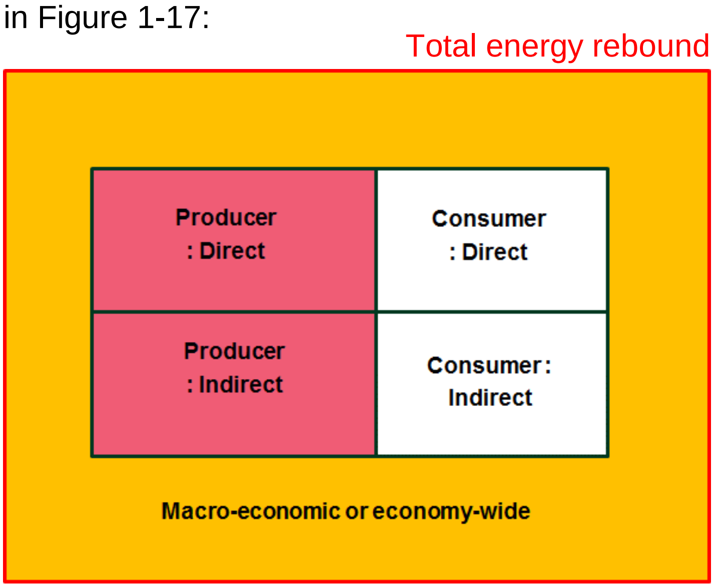

Figure 1-17: Components of total energy rebound, based on Jenkins et al (2011) and Saunders (2015)

To explain these terms, direct rebound is using more of the same energy service, indirect rebound is via monetary respending (of energy savings) on other energy services, and economy-wide (or macro-economic) rebound are remaining longer term structural aspects.

Quantitative efforts to estimate energy rebound have typically focussed on consumer-sided direct and indirect respending analysis, probably due to better availability of data. Studies of this type of rebound for the UK (Druckman et al., 2011; Chitnis et al., 2014) and US (Azevedo et al. 2013; Thomas & Azevedo, 2013a; Thomas & Azevedo, 2013b; Thomas et al., 2014) typically estimate direct and indirect rebound (via input-output analysis) to be in total around 20%. Interestingly, a more recent UK study by Chitnis and Sorrell (2015) takes a novel cross-price elasticity approach, and estimates larger (direct plus indirect) consumer rebound values: 41% for efficiency of domestic gas use, 48% for electricity use and 78% for vehicle fuel use.

Estimating other components of rebound (producer or macroeconomic) or total rebound is tricky, since it requires account be taken (versus the counterfactual) of effects such as long term structural change on the producer side, or the growth-augmenting macroeconomic effect of efficiency on economic growth (and thus energy use). Various approaches have been used. Barker et al (2009) use Keynesian macro-economic analysis to estimate total rebound for the world economy of 35% by 2030. A second approach is to use an aggregate cost/production function approach to estimate total short or long term rebound, following theoretical approach of Saunders (1992; 2000; 2008) and Wei (2010). Zhang and Lin (2013) and Saunders (2015) provide rare empirical examples, but importantly estimate large (over 50%) total rebound. Third, price elasticities are taken as a measure of sector rebound: for example Fouquet and Pearson (2011) and Tsao et al (2010) estimate total rebound of around 70% for lighting (i.e. producers and consumers), whilst Bentzen (2004) estimates final energy rebound of US industrial sectors (i.e. producers) to be 24%.

Overall, the IPCC (IPCC, 2014) consider that whilst there is general agreement on the presence of rebound, there is low agreement on the magnitude of rebound. Sorrell (2009, p.1467) agrees, suggesting “the case for Jevons’ paradox … relies largely upon theoretical arguments, backed up by empirical evidence that is both suggestive and indirect". This is in part because "from a producer/industry perspective, information on the rebound effect is almost non-existent" (Barrett and Scott, 2012, p.306). This means the majority of energy use is unaccounted for in rebound estimates (Saunders, 2015).

With a lack of estimates of total rebound, or even consistent estimates for consumer-sided rebound, the effect on energy policy appears to be that rebound is largely ignored. For example, the 2012 EU Energy Efficiency Directive (European Parliament, 2012) has 205 references of 'energy efficiency', but not a single reference to the term 'rebound'.

1.3.2.2 Alternative UWA-enabled exergy-economic approach

No UWA-based quantitative estimates of total energy rebound exist in the literature. The closest approach is by Warr et al (2010), who refer to specific quantitative results but stop short of estimating energy (useful work) rebound:

"The period of most rapid work 'productivity' decline – as measured by increasing U:GDP [i.e. useful work to Gross Domestic Product ratio] – coincides with the period of most rapid efficiency improvements. Stated alternatively, growth in the demand for work exceeded the rate of output growth. This is a characteristic of a 'rebound effect" (Warr et al., 2010, p.1914).

Therefore a gap exists to explore energy rebound at either end of the energy conversion chain. First, at the energy services level, taking useful work as a proxy for energy services, since it is as close as can be thermodynamically measured (e.g. in Joules) to energy services. This would add to the literature of Fouquet and co-authors (Fouquet & Pearson, 2011; Fouquet, 2014), who estimate price elasticities for energy service rebound. Second, UWA may also help estimates of primary energy rebound, which matters most for climate policy.

1.3.3 Qu 3. How does energy use relate to economic growth?

There are two main methods used for studying this question: this first is to consider energy as a factor of production in economic growth, whilst the second studies the statistical links between energy and economic growth. These are considered below, within mainstream energy economics and alternative exergy-economic approaches.

1.3.3.1 Mainstream energy economic approaches

First aggregate production functions (APFs) are considered. Actually the mainstream (neo-classical) approach to this issue, led by Denison (1979) and other influential economists, is to ignore energy since its low cost-share is GDP - typically below 10% (US EIA, 2011) - translates (they believe) to a negligible impact on economic output. Their view is that labour (L) and capital (K) form the two canonical factors of production for economic output (Y), thus Y = f (K,L). Empirical research using the neo-classical approach is not wholly supportive of this view, given exogenous growth (i.e. the Solow residual – named after Solow (1957)) “amounts to more than 50% of total growth in many cases” (Stresing et al., 2008, p.279). As Solow - the Nobel prize winning pioneer of modern growth theory – stated, “it is a theory of growth that leaves the main factor of growth unexplained” (Solow, 1994).

The 1970s oil-crises era led to a rethink of the exclusion of energy in some quarters. At that time, Binswanger and Ledergerber (1974) wrote “the decisive mistake of traditional economics... is the neglect of energy as factor of production”. In parallel, quantitative studies followed in the 1970s which modelled capital, labour and primary energy in an aggregate function, (Berndt & Wood, 1975; Hudson & Jorgenson, 1974; Rasch & Tatom, 1977), and found that energy did make a meaningful contribution to economic growth: Rasche and Tatom (1977, p.15) found “the output elasticity of the energy resource is 12 percent which is consistent with … the cost share of energy”.

In more recent times, energy has become a prominent estimated factor within production (and cost) functions, since the estimated parameters (e.g. elasticity of substitution) are key variables in energy economic models to study effects of policies on energy and emissions (van der Werf, 2008). Commonly studies use more flexible Constant Elasticity of Substitution (CES) rather than Cobb-Douglas (C-D) functions (Dissou et al., 2012; Kemfert & Welsch, 2000; Shen & Whalley, 2013). This is discussed further in Chapter 4.

A second approach seeks to establish econometric relationships between energy and GDP (Ockwell, 2008; Sharma, 2010; Wolde-Rufael, 2010). Meta studies include Kalimeris et al (2014) and Stern (2011, p.45), who suggests “the theoretical and empirical evidence indicates that energy use and output are tightly coupled”. Figure 1-18 shows how GDP and primary energy use (with its associated carbon emissions) are tightly coupled. This explains the conflict of economic against energy goals: i.e. the desire for continued economic growth versus the desire to reduce energy-related emissions.

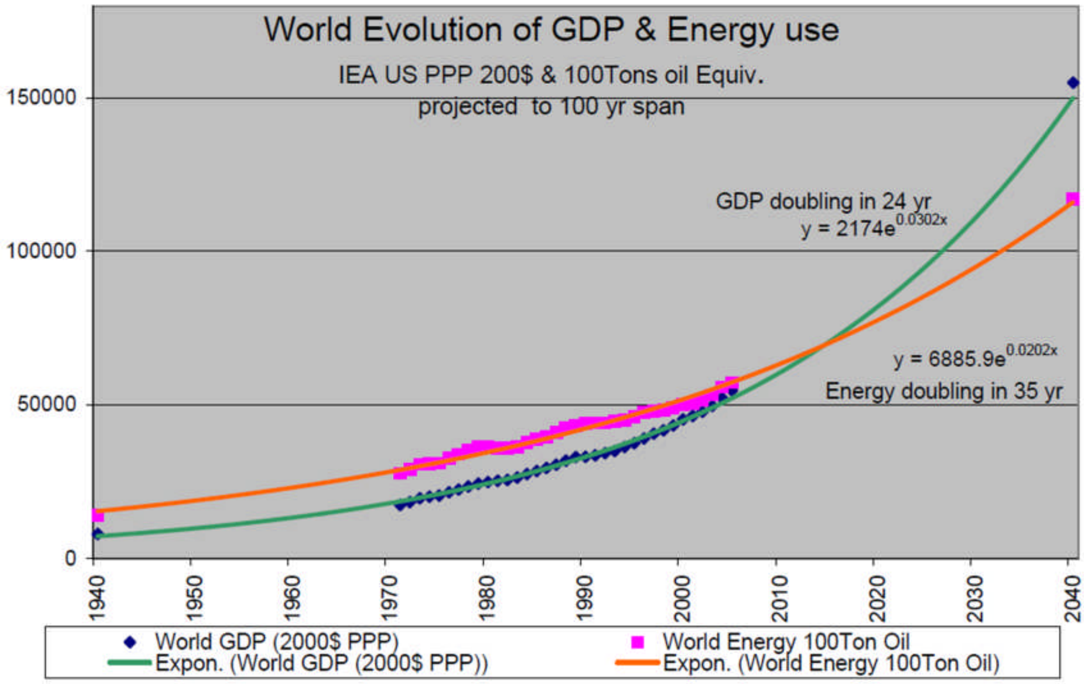

Figure 1-18: World GDP and energy use 1940-2040 (Henshaw, 2008)

However, whilst a clear statistical link exists between (primary) energy and GDP, the direction of causality - i.e. does economic growth drive energy use increases, or vice versa? - remains unresolved (Kalimeris et al., 2014; Bruns et al., 2014).

Some studies remove population effects by studying per capita energy use and economic output, such as Csereklyei and Stern (2015) and Steinberger and co-authors (Steinberger & Roberts, 2010; Steinberger & Krausmann, 2011). The latter is also a good example of the study of sufficiency (via per capita energy use) to derive implications for future national-level energy use, as shown in Figure 1-19:

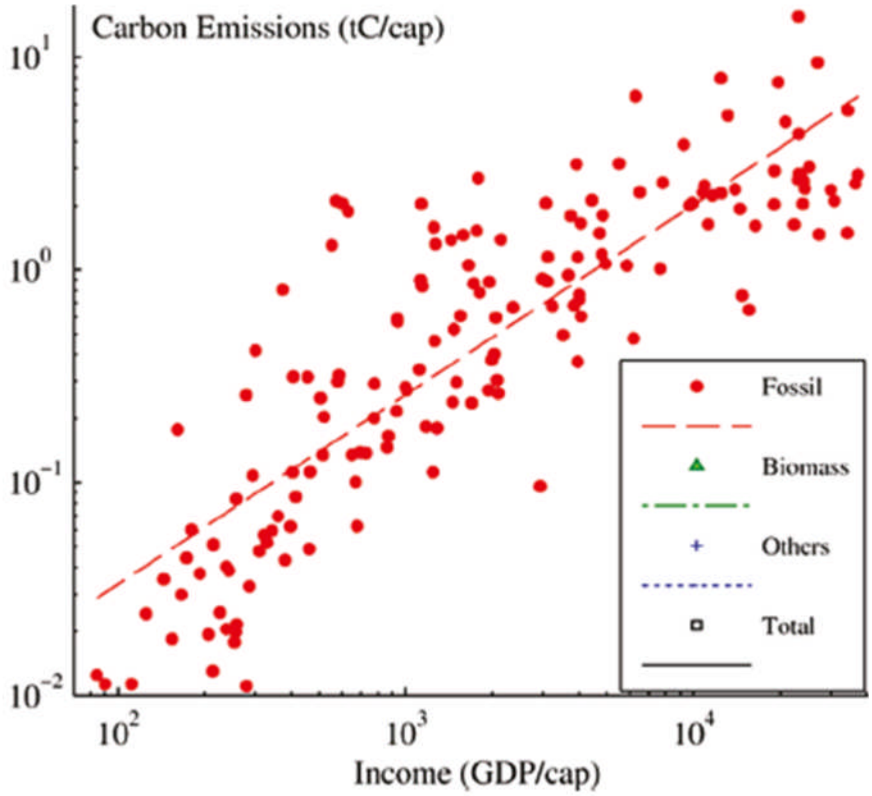

Figure 1-19: Carbon emissions to income (Steinberger & Krausmann, 2011)

1.3.3.2 Alternative UWA-enabled exergy-economic approach

The main application of useful work approaches in the context of energy-GDP studies has been through the use of APF studies. Kümmel (1982) introduced the LINear EXponential (LINEX) energy dependent production function, and suggested primary energy was a key factor of production in the West German economy. Ayres and co-authors (Ayres, 2001; Ayres et al., 2003; Ayres & Warr, 2005) tested both energy augmented Cobb-Douglas and Kümmel's LINEX based APFs, by including useful work as a factor of production in addition to labour and capital. They found that by including useful work (rather than primary energy) as a third production factor "the historical growth path of the US is reproduced with high accuracy from 1900 until the mid-1970s, without any residual except during brief periods of economic dislocation, and with fairly high accuracy since then" (Ayres & Warr, 2005, p.181), as shown in Figure 1-20:

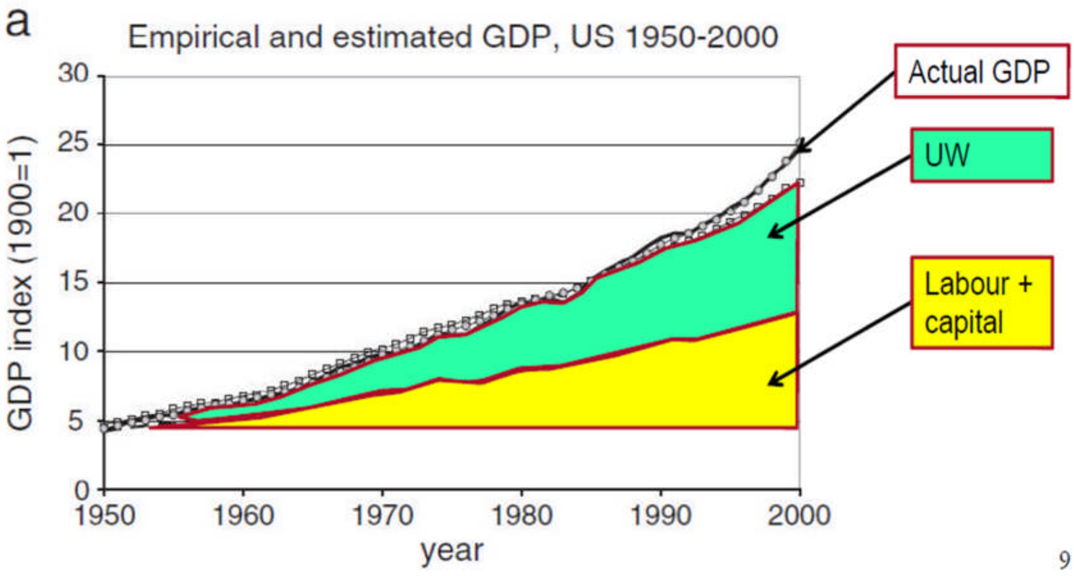

Figure 1-20: Useful work and the Solow residual (adapted from Warr & Ayres, 2012)

Useful work based studies have also used econometric methods, for example Warr and Ayres examined GDP-energy causality in the US for 1946-2000. They found causality ran from both useful work and (primary) exergy to GDP but not the other way, suggesting "output growth does not drive increased energy consumption and to sustain long-term growth it is necessary to either increase energy supplies or increase the efficiency of energy usage" (2010, p.1688). More recently, Ayres and Voudouris use a novel econometric technique to find that "[economic] growth since the industrial revolution has been driven largely by the increased stock of capital and the adequate supply of useful energy [useful work]" (2014, p.27).

1.3.4 Qu. 4 How much energy will we need in the future?

The previous three questions focus on important single factors which are linked to energy demand: energy efficiency, energy rebound and economic growth. Other factors noted earlier which affect energy use include economic structure, energy quality, population, energy prices, and income. Consideration of all relevant energy use drivers and their impacts on energy demand is a key goal of energy analysis, since this provides a broader evidence base to study future energy policies or to project energy demand.

1.3.4.1 Mainstream energy economic approaches

The first approach is a top-down estimation of energy use. At its most simple, it involve the projection or extrapolation of historical energy intensity (E/GDP), which based on an estimate of future GDP will reveal the projected energy demand, E. Decomposition can be applied to refine this method, where the aggregate variable (e.g. energy use) is first split into various components, such as energy intensity, structural changes, GDP or population. This enables forecasts of the aggregate energy variable to be based to projections of the decomposed components. Typical studies use Kaya (1989) or IPAT (Chertow, 2001) identities - where impacts (e.g. of energy use, or carbon emissions) are typically increased by population (P) and affluence (A) but reduced by technology (T). These studies commonly find primary energy intensity (GJ/$) and effects of technology have a decreasing effect, whilst rising population and incomes have upward influence on energy demand. As an example, Figure 1-21 shows how differences in CO_2 emissions between Czechoslovakia and Austria have been affected by income effects, intensity, population and composition changes.

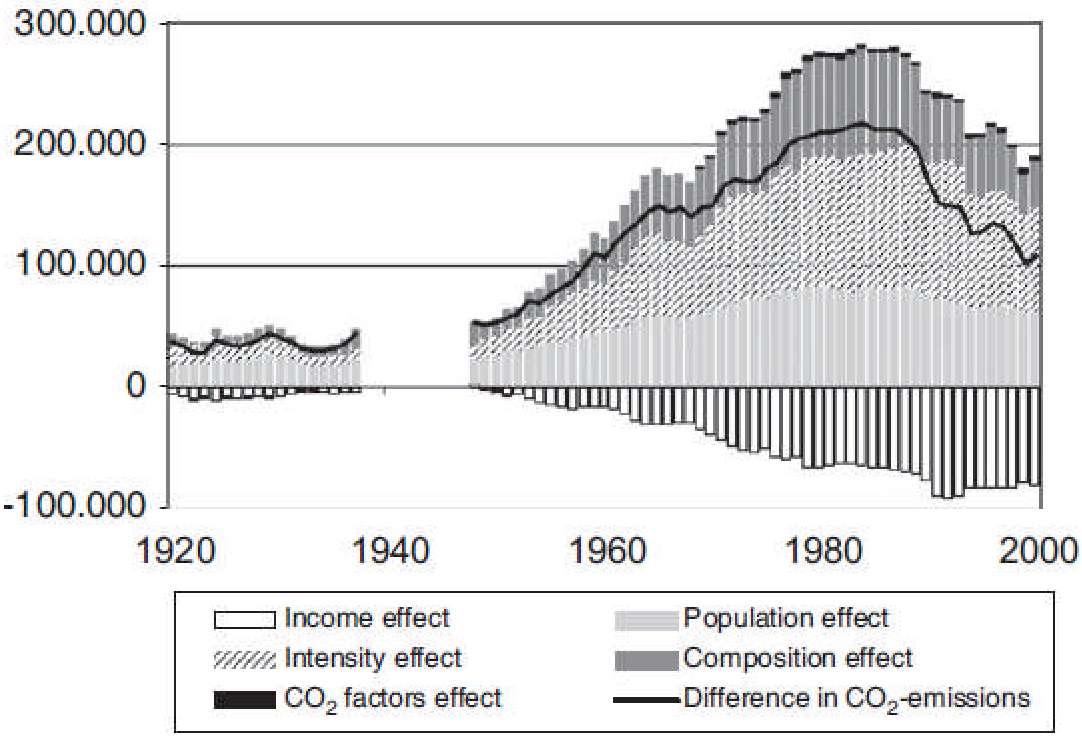

Figure 1-21: Drivers of Czechoslovakia and Austria emissions (Gingrich et al., 2011)

Index decomposition analysis (IDA) can be applied to more detailed (e.g. industry sector) data. Ang and co-authors (Ang & Liu, 2001; Zhou & Ang, 2008; Ang, 2005; Ang, 2015) have led efforts to popularise the method – particularly Log Mean Divisia Index (LMDI) decomposition, such that it is now widely used. Equation 1-6 gives an example for IDA of energy use E:

$$E = \sum_i E_i = \sum_i Q \frac{Q_i}{Q} \frac{E_i}{Q_i} = \sum_i Q S_i I_i. \tag{1-6}$$

Where:

$E =$ total energy consumption in the sector
$E_i =$ energy consumption in sub-sector i
$Q =$ total activity level of the sector
$Q_i =$ activity level of sub-sector i
$S_i =$ activity share of sub-sector i $(= Q_i/Q)$
$I =$ aggregate energy intensity $(= E/Q)$
$I_i =$ energy intensity of sub-sector i $(= E_i/Q_i)$

Decomposition studies include energy intensity (Ma & Stern, 2008; Choi & Ang, 2012; Cahill & Ó Gallachóir, 2012), CO_2 emissions (Agnolucci et al., 2009; Guan et al., 2008; Hammond & Norman, 2012; Wang et al., 2005), or carbon intensity (Wei et al., 2007).

A second approach uses bottom-up quantitative energy-economy models to estimate future energy demand. The IEA's World Energy Outlook (WEO) model is a good example (IEA, 2013c) of such models, built on assumptions made for aspects including population, GDP, historical energy use, future energy prices, energy supply, investment, and sector energy intensity (e.g. GJ/tonne steel output).

1.3.4.2 Alternative UWA-enabled exergy-economic approach

Relatively few studies relating to exergy economics have specifically considered future energy use, instead being focussed more on quantification of energy efficiency in first and second law terms (Section 1.3.1), or useful work's link to economic growth (Section 1.3.3).

That said, Warr et al's (2010) conceptual framing is relevant, since they make a case that exergy efficiency is a dynamic of economic growth, asserting "energy efficiency improvements drive economic growth through a .. rebound effect" (ibid, p.1914). Their proposed growth cycle (Warr & Ayres, 2012) is given in Figure 1-22, which identifies exergy (as a substitute for labour and capital) as a key part of the growth cycle.

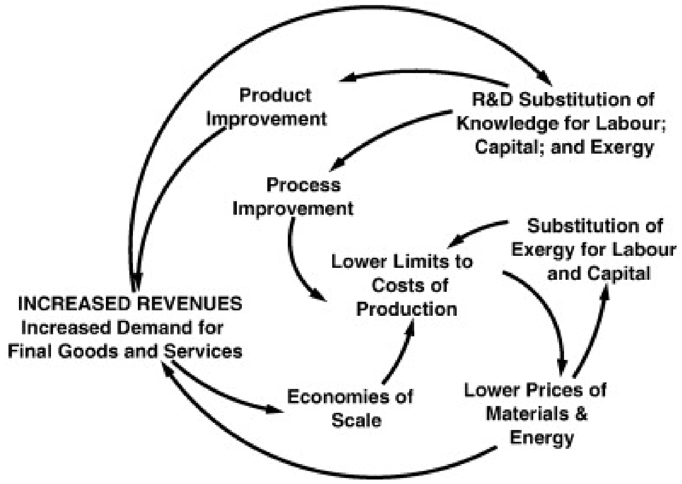

Figure 1-22 The Ayres–Warr endogenous growth mechanism (Warr & Ayres, 2012)

In addition, Warr and Ayres (2006) used a UWA based exergy-economic model to investigate future energy economic growth, and found that reducing exergy efficiency had a restrictive role on economic growth, as shown in Figure 1-23. Since economic growth (in their analysis) is tightly linked to useful work, a knock-on restriction to future useful work follows.

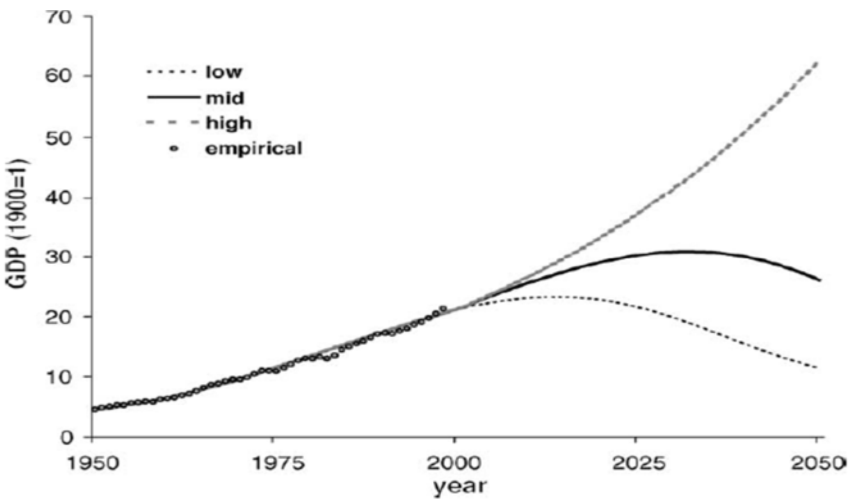

Figure 1-23: US GDP versus different exergy efficiency scenarios (Warr & Ayres, 2006)

Overall, whilst Ayres and Warr's work suggests that useful work and exergy analysis may help provide a clearer understanding of the role of energy in economic growth, their work has not been applied to estimations of future (primary or useful) energy use. This research gap is addressed in Section 1.4.

1.4 Research framing

1.4.1 Insights from the literature review:

1.4.1.1 Unanswered questions from energy economics

The earlier sections suggest traditional mainstream energy analysis has not provided all the answers to the four key energy questions posed in Figure 1-5. In Question 1, I found that aggregate energy efficiency is not commonly estimated on a thermodynamic basis. Thus as the proxy indicators (for thermodynamic efficiency) can be estimated cannot be linked to the study of thermodynamic energy rebound in Question 2. Whilst primary energy as a factor of production and its statistical linkage to GDP appear well studied in Question 3, a useful work based approach could offer an alternative, quality-adjusted energy variable as inputs to these studies.

Improved consideration of the first three question will help with the fourth, complex question of future energy demand. Smil (2008) is particular dismissive of current approaches: that projections of future energy forecasts and pathways are just computerized fairy tales. Solomon and Krishna continue, stating "the energy transition of the 21st century will need to be more rapid. Unfortunately, little is known about how to accelerate energy transitions" (2011, p.7423).

Overall, perhaps Sorrell (2015, p.81) summarises best the current status-quo:

"it can be misleading to equate improved energy efficiency with reduced energy demand. The definition and measurement of these terms deserves more careful attention, The common expectation of energy efficiency improvements leading to proportional reductions in energy demand is misconceived—the linkages between the two are complex and rebound effects are frequently large".

1.4.1.2 UWA-enabled exergy economics as an alternative approach

The alternative exergy-economic approach based on UWA offers a different approach to the four key energy questions. Thermodynamic (first and second law) energy efficiency via UWA may have an important role in unlocking greater understanding of energy use, rebound and economic growth. As Sorrell notes, “far from being a minor contributor to economic growth, improvements in thermodynamic efficiency become the dominant driver” (2009, p.1466). Therefore UWA and economy-wide exergy analysis exists as a potential candidate to broaden this evidence base, and directly inform both economic and energy policy,

However, two other points are important in the context of the PhD. First is that it has made little real-world contribution thus far, and remains in a hinterland even within academia - when compared to energy economics. Second, there are methodological issues and gaps which could be explored in this PhD. For example Warr et al note “Subsequent research will seek to quantitatively assess the importance of [first and second law] energy efficiency improvements as a source of growth and the potential for decoupling of energy use from growth in the future” (2010, p.1915). Other methodological aspects are considered by Sousa et al (2016), such as industrial efficiency, electricity efficiency, cooling and non-energy use. Below is a list of possible aspects to be included in the PhD – whilst also focussing on how the technique can contribute to a better understanding of energy use, rebound and economic growth.

- Robust and comparable measurement of UW and exergy efficiency
- Cross-country comparisons
- Decomposition of energy use
- Use in energy forecast scenarios
- Consideration of energy rebound
- Links to economic growth

1.4.2 Research question, aims and objectives

The insights frame the proposed research gap set out in Figure 1-24:

Economy-wide energy reduction (via energy efficiency) forms a key part of carbon emissions reduction policies. However, mainstream energy analysis has not provided a sufficient evidence base for effective energy efficiency policies, since it cannot quantify the magnitudes of county-level energy efficiency and rebound, and hence study their impacts on energy use and economic growth. An alternative approach – useful work accounting and exergy economics - is an under-used technique that exists as a potential candidate to gain valuable insights and widen this evidence base.

Figure 1-24: Proposed research gap

Figure 1-25 gives a summary graphic of UWA's potential contribution to energy economic fields:

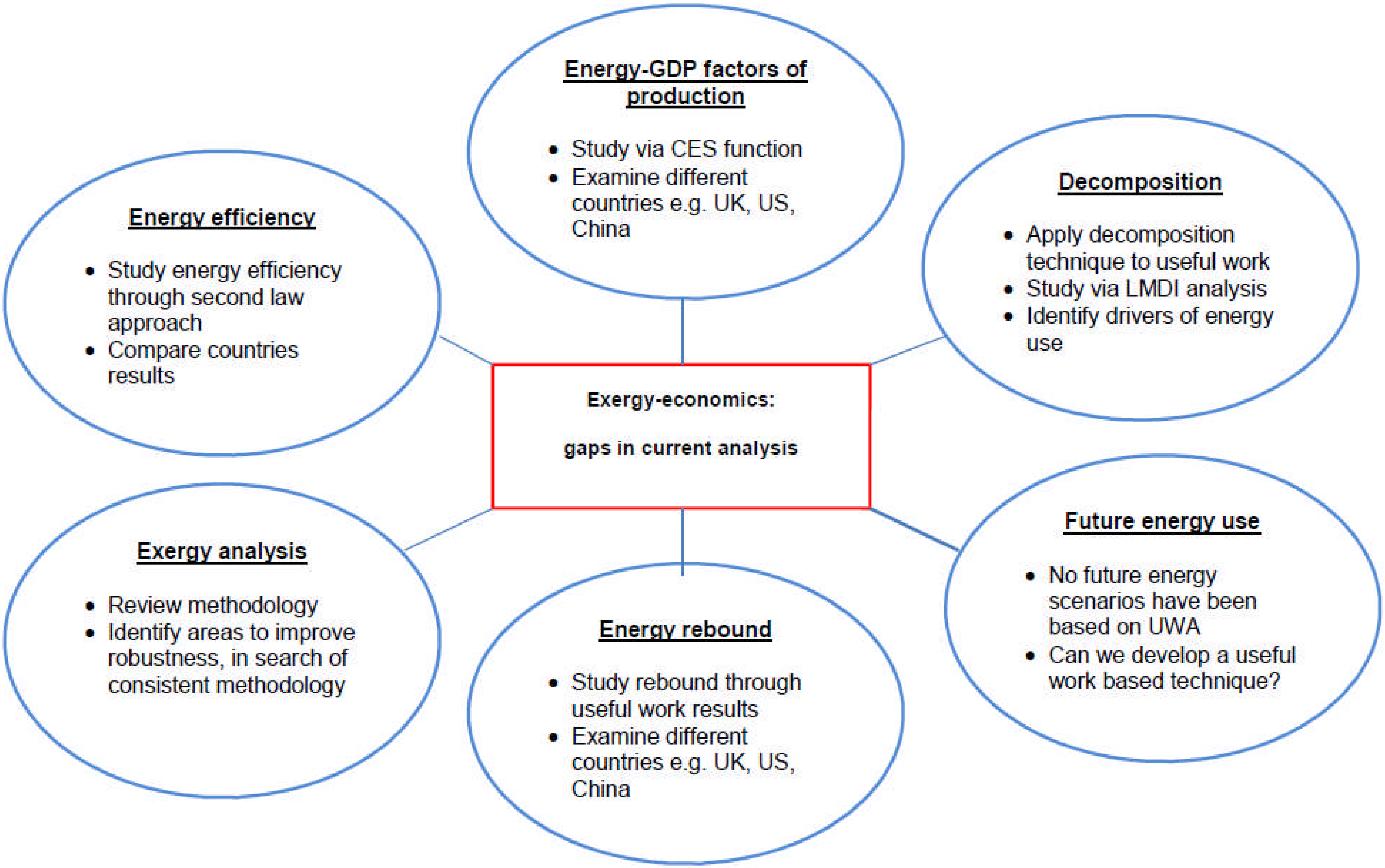

Figure 1-25: Exergy related topics and linkages

This leads us to the following the research question:

Research Question
How can useful work and exergy analysis inform understanding of energy use, rebound and economic growth?

Based on this question, I set out the following aims (of the overall research project, i.e. to address the research question) and objectives (i.e. how I intend to achieve the aims and answer the research question):

Research Aim
To develop and test useful work based techniques for understanding national-scale energy use, rebound and economic growth.

The Research Objectives are listed below:

- **Objective A:** Use useful work analysis to understand historical energy use and energy efficiency in three countries (UK, US and China)
- **Objective B:** Develop and test a useful work accounting approach for future energy projections
- **Objective C:** Undertake a quantitative study of long term total energy rebound using useful work and exergy analysis data for UK, US and China.
- **Objective D:** Synthesise the contribution that useful work and exergy analysis can make to the study of energy use, rebound and economic growth. This includes consideration of improvements to the UWA methodology.

1.5 Research design

Due to the broad nature of the overall research question and associated objectives, a multi-method research strategy was developed in response, as shown in Table 1-3:

Table 1-3: Research Strategy

	Objective	Output	Study Focus	Methods	Link to energy questions
Research Aim: To develop and test useful work based techniques for understanding national-scale energy use, rebound and economic growth.	A – Use UWA to better understand historical energy use and energy efficiency	Chapter 2	UK-US national level exergy analysis 1960-2010	Quantitative: National scale exergy analysis	Qu.1 Energy efficiency Qu.4 Overall energy drivers
		Chapter 3	UK-US-China UW analysis 1971-2010	Quantitative: National scale exergy analysis & LMDI decomposition	Qu.1 Energy efficiency
	B – Use UWA to study future energy use scenarios	Chapter 3	China national level exergy analysis 2010-2030	Quantitative: UWA	Qu.1 Energy efficiency Qu.3 Energy-GDP Qu.4 Future energy demand
	C – Use UWA to estimate total energy rebound	Chapter 4	Review of aggregate production function theory and flexible rebound applications	Qualitative: Review of literature	Qu.3 Energy-GDP
		Chapter 5	Energy rebound analysis of China, UK, US	Quantitative: APFs and rebound analysis	Qu.2 Energy rebound Qu.4 Future energy demand
	D – overall assessment of UWA-based exergy economics technique	Chapter 6	Synthesise the results and provide overall UWA / exergy economics conclusions	Qualitative review of Chapters 2-5	Qu.1 Energy efficiency Qu.2 Energy rebound Qu.3 Energy-GDP Qu.4 Future energy demand

In overall terms, the basic principles of the analyses for this thesis were empirically based, national-scale exergy-economic analyses of UK, US and China for the time-series 1960-2010 (UK-US) and 1971-2010 (China). From these analyses, insights into energy use, rebound and economic growth were drawn.

Four academic journal papers were written for this thesis, and are presented sequentially in Chapters 2-5. Chapter 2 estimates the 1960-2010 national-level UK-US exergy efficiencies, comparing trends. Chapter 3 estimates China's 1971-2010 aggregate efficiency, compares the results to those for the US and UK, and also estimates China's primary energy demand for 2010-2030 using a UWA-based approach. Chapters 2 and 3 required the use and adaptation of techniques for UWA analysis and LMDI decomposition. To estimate overall energy rebound, two methods based on the solution of CES-based aggregate production functions (APFs) were required. The presentation of the issues involved with econometric specification and solution of these functions are given in Chapter 4, and thereby underpin the empirical rebound estimation for the UK, US and China for 1980-2010 in Chapter 5.

A summary of the research methods and data is given in Section 1.5.1, stated collaboration is given in Section 1.5.2, and finally the thesis structure is reported in Section 1.5.3. More detailed descriptions of the methods and input datasets are found in the subsequent chapters.

1.5.1 Methods and data

1.5.1.1 National-scale 'energy carriers for energy use' exergy analysis

I adopt the "energy carriers for energy use" (Ertesvag, 2001, p.254) method, because I am seeking insights into energy-related aspects of energy use, rebound and economic growth.

Input energy sources are calculated in equivalent primary exergy terms, and then mapped to categories of end use: e.g. mechanical work, heat, electrical end uses, muscle work. These categories may also mapped to sectors of the economy, i.e. energy production, industry, residential, transport. The calculation process is shown in Figure 1-26:

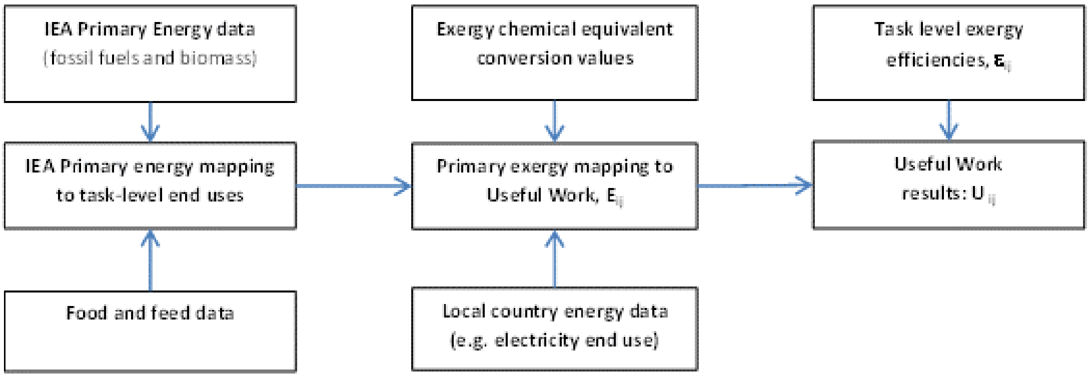

Figure 1-26: Overall calculation flowchart (Brockway et al., 2015)

Various groups of input data are required. First, primary exergy data is obtained. The main dataset is from the IEA (2013b), which provided time-series data on fossil fuels, renewables and nuclear energy sources, as well as mapping to end use sectors. Biomass food and feed inputs (for muscle work) required separate calculation, based on estimates of the numbers of draught animals and manual labour force, and their required food intake, using various published sources (Ramaswamy, 1994; O'Neill & Kemp, 1989; Wirsenius, 2000; FAOSTAT, 2013)

Mapping of energy inputs to end use sectors is based on the IEA structure, with additional granularity based on the work of Serrenho (2014) who made great advances to greatly standardise front end mapping. Mapping for the UK-US paper (Chapter 2) is given in Appendix A. The main end use sectors are:

- **Heat (combustion)**: Low, medium, high temperature heat
- **Mechanical drive**: motion (road, rail, air, water), industry static engines
- **Electrical end uses**: motors, appliances, lighting, heating, cooling
- **Muscle work**: human and animal mechanical work

Next, primary exergy inputs are combined with time-series exergy efficiency estimations, to produce useful work estimates. The basic groupings of second law efficiency types is given in Table 1-4. For processes involving heating or cooling, a Carnot temperature ratio provides a limitation on the amount of physical work that can be extracted: taking low temperature heat as an example: "the work performed to heat a room is defined as that required by an ideal Carnot engine to move heat from outside (e.g. 0 °C) to the inside (e.g. 20 °C)". (Williams et al., 2008b, p.4). In this case the basic equation for work in a Carnot cycle is given by equation (1-7:

$$Work\ (LTH) = \ Q_{in}\left(1 - \frac{T_{273}}{T_{293}}\right) \qquad \textbf{(1-7)}$$

Table 1-4: Second law efficiencies of some end use devices (Carnahan et al., 1975)

End Use \ Source		Work W_{in}	Fuel Heat of combustion $\lvert\Delta H\rvert$	Exergy B Heat Q_1 from hot resevoir at T_1
		$W_{max} = W_{in}$	$W_{max} = B$	$W_{max} = Q_1\left(1 - \frac{T_0}{T_1}\right)$
Work W_{out}	$W_{min} = W_{out}$	$\epsilon = \eta = \frac{W_{out}}{W_{in}}$ (6)	$\epsilon = \frac{W_{out}}{B} \approx \eta$ (7)	$\epsilon = \frac{W_{out}}{Q_1\left(1 - \frac{T_0}{T_1}\right)} = \frac{\eta}{1 - \frac{T_0}{T_1}}$ (8)
Heat Q_2 added to warm reservoir at T_2	$W_{min} = Q_2\left(1 - \frac{T_0}{T_2}\right)$	$\epsilon = \frac{Q_2}{W_{in}}\left(1 - \frac{T_0}{T_2}\right) = \eta\left(1 - \frac{T_0}{T_2}\right)$ (9)	$\epsilon = \frac{Q_2}{B}\left(1 - \frac{T_0}{T_2}\right) \approx \eta\left(1 - \frac{T_0}{T_2}\right)$ (10)	$\epsilon = \frac{Q_2\left(1 - \frac{T_0}{T_2}\right)}{Q_1\left(1 - \frac{T_0}{T_1}\right)} = \eta\frac{1 - \frac{T_0}{T_2}}{1 - \frac{T_0}{T_1}}$ (11)
Heat Q_3 extracted from cool reservoir at T_3	$W_{min} = Q_3\left(\frac{T_0}{T_3} - 1\right)$	$\epsilon = \frac{Q_3}{W_{in}}\left(\frac{T_0}{T_3} - 1\right) = \eta\left(\frac{T_0}{T_3} - 1\right)$ (12)	$\epsilon = \frac{Q_3}{B}\left(\frac{T_0}{T_3} - 1\right) \approx \eta\left(\frac{T_0}{T_3} - 1\right)$ (13)	$\epsilon = \frac{Q_3\left(\frac{T_0}{T_3} - 1\right)}{Q_1\left(1 - \frac{T_0}{T_1}\right)} = \eta\frac{\frac{T_0}{T_3} - 1}{1 - \frac{T_0}{T_1}}$ (14)

A summary graphic of the Excel based model is given in Figure 1-27 – where each green box is a separate sheet in Excel:

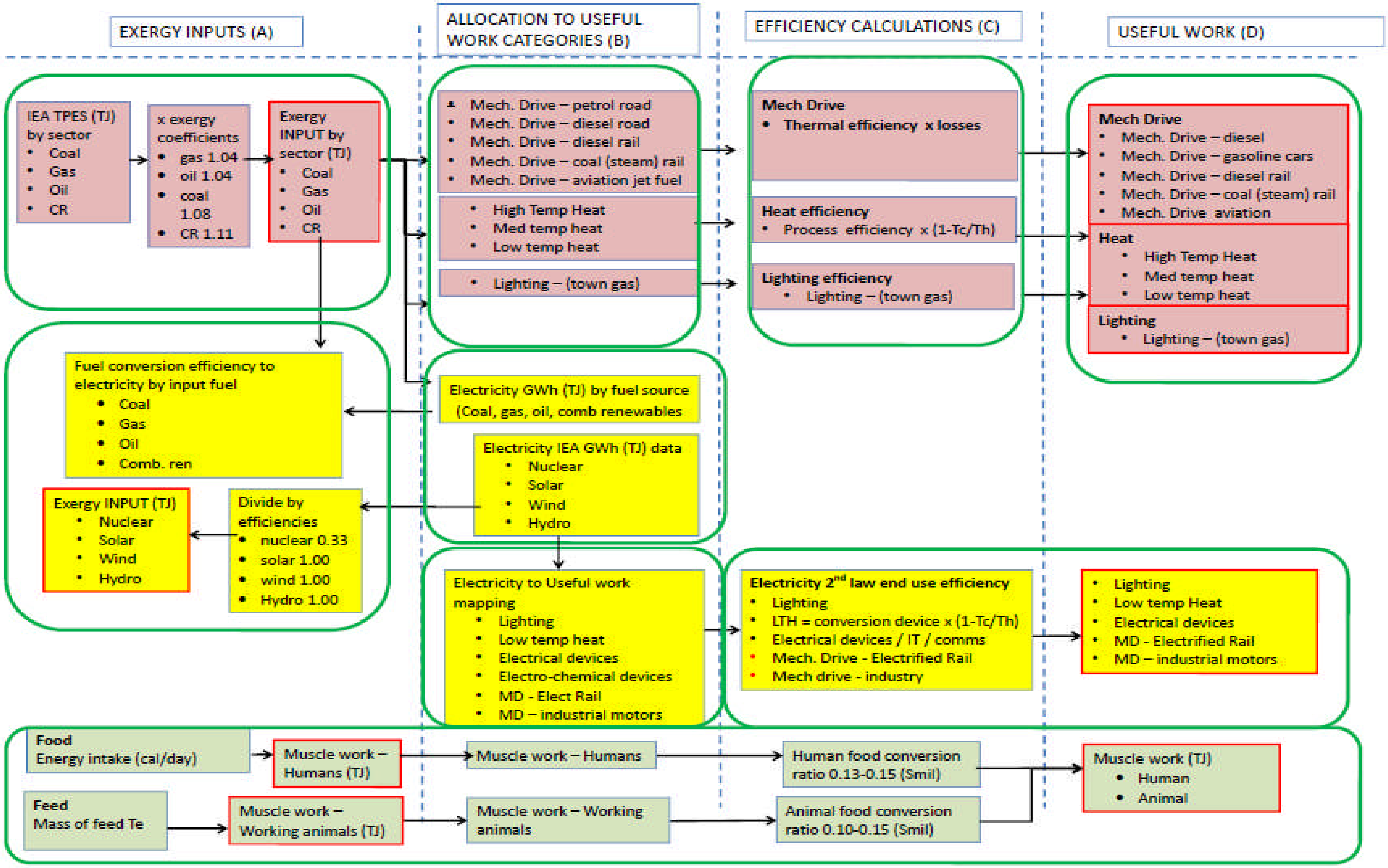

Figure 1-27: Excel model structure

Input datasets for the estimation of task-level efficiencies were obtained from a range of sources including transport (vehicle fuel economy data (DECC, 2013) and powertrain data (Thomas, 2014)); industry (Worrell et al., 2000; Energetics Inc., 2004); and residential (Letschert et al., 2010) sectors. More detail is given in Paper 1 (UK-US) and Paper 2 (China).

The main novel contributions that I made to the current state-of-the-art UWA method (let us call it the Ayres-Warr-Serrenho method) was first for the UK-US paper (Chapter 2) to increase granularity of electricity end uses, correct a previous cooling efficiency error and develop a new method for transport exergy efficiency. Second, for the China paper (Chapter 3), this was a new application - a time-series ‘energy carriers for energy use’ analysis had not previously been completed – which necessitated novel analytical features: splitting residential energy use between rural and urban populations, and including draught animal work.

The outputs from the modelling are presented in Sankey type outputs, as shown in Figure 1-28. They are similar in appearance to the previous outputs of Reistad (1975) and Ayres et al (2011).

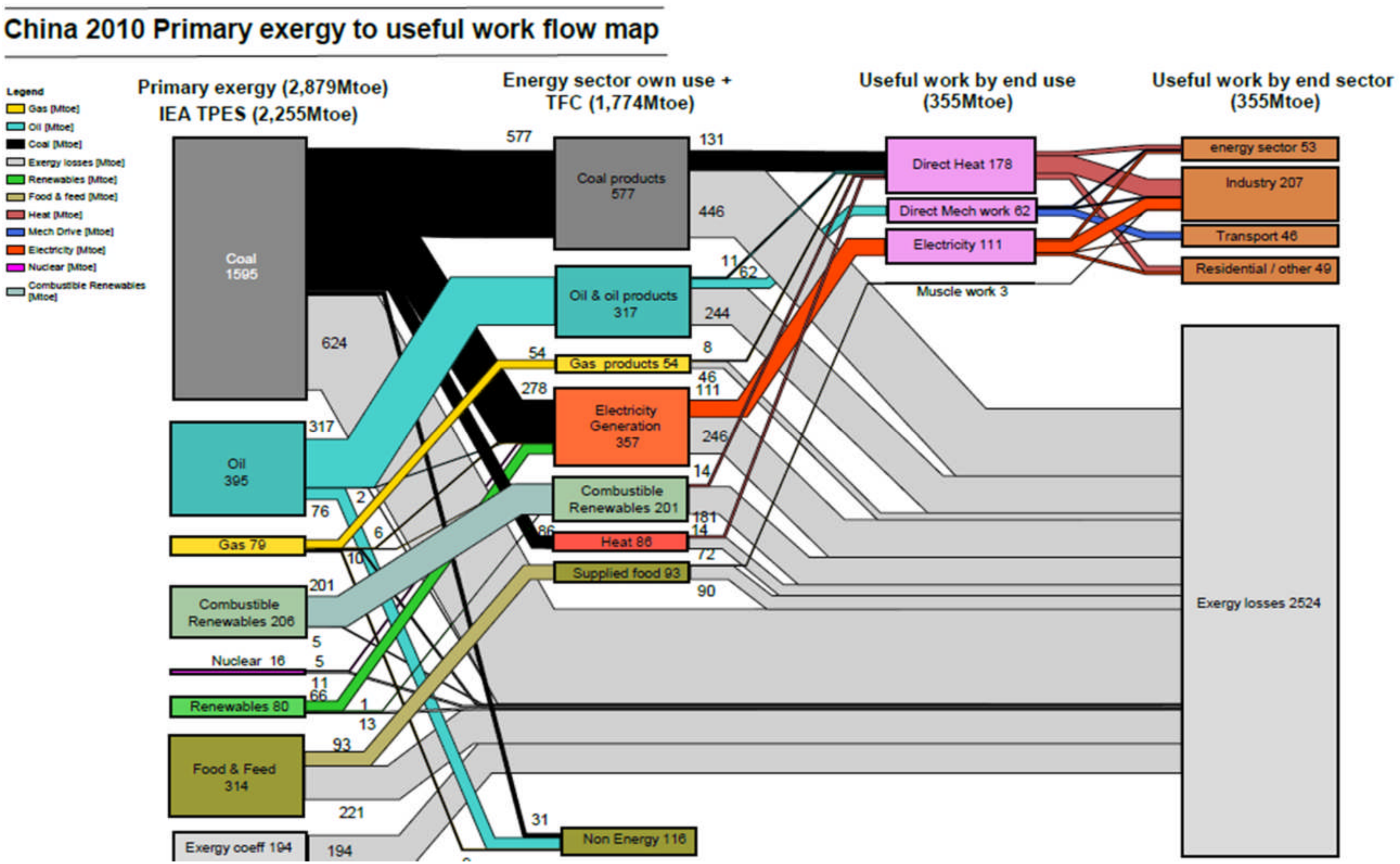

Figure 1-28: Sankey type diagram (Brockway et al, 2015)

1.5.1.2 Exergy analysis based primary energy forecasting

I developed a new useful work based method to estimate China's future energy demand. It is based on projecting task-level useful work and exergy efficiencies to 2030, then collating and providing an outturn estimate of primary energy demand as given in equation 1-8:

$$\Sigma \boldsymbol{E_i} = \Sigma \left(\frac{\boldsymbol{U_i}}{\varepsilon_i} \right) \quad \textbf{(1-8)}$$

The process of calculation is summarised in Figure 1-29, and described fully in Paper 2 (Chapter 3). The main novelty is that the analysis is essentially completed at the end of the energy chain that is closest to energy services, since I assume that useful work – and not primary energy – is the key energy input to the economy. After completing the projections of useful work and exergy efficiency to 2030, then the results and can translated back into estimates of primary energy demand.

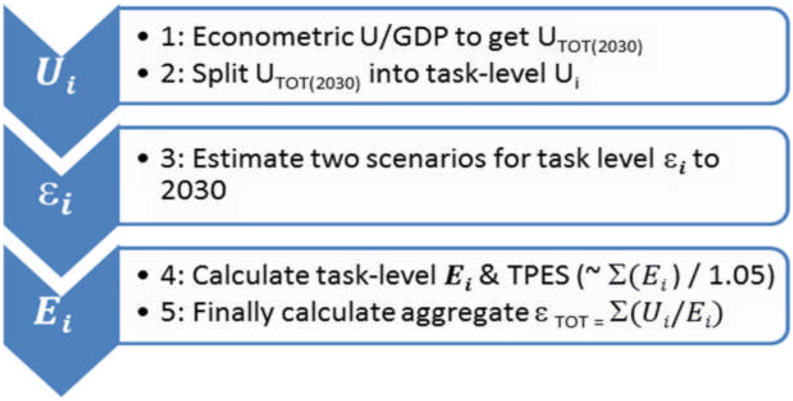

Figure 1-29: Calculation process for primary energy forecasts

1.5.1.3 LMDI decomposition

Using the results of the historical UWA studies for UK-US (Paper 2) and China (Paper 3), LMDI decomposition is applied to study the drivers of useful work changes in Paper 3 (Chapter 4).

First, by expanding U = $\Sigma E_{ij}\ \varepsilon_{ij}$ this yields equation 1-9, which is based on task-level useful work (U_{ij}) and primary exergy (E_{ij}), enabling the historical results to act as the input data for the LMDI analysis. Equation 1-10 give the four drivers of useful work changes: Input Exergy (D_{eX}); Main class structure (D_{Str}); sub-class (i.e. task) level structural change (D_{diL}); and task-level efficiency (D_{efF}). Thus LMDI decomposition breaks down overall exergy efficiency changes (from the main analyses) into three parts: D_{Str}, D_{diL}, and D_{efF}.

$$U = \sum_{ij} U_{ij} = \sum_{ij} E \frac{E_i}{E} \frac{E_{ij}}{E_i} \frac{U_{ij}}{E_{ij}} \qquad \textbf{(1-9)}$$

$$D_{tot} = \frac{U^t}{U^0} = D_{eX} D_{Str} D_{diL} D_{efF} \qquad \textbf{(1-10)}$$

1.5.1.4 APFs: theory and analysis

APFs were used as the basis for Paper 3 (Chapter 4) and Paper 4 (Chapter 5). Energy (useful work) is included as a third factor of production, and CES production function was chosen is shown in equation 1-11. This particular APF was selected – i.e. a CES which is nested in a KL(E) format - as this is the only APF which allows a full range of rebound solutions (Saunders, 2008). Two solved parameters of the APF (λ and ρ) were used as inputs to the empirical rebound study (Chapter 5).

$$Y = \theta\, A[\delta_1[(\delta\, K^{-\rho_1} + (1-\delta)L^{-\rho_1}]^{\rho/\rho_1} + (1-\delta_1)E^{-\rho}]^{-\frac{\nu}{\rho}}\,;\;\; A \equiv e^{\lambda t} \qquad \textbf{(1-11)}$$

where:

Y	= (economic) Output
K	= Capital
L	= Labour
E	= Energy
λ	= Solow Residual (gain in total factor productivity)
ρ	= a substitution parameter
δ	= share parameter
ν	= variable returns to scale parameter

For input data, quality-adjusted values of capital, labour and energy were used. By quality adjusted, I mean basic, unadjusted data which is then enhanced by including for the productive effect of the input. This changes capital stock to capital services, human labour to human capital, and primary energy to useful work. For quality adjusted labour, Penn World Tables (Feenstra et al., 2015) data was obtained for work hours data, multiplied by human capital data from Barro and Lee (2014). For capital services, I used available data for the study period for the UK (Wallis & Oulton, 2014), and for the US by splicing 1987-2010 data (US Bureau of Labour Statistics, 2015) and 1980-2001 data (Schreyer et al., 2003). For China, I used data I obtained directly from Harry Wu (Wu, 2015). For GDP data, I used constant price data ($2005US) from PWT (Feenstra et al., 2015). For useful work, the timeseries data for UK-US-China obtained from earlier studies (paper 1 and 2) was used.

The CES solution was solved via non-linear analysis using the programme R, using Henningsen and Henningsen (2011). The solution parameter ρ was inserted into the long term APF rebound equation, given in equation 1-12. This was a more general version of the long term CES equation derived earlier by Saunders (2008).

$$Re = \frac{(1 + s_F + s_K)(1 + \rho) + (\rho(s_F - s_K - 1) + s_F)}{(1 + s_F + s_K)(1 + \rho)} \tag{1-12}$$

Where

S_F = cost share of fuel

S_K = cost share of capital

ρ = elasticity parameter obtained from the CES equation 1-11

A second, alternative rebound equation was derived using an Actual Energy Savings versus Potential Energy Savings approach (AES-PES), as shown in equation (1-13):

$$Re_t = \frac{\lambda(Y_{t+1} - Y_t)(EI_{t+1})}{Y_{t+1}(EI_t - EI_{t-1})} \tag{1-13}$$

where

λ is the estimated rate of technical progress (i.e. the Solow residual)

Y is GDP output ($)

EI is energy intensity (E/Y) (TJ/$).

1.5.2 Collaboration

During the PhD, I helped to set up and now work in a collaborative network of researchers aimed at the economy-wide study of exergy economics. In 2014, an exergy economics workshop was held in Leeds[12], as shown in Figure 1-30:

Figure 1-30: International Exergy Economics Workshop, Leeds, 2014

The network met again in 2015, and, as part of ongoing research outputs, a set of four special session papers were presented at the European Society of Ecological Economics (ESEE) 2015[13]. These papers are now being submitted to Journals, and I am a co-author on three of these papers (Sousa et al., 2016; Correa et al., 2015; Santos et al., 2016), as given below:

- Sousa, T., Brockway, P.E., Cullen, J.M., Henriques, S.T., Miller, J., Serrenho, A.C. & Domingos, T., 2016. Improving the Robustness of Societal Exergy Accounting. *Energy (submitted)*.
- Correa, L.I.B., Brockway, P.E., Carter, C., Foxon, T.J., Owen, A., Steinberger, J.K. & Taylor, P., 2015. Measuring EROI (energy return on investment) on a national level: two proposed approaches. *Energy Policy (submitted)*.

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[12] http://sure-infrastructure.leeds.ac.uk/exec/ Exergy-Economics Workshop, May 19-20 2014, Leeds

[13] Special session 7.26: New tools for understanding rapid transitions: insights from Exergy and Useful Work Analysis for Global Energy Use, Low Carbon Transitions and Economic Growth

- Santos, J., Heun, M.K., Brockway, P.E., Pruim, R. & Domingos, T., 2016. Econometric estimation of CES aggregate production functions: Cautionary tales from an ecological economics approach. *Ecological Economics (in preparation)*.

The network has an exergy economics website[14], and plans are underway for the 3rd International Exergy Economics Workshop (IEEW 2016) in July 2016, in Sussex, UK.

The network, workshops and subsequent papers are relevant to this PhD, since it supported my hypothesised research gap and Research Objectives. Within this PhD, I need to be clear on the undertaking of tasks contained within this thesis. Firstly I can confirm that I am lead author for the four papers (Chapter 2 to 5). Secondly, collaborative work (from mainly members of the network) has been a key feature of the CES paper (Chapter 4) and rebound paper (Chapter 5).

To be specific, the background learning for the rebound paper (Chapter 4) and the quantitative ESEE paper (Santos et al., 2016) completed with Joao Santos and Matt Heun was completed in parallel. This learning formed the framing and content of the CES landscape paper (Chapter 4), which I wrote as lead author, but was supported by various iterative reviews by the co-authors and Steve Sorrell. For quantitative analysis in the rebound paper 4 (Chapter 5), various aspects were completed by collaboration. First, the extended rebound equation was derived by Harry Saunders, and later amended by myself. Second, after I specified and supplied the input data for the rebound analysis' CES functions, the CES analysis was completed by Matt Heun at Calvin College, US, who then returned output results. I then used the parameter values ρ and λ in the rebound equations to estimate the long term rebound for the UK, US and China.

In addition, various people sent me valuable datasets for my empirical analyses. These were Roger Fouquet, John F. Thomas and Phil Hunt (Paper 1), and Harry Wu and Joao Santos (Paper 4).

1.5.3 Structure of thesis

The thesis structure follows the research strategy summarised in Table 1-3. Each of Chapters 2 to 5 are presented in journal paper format, and consider

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[14] Exergy Economics research website at https://exergyeconomics.wordpress.com/

sequentially US-UK exergy efficiencies; Chinese energy use and efficiency; CES based production functions, and energy rebound. Synthesis and Conclusions are presented in Chapter 6.

1.6 References

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Chapter 2
Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010

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2.1 Abstract

National exergy efficiency analysis relates the quality of primary energy inputs to an economy with end useful work in sectoral energy uses such as transport, heat and electrical devices. This approach has been used by a range of authors to explore insights to macro-scale energy systems and linkages with economic growth. However, these analyses use a variety of calculation methods with sometimes coarse assumptions, inhibiting comparisons. Therefore, building on previous studies, this paper firstly contributes towards a common useful work accounting framework, by developing more refined methodological techniques for electricity end use and transport exergy efficiencies. Secondly, to test this more consistent and granular approach, these advances are applied to the US and UK for 1960 to 2010. The results reveal divergent aggregate exergy efficiencies: US efficiency remains stable at around 11%, whilst UK efficiency rises from 9% to 15%. The US efficiency stagnation is due to 'efficiency dilution' where structural shifts to lower efficiency consumption (e.g. air-conditioning) outweigh device-level efficiency gains. The results demonstrate this is an important area of research, with consequent implications for national energy efficiency policies.

2.2 Introduction

Energy efficiency has been an important global issue since the 1970s, when energy security issues stemming from the 1973 oil crisis triggered the formation of the International Energy Agency (IEA) in 1974, prompting seminal research into national energy efficiency (e.g. (Carnahan et al., 1975a; Reistad, 1975)). We distinguish between energy efficiency - which relates energy inputs and outputs, and energy intensity - which relates energy use to economic outputs (e.g. primary energy / GDP, see (Goldemberg & Prado, 2011)).

National energy efficiency analysis plays a key role in advancing research into energy issues, including energy projections. It does this by studying firstly technology use at device levels and secondly energy consumption at economic sector (e.g. residential/commercial, industry and transport) and aggregate levels. Exergy and useful work analysis is distinct from traditional 'first law' energy analysis by accounting for the quality of energy, thus incorporating the degradation of useful energy according to the second law of thermodynamics. This also enables the linking of macro and micro-scale efficiency analysis to give a complete energy picture of an economy, enabling additional insight into energy use and drivers of change. These aspects are important for understanding the role of exergy inputs and conversion efficiency improvements as drivers of economic growth (Kümmel et al., 1985; Warr & Ayres, 2010).

Exergy, a term introduced in 1956 by Rant (1956), is simply defined as "available energy" (Reistad, 1975, p.429). 'Availability' is a key thermodynamic concept: the second law of thermodynamics means not all input energy is transformed into work, and thus exergy is lost during energy conversion processes. A heat engine provides a classic second law example, as the maximum thermodynamic efficiency is the Carnot temperature ratio ($1-T_2/T_1$). The main classes of 'work' in national exergy analyses are heat, mechanical drive (e.g. transport), muscle work and electricity uses. We use the 'task-level' terminology introduced by Carnahan et al (1975a) to refer to work in sub-class applications (e.g. room heating), rather than use 'sub-sector' to avoid confusion with economic terminology. It also allows us to adopt their 'useful work' definition as "the minimum available work [exergy input] to achieve that task work transfer" (Carnahan et al., 1975a). Task-level exergy efficiency is therefore given by equation 2-1:

$$\varepsilon_{task} = \frac{Useful\ work}{Primary\ Exergy} \quad \textbf{(2-1)}$$

$$= \frac{The\ minimum\ exergy\ input\ to\ achieve\ that\ task\ work\ transfer\ (Bmin)}{Maximum\ amount\ of\ reversible\ work\ done\ as\ system\ reaches\ equlibrium\ (Wmax)}$$

Figure 2-1 helps visualise the difference between first law energy efficiency, η, and broader (first and second law) exergy efficiency, ε. In the example, a gas boiler heats an internal room to 20ºC, with an outdoor temperature of 5ºC. Due to the Carnot temperature ratio penalty, the second law efficiency, $\varepsilon = \eta(1-T_{outside}/T_{room}) = 4.1\%$, significantly lower than the 80% first law boiler efficiency.

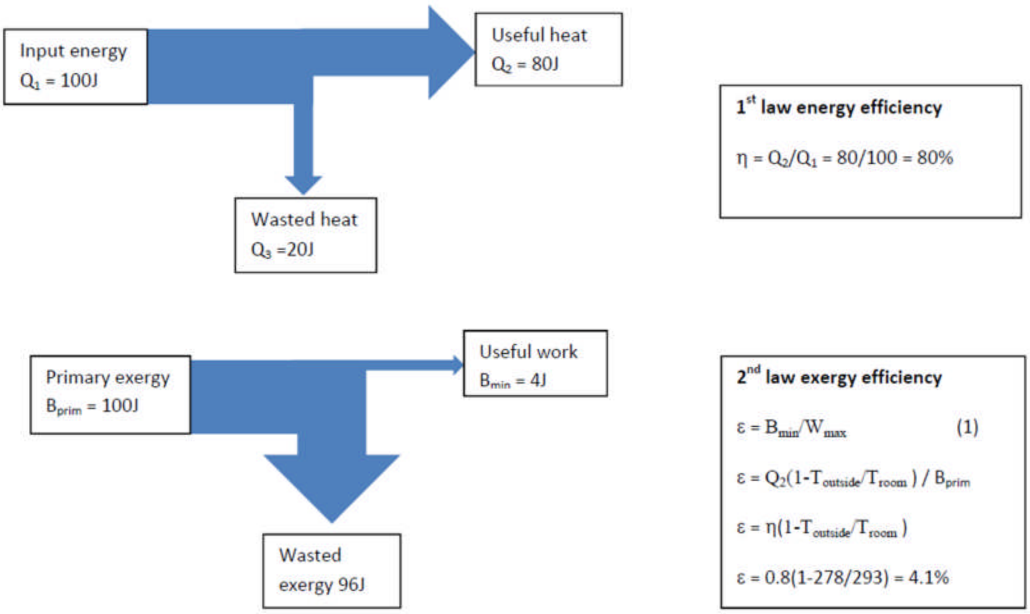

Figure 2-1: Energy versus exergy efficiency for typical domestic boiler heating system

Exergy therefore flows through a national economy, starting with primary exergy, reducing to a smaller exergy value at its transformed end use stage (e.g. heat), which is considered as 'useful work' to the economy. At this point, it is consumed to help produce a final 'energy service' (e.g. passenger-km or thermal comfort). In the last stage, any remaining exergy dissipates to zero by reaching thermodynamic balance with its surroundings. As useful work is the last stage measurable in energy units (joules) within a consistent exergy analysis framework, we focus on primary exergy and useful work, and not energy services. The resulting exergy efficiencies (ratios between 0 and 1) measure energy quality in terms of the efficiency with which the exergy content of primary energy sources is converted to useful work. This paper measures aggregate exergy efficiency at a national level, which is simply the sum of all task-level useful work divided by total input exergy as shown in equation 2-2:

$$\varepsilon_{tot} = \frac{\Sigma\, Useful\, work}{\Sigma Primary\ Exergy} \tag{2-2}$$

Significant effort has been expended on national exergy analysis since Reistad's 1970 US analysis (Reistad, 1975), with single year analyses published at country (e.g. (Wall, 1987; Wall, 1990; Hammond & Stapleton, 2001; Ertesvag, 2001)) and global levels (Nakicenovic et al., 1996; Cullen & Allwood, 2010). Time-series national exergy analyses are rarer due to data availability, but have most notably been undertaken by Ayres, Warr and colleagues who estimated 1900-2000 aggregate efficiencies for the US, UK, Japan and Austria (Ayres et al., 2003; Williams et al., 2008; Warr et al., 2010). Most recently, Serrenho et al (Serrenho et al., 2016; Serrenho et al., 2014) published analysis covering Portugal 1859-2009 and EU-15 countries 1960-2010.

Despite exergy analysis's advantage that it "quantifies the locations, types and magnitudes of [energy] wastes and losses" (Rosen et al., 2008, p.130) it remains the poor relation of energy analysis, with a key issue being the need for methodological consistency to improve comparability of results. This paper seeks to address this issue. Firstly, it builds on recent efforts by Serrenho et al (2016) towards a common accounting framework using IEA input energy data – which represents the state-of-the-art in comparable worldwide energy data - by developing more granular techniques for electricity end use and transport (mechanical drive) efficiencies. Secondly, the improved methodology is then applied to UK and US exergy and useful work analyses for the period 1960-2010, aligning with input IEA energy data availability. The US and UK are chosen as they were previously analysed for the period 1900-2000 by Warr et al (2008; 2010), allowing comparisons and insights into post-industrial energy use patterns.

We align our analysis with the energy carriers boundary taken by Ayres et al (2003) and Serrenho et al (2016), meaning the main appropriated energy flows intended for energy use are considered: coal, gas, oil, nuclear, food (for manual labour), combustible renewables, hydropower, and other renewables. The alternative bio-physical approach, adopted by Scuibba (2001) and Krausmann et al (2008), includes material flows (e.g. cotton, iron ores) which are both outside our energy carriers boundary and have a minimal contribution (~2% for Chen et al's (2006) China analysis). Our useful work analysis is distinct from the important field of energy services (e.g. (Fouquet, 2014; Cullen et al., 2011)), and whilst we use 'device' (i.e. domestic boiler) energy transfer efficiencies, we do not include passive systems (e.g. house or insulation) in our analysis.

The paper is structured as follows: Section 2.3 describes Methods, Results are in Section 2.4, and a Discussion is given in Section 2.5. Appendix A contains more detail on the mapping categories to useful work, exergy to useful work calculations and post-results analysis.

2.3 Methods

The basic useful work accounting method follows Ayres and Warr's (e.g. 15) approach. Their method, well documented in sections 3 and 4 of their book "The Economic Growth Engine" (Ayres & Warr, 2010), is based on five key steps. First, national-level primary energy data (i.e. oil, coal, gas, nuclear, renewables, food and feed) is converted back to primary exergy via 'chemical equivalent' conversion factors for fossil fuels (Szargut et al., 1988) and technology conversion values for renewables. In step 2, the primary exergy values (by energy type) are mapped to task levels within each main useful work category (heat, mechanical drive, electricity and muscle work). For example, work done by cars, trucks, aircraft and rail are task levels within the mechanical drive category. Step 3 establishes task-level conversion efficiencies, using published values or new estimations. In step 4, individual task-level useful work by energy source is calculated by multiplying task-level inputs and conversion efficiencies from steps 2 and 3. Finally, step 5 calculates the overall national exergy efficiency value by summing end useful work and dividing by total primary exergy inputs (equation 2-2).

Serrenho et al (2016) made significant advances to the approach in steps 1 and 2 by standardising the primary energy mapping to useful work categories based on IEA datasets (International Energy Agency (IEA), 2013). This paper follows the IEA mapping approach for the US and UK analyses, as shown in Appendix

A. The IEA energy data may differ from national datasets, but such differences are typically small (<5%), and being based on a single methodology greatly strengthens cross-country comparisons. This paper proposes methodological advances for task-level exergy efficiencies within step 3, to help build a common analytical useful work accounting framework. The main features are given below, with more detailed descriptions in Appendix A.

The first major revision is to electricity, giving more granular treatment to electricity end uses. Originally Ayres and Warr categorized electricity as pure work (Ayres et al., 2003), so electricity exergy efficiency was just equal to electricity generation efficiency (~35%). Subsequently, Ayres et al (2005) estimated task-level efficiencies for end uses of electricity, by including end-use device efficiencies for motors, heating, cooling and cooking, and these were incorporated into national exergy analyses (Warr et al., 2010; Serrenho et al., 2016). We make two important changes, which reduce the overall electricity exergy efficiency. Firstly, we include Carnot temperature ratio penalties for electrical high temperature heat (HTH), refrigeration and air-conditioning, omitted from previous studies (e.g. Figure 4.19, (Ayres & Warr, 2010)), to match the second law approach to other heating/cooling applications. Secondly, we provide more granular mapping of IEA electricity consumption to main end uses (e.g. electric motors, heat, electrical appliances, computers, lighting) within each main economic sector (e.g. industry, commerce, residential) based on local country end use consumption data (Department of Energy & Climate Change (DECC), 2013; US Department of Energy, 2011). Particular attention is given to adding granularity to residential electricity use, a significant and growing proportion of total electricity consumption (see Appendix A), including household appliance exergy efficiency calculations. Electricity exergy efficiencies are then equal to electrical generation efficiency multiplied by electrical end-use device efficiencies. These methodological changes reveal a dilution effect within electricity usage, shown in Figure 2-2 for the US: overall electricity exergy efficiency decreases from 11% to 8% over time, as structural shifts to less efficient electricity uses (e.g. air conditioning) occur faster than task-level efficiencies rise for each electricity end use type.

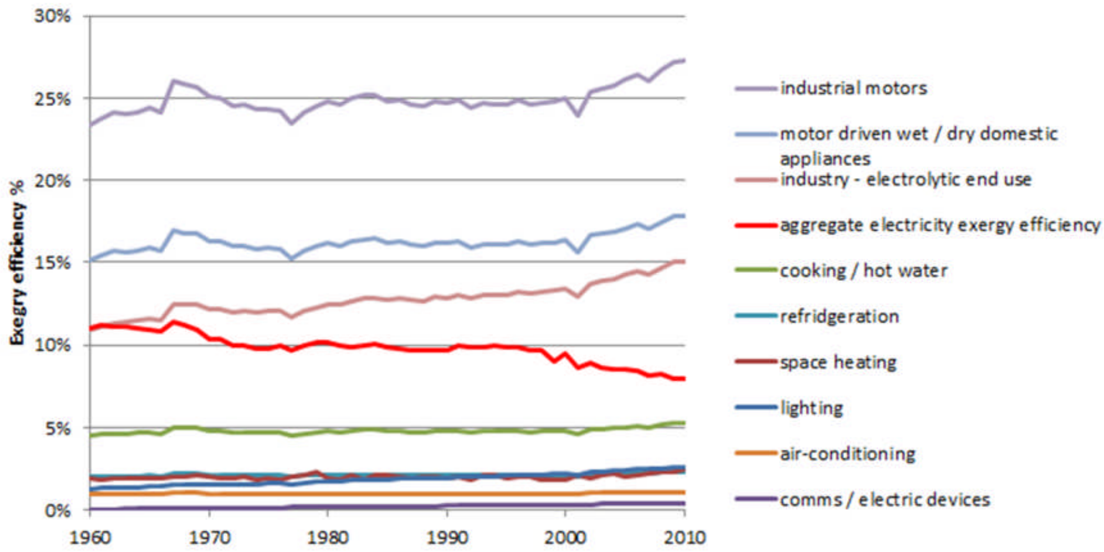

Figure 2-2: US electricity exergy efficiencies by end use 1960-2010

Secondly, a novel approach is developed for mechanical drive (transport) to improve the estimation of time-series exergy efficiency in this important sector, which forms ~30% of total primary energy demand. Traditional techniques (e.g. (Warr et al., 2010; Hammond & Stapleton, 2001)) follow Carnahan et al (Carnahan et al., 1975b), where overall exergy efficiency is derived from thermal engine efficiency (~30%) multiplied by assumed (~30%) post-engine losses (e.g. heat, internal friction and other drive-line losses), leaving the estimated exergy efficiency at 8%-10% for a typical car. Although some engine efficiencies have been tracked over time, post-engine loss factors have not, resulting in arbitrary judgment about their time-series variation.

Ayres et al (2003) adopted a road transport exergy efficiency, $\varepsilon = 0.52 \times \text{mpg}$ as a proxy for mechanical drive efficiency, as improved fuel economy (in miles per gallon (mpg)) is assumed to reflect increases in power train efficiency. We advance this approach, by estimating exponential curves which relate exergy efficiency as a function of vehicle fuel economy, for all UK and US major transport modes (road, rail, air) during 1960-2010. Our method is based on a detailed investigation of US gasoline cars, since this transport mode had the most detailed source data, from Oak Ridge National Laboratory, who had measured power-train force and fuel economy for 68 US road vehicles (Thomas, 2014). Power-train force is the residual force available at the wheels after engine, idling, drive-train and parasitic losses are incurred (note all power-train force gets dissipated subsequently via drag, tyre rolling and braking losses). It is estimated by the US Department of Energy (USDoE) to be 14-26% of starting fuel energy (primary exergy) for new cars, depending on drive cycle (USDoE, 2014). Dynamometer power-train results enabled useful work (power-train tractive force x distance travelled) - and thus exergy efficiency (useful work / primary exergy) - to be calculated for all vehicle test data for years 2005 and 2013. In order to estimate a best-fit curve for the whole period, we combine these results with the estimates of vehicle exergy efficiencies from 1970 (Reistad, 1975; Carnahan et al., 1975b) and 1994 (American Physical Society, 2008), and an estimated maximum exergy efficiency of 35% for gasoline cars (assuming current best practice engine thermal efficiency = future limiting exergy efficiency). This gives an empirical best-fit inverse exponential $\varepsilon = 35(1-e^{-0.025x})$ relating exergy efficiency ε to fuel economy x (in mpg), shown in Figure 2-3. We acknowledge the lack of historical data prior to 2005 (except single point 1970 and 1994 values) is a weakness, and would redraw the best-fit curve if such historical data was found. Nevertheless, it represents progress against the incumbent arbitrary loss factor or linear ε-mpg systems, and provides a better trajectory for future energy scenarios, where higher fuel economy values lie.

This approach was then extended to diesel-road, rail and air sectors using the same principle, i.e. fitting curves relating vehicle exergy efficiencies to fuel economy by combining historical and estimated maximum values. The fitted curves (plotted in Appendix A) enable exergy efficiencies (and hence useful work) to be estimated based on 1960-2010 UK and US fuel economy data (Department of Energy & Climate Change (DECC), 2013; Network Rail, 2013; Civil Aviation Authority, 2013; Department for Transport (Dft), 2011; US Department of Transportation, 2013).

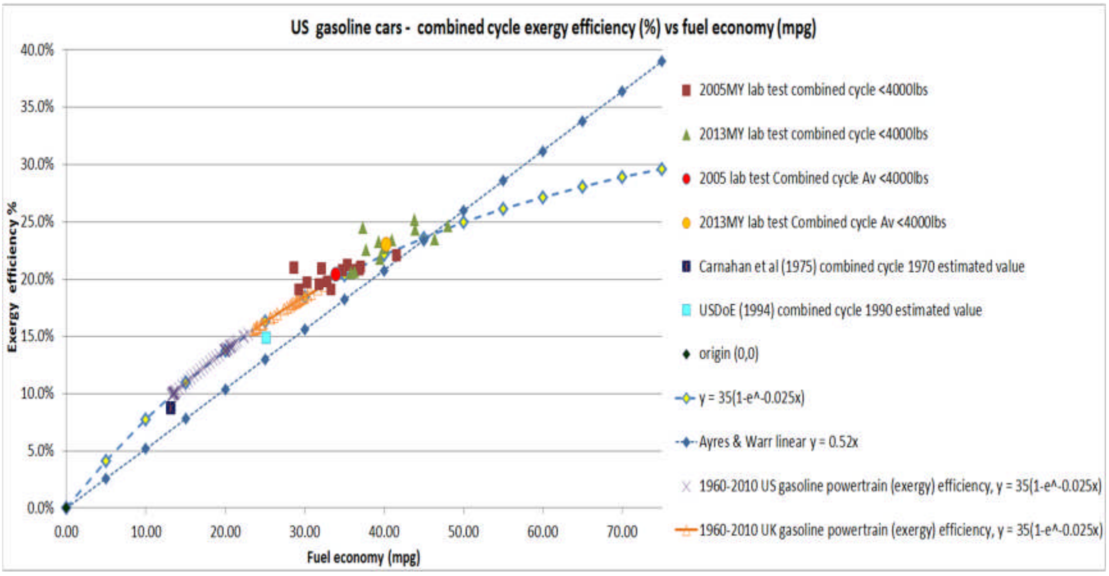

Figure 2-3: US gasoline cars (mechanical drive) empirically derived exergy efficiency (%) vs fuel economy (mpg)

The other analysis elements are largely similar to Ayres and Warr (2010) and Serrenho et al (2016) approaches. Heat is mapped to four task-levels: HTH at 600ºC; Medium Temperature Heat (MTH2) at 200ºC and 100ºC (MTH1), and Low Temperature Heat (LTH) at ~20ºC. For HTH, a weighted average of the two largest HTH consuming industrial sector efficiencies (steel and petro-chemicals) is taken. MTH2 is lower temperature (~200ºC) industrial heat, which was estimated as the Carnot temperature pro-rata of the HTH efficiency (as no more specific data was available). For LTH and MTH1, the exergy efficiency is the assumed device (gas boiler) conversion ratio (70-90%) multiplied by the Carnot temperature ratio. Manual labour follows Serrenho et al (2016) by calculating the amount of manual labour involved in human ‘mechanical drive’ outputs (UK and US draught animals useful work contribution is negligible post-1960), and taking the additional manual labour calories into the exergy and useful work calculations. We also remove non-energy uses of primary exergy from our analysis (e.g. bitumen and petrochemical feedstocks) as others (e.g. (Ertesvag, 2001; Ayres & Warr, 2010)) have done. However, Serrenho et al (2016) asks whether it should be included, and as non-energy use is a small but growing sector, accounting for ~5% of primary energy demand, we discuss it further in Appendix A.

Incorporating these methodological changes, the national-level aggregate exergy efficiencies for the US and the UK are calculated on an annual basis for the period 1960 to 2010 using equation 2-2, following the five step approach summarized above (detailed in Appendix A). The exergy efficiency is calculated on the primary-to-useful basis adopted by Warr et al. (2010), Nakicenovic et al. (1996) and Reistad (1975), as opposed to the final-to-useful basis of Serrenho et al (2016). The latter approach gives higher quoted efficiency values, since typical primary to final energy conversion efficiencies are 65-70%.

2.4 UK and US exergy efficiency 1960-2010: Results

Figure 2-4 shows the aggregate US exergy efficiency has remained stable at around 11% over the period 1960-2010. This stability is due to heat exergy efficiency gains (9% to 13%) being offset by reductions in electricity exergy efficiency (11% to 8%). Muscle work has limited impact on the overall US efficiency due to the small size of its exergy and useful work contribution compared to that from heat, mechanical drive and electricity sectors (see Appendix A).

Figure 2-5 shows the UK aggregate exergy efficiency rose from 9% to 15%, with gains in all three main sectors: heat rose from 8% to 12% (due to significant gains in all task-level efficiencies); electricity 8% to 14% (largely due to a rise in electricity generation efficiency from 30% to 43%); and mechanical drive 11% to 21% (due to dieselisation and increases in fuel economy). Task-level efficiency plots and electricity generation efficiencies are shown in Appendix A.

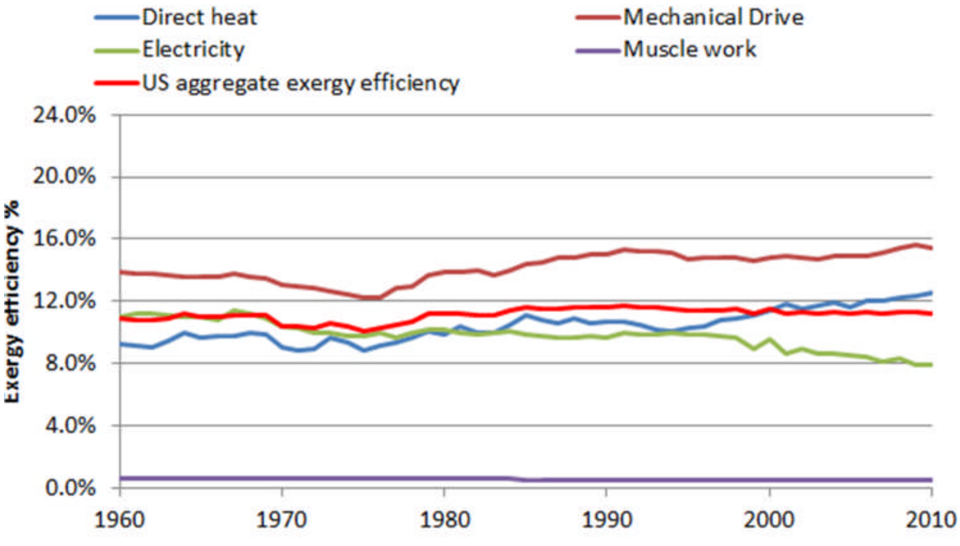

Figure 2-4: US exergy efficiency 1960-2010 by end use

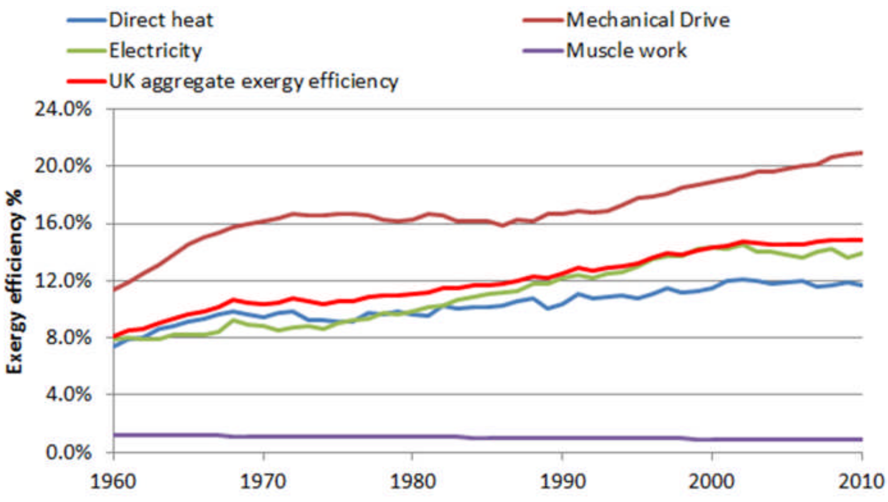

Figure 2-5: UK exergy efficiency 1960-2010 by end use

Figure 2-6 and Figure 2-7 show the normalised plots of exergy, exergy efficiency and useful work versus a 1960 datum. The US exergy efficiency stagnation means the doubling of useful work in this period is almost all due to an increase in primary exergy. In contrast, the UK's almost identical doubling of useful work since 1960 has been mainly delivered by a large rise in exergy efficiency.

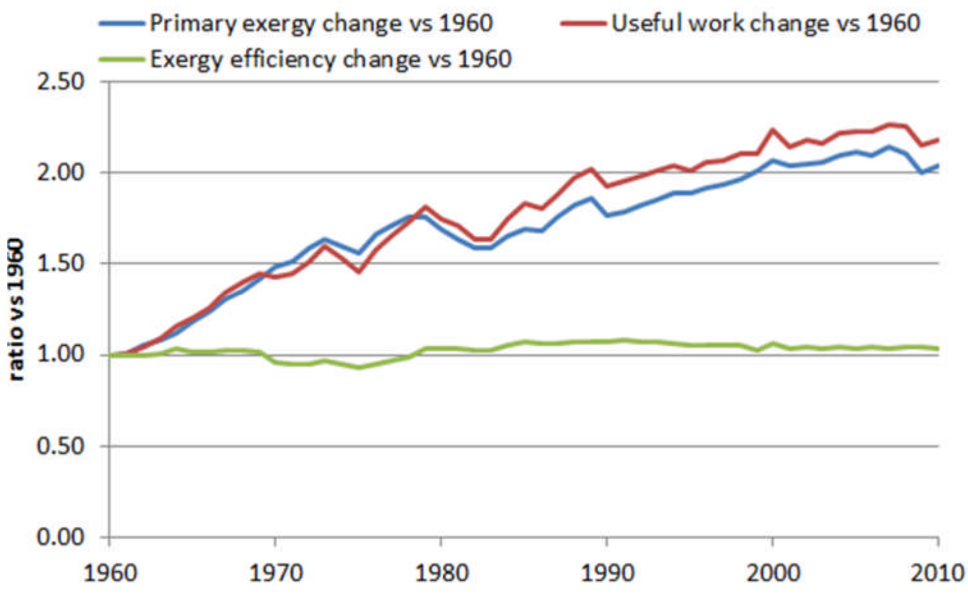

Figure 2-6: US normalised exergy, efficiency, useful work vs 1960

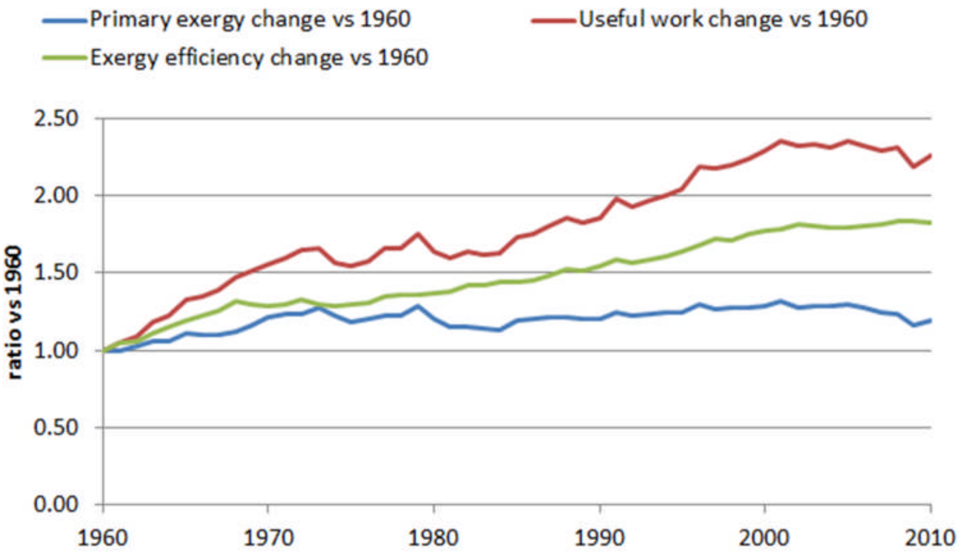

Figure 2-7: UK normalised exergy, efficiency, useful work vs 1960

Figure 2-8 shows the 2010 flow diagram from primary exergy to useful work for the UK. It shows how 86% of the input primary exergy is lost and only 14% remains at the useful work stage. Useful work by end use is split fairly evenly between direct heat (30%), direct mechanical work (32%) and electricity end uses (38%). Manual mechanical work forms only 0.03% of total end useful work, reflecting the UK's mature industrialized economy.

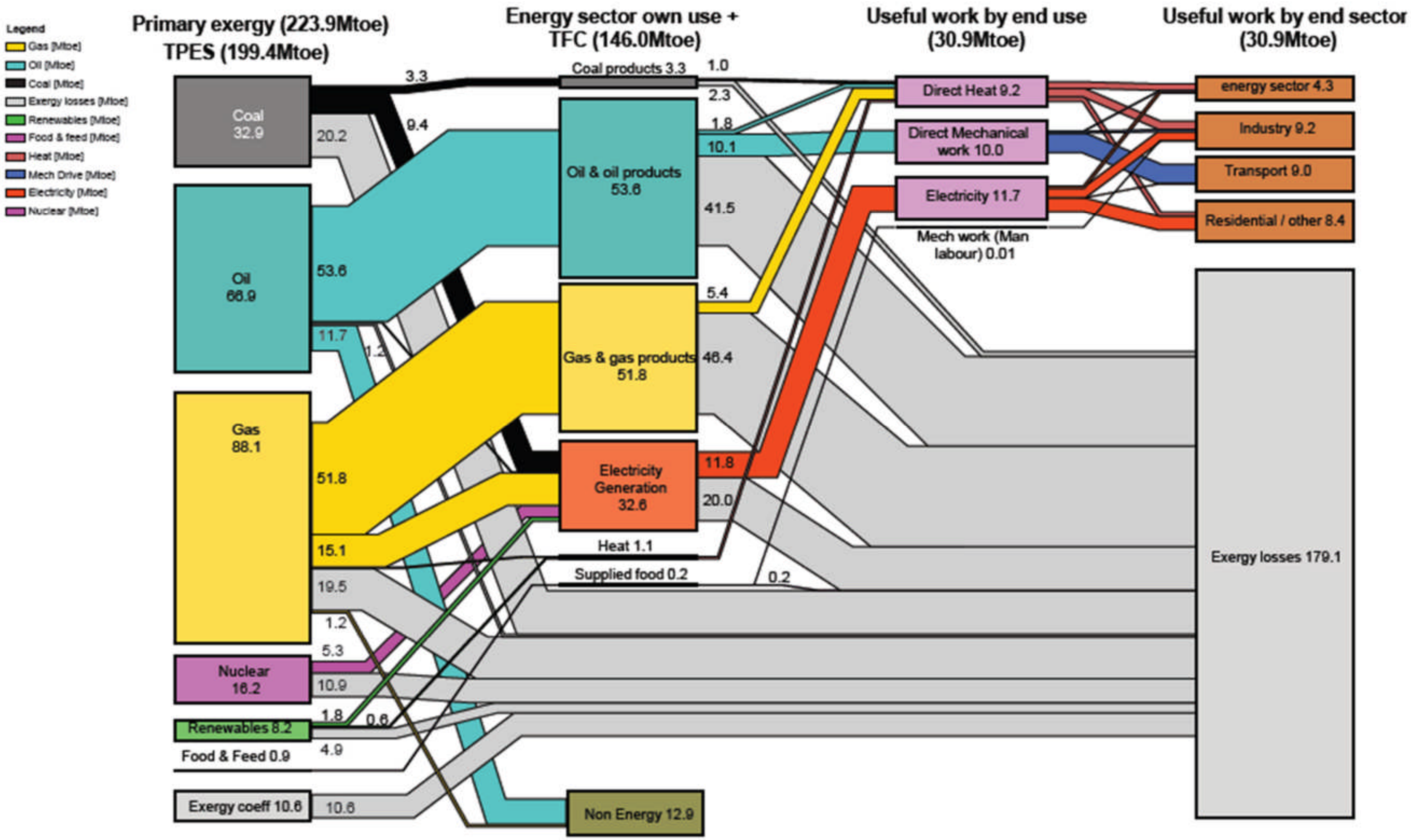

Figure 2-8: UK exergy to useful work flowchart (2010)

2.5 UK and US exergy efficiency 1960-2010: Discussion

The 50 year stagnation in overall US exergy efficiency is a striking and hitherto unexpected result. It has remained remarkably stable at around 11% since 1960, in contrast to the UK, which increased from 8.8% in 1960 to a 2008 peak of 15.0%, as shown by Figure 2-9. The divergence in UK-US overall exergy efficiencies occurred as the UK became more efficient in all three main useful work categories: heat, electricity and mechanical drive, whereas US heat efficiency gains were offset by a large reduction in electricity efficiency.

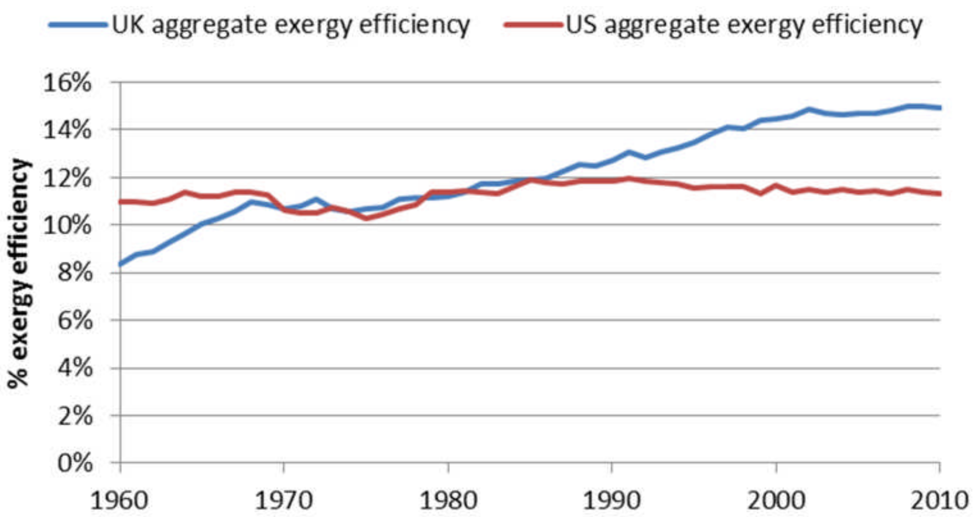

Figure 2-9: Divergence in UK-US exergy efficiencies

The UK-US exergy efficiency divergence is revealed due to our methodological changes to electricity and mechanical drive. First, the more granular treatment of electricity task-level uses has more influence on US electrical exergy efficiency (largely owing to greater use of air-conditioning), and result in US electricity aggregate efficiency decreasing from 11.0% in 1960 to 7.9% in 2010. Second, by adopting our empirical ε-mpg approach for major transport modes, we assembled a time-history profile of task-level exergy efficiencies that represents a more robust improvement on previous strategies of either arbitrary loss-factor adjustments or linear ε-mpg relationships. The result is a more realistic time-series representation of task-level exergy efficiencies for transport: for example, as road-based fuel economy has remained static in the US since 1980 (American Physical Society, 2008), due to the trend for larger and faster accelerating cars (and trucks), the derived US transport mechanical drive efficiencies have not increased, in contrast to the UK, where fuel economy and hence exergy efficiency (via the empirical relationship) has improved significantly.

The stagnating US national exergy efficiency appears to mimic the 'efficiency dilution' effect first described in exergy analysis literature by Williams et al. (2008) for Japan. This is where greater use of lower efficiency processes (e.g. US air conditioning has risen from 10% to 20% of electricity end use) outweigh task-level efficiency gains. It is most evident in the electricity sector, but similar shifts to lower efficiency processes also occurred in the US heat sector: HTH halved from 1960 to 2010 (due to declining manufacturing HTH use), whilst LTH increased 20% in the same period (due to gains in residential consumption). In the UK, dilution within heat and electricity sectors was more than offset by gains in task-level exergy efficiencies over this period. Nevertheless, UK heat and electricity efficiencies also peaked around 2000 (as with the US), and were stable to 2010. Compounding the structural dilution effect (e.g. shifting from HTH to LTH within heat sector) are approaching asymptotic device efficiency limits. Annual increases in task-level efficiencies are lower now than in 1960: for example boiler (first law) efficiencies have increased from 70% towards an asymptotic limit somewhere over 90%. This highlights the importance of passive system analysis (e.g.(Cullen & Allwood, 2010)), as this provides larger energy reduction scope when reaching device efficiency limits.

Comparing our US results to earlier studies, Ayres and Warr (Warr et al., 2010; Ayres & Warr, 2010) estimated US efficiency in 1960 as 8%, lower than our result of 11%. Differences lie in their higher assumed intake of food for muscle work (with a low ~2% overall efficiency), a lower mechanical drive efficiency (8% versus 11%) compared to that from our more granular ε-mpg empirical approach, and a lower heat efficiency (7% vs 12%) as more heat is allocated to LTH in their analysis. Laitner's (2013) subsequent 2000-2010 extension of their results estimated US efficiency to be 14% in 2010, higher than our static 11%. This is due to a much lower overall electricity efficiency in our analysis - resulting from the Carnot and granularity refinements noted above – coupled to the fact that electricity is a larger share of useful work by 2010. Reistad's (1975) estimated 1970 US exergy efficiency of 22% is double our 11% value. This is because he estimated higher efficiencies for both transport (22% vs 13%, due to using significantly higher car/truck efficiencies versus other studies (e.g. Carnahan et al., 1975b) and heating (20% vs 10%, based on much higher HTH operating temperatures and incorrectly omitting 'first law' process efficiencies).

Warr et al (2010) estimated UK exergy efficiency to rise from 8% to 14% from 1960-2000, which compares well to our results. The 1960 values are similar (8%) as their greater allocation of muscle work is offset by our lower electricity efficiency noted earlier. By 2000, our overall efficiency also matches theirs, as our lower efficiency values for heat (12% vs 17%) and electricity (14% vs 20%) are balanced by our higher efficiencies for mechanical drive (19% vs 14%) and our lower allocation of muscle work. Warr et al's earlier analysis (Warr et al., 2008) estimated UK exergy efficiency rose from 10% (1960) to 15% (2000), similar to our values but the reasons for differences to their later results (Warr et al., 2010) cannot be determined. Hammond and Stapleton's (2001) analysis for the UK doesn't include an overall exergy efficiency estimate, but their results for electricity, residential, industrial and transport sectors appear broadly similar to ours.

Differences between directly comparable exergy efficiency results (i.e. for same country and year) lie less in primary exergy (main differences exist in assumed food/muscle work inputs) and more in assumed task-level exergy efficiencies (e.g. LTH, MTH, HTH). Such differences to (and between) previous analysis results highlight the need for a common methodology, which is the goal to which this paper contributes. A consistent, comparable approach allows better understanding ofenergy consumption patterns and differences. But it also provides a solid analytical basis for exploration of extensions to energy services, linkages to economic growth, and informing future energy demand scenarios. For example, our analysis indicates that almost all of the useful work growth in the US has come from increasing primary exergy inputs, raising the question of the sustainability of this going forward. On the other hand, UK exergy efficiency improvements appear to be levelling off, raising the challenge of how to achieve further efficiency improvements. This is important as Ayres and Warr (2010) argue that increases in primary exergy inputs and efficiency of conversion to useful work have been key drivers of economic growth in the US and UK.

Overall, the methodological framework and results in this paper have important implications which are the basis for suggested further studies. First, further standardisation of the IEA-based calculation approach would be helpful, including consistent treatment of renewables, electricity end uses and non-energy. For renewables, we follow exergy analyses (e.g. (Warr et al., 2008)), which typically take solar and wind conversion device factors of 0.07-0.13, whereas the IEA assumes factors of 1.00. Second, evidence of efficiency dilution needs decomposition scrutiny, but if confirmed, it suggests aggregate exergy efficiency is no longer rising in either US or UK, despite implementing various energy efficiency measures in industry, residential and transport sectors, and this poses important questions. For example: does this indicate the UK (due to dilution) is close to a practical maximum for national energy efficiency? Or are higher efficiency processes are 'offshored' through exergy trade flow, in a similar way to carbon emissions (Wiedmann et al., 2013)? Is dilution evidence of energy rebound (e.g. (Saunders, 2000; Sorrell, 2009))? And if this exergy efficiency stagnation continues, would any future growth in useful work come wholly from primary exergy (energy) supply? Thus both dilution and stagnation effects could have impacts on energy efficiency and energy supply policies.

Third, the links between exergy and economic growth are worthy of continued study. For example, studying the role of prices in the evolution of US-UK exergy efficiencies would add to existing econometric literature (e.g.(Fouquet, 2014)), whilst the question of whether exergy efficiency stagnation would threaten the engine of economic growth (Ayres & Warr, 2010) could be considered. Useful work intensity (useful work / GDP) may also offer additional insights into links between end energy use and efficiency, as Serrenho et al (2014; 2013) propose, compared to traditional energy intensity (TPES/GDP) metrics, which some have criticised (e.g. Steinberger & Krausmann, 2011; Fiorito, 2013). Fourth, the valuable extension of this technique to include research on energy services will help review practical and theoretical exergy efficiency limits, and be clearer on the delineation between active device and passive system efficiencies (e.g. (Cullen et al., 2011)). Last, is the effect on CO_2 reduction, since stagnation in exergy efficiencies result in closer coupling of energy and emissions, making it difficult to deliver on global mitigation objectives.

By considering end energy use from a quality viewpoint, exergy and useful work analysis appears well suited to examine current issues such as the use of lower grade fossil fuels, mainstreaming of renewables, and future energy and economic forecasting. However, there are limits to a useful work based (first and second law) approach: for example exergy efficiency does not capture the effect of insulation/leak proofing on buildings except through reduced exergy inputs. For this, a passive system approach is required. Therefore, as Hammond and Stapleton (2001) suggest, exergy and useful work approaches should be seen as complementary and not competing with traditional (first law) energy analysis techniques.

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Chapter 3

Understanding China's past and future energy demand: an exergy efficiency and decomposition analysis

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Highlights

1. We complete the first time series exergy and useful work study of China (1971-2010)
2. Novel exergy approach to understand China's past and future energy consumption
3. China's exergy efficiency rose from 5% to 13%, and is now above US (11%)
4. Decomposition finds this is due to structural change not technical leapfrogging
5. Results suggests current models may underestimate China's future energy demand

3.1 Abstract

There are very few useful work and exergy analysis studies for China, and fewer still that consider how the results inform drivers of past and future energy consumption. This is surprising: China is the world's largest energy consumer, whilst exergy analysis provides a robust thermodynamic framework for analysing the technical efficiency of energy use. In response, we develop three novel sub-analyses. First we perform a long-term whole economy time-series exergy analysis for China (1971-2010). We find a 10-fold growth in China's useful work

since 1971, which is supplied by a 4-fold increase in primary energy coupled to a 2.5-fold gain in aggregate exergy conversion efficiency to useful work: from 5% to 12%. Second, using index decomposition we expose the key driver of efficiency growth as not ‘technological leapfrogging’ but structural change: i.e. increasing reliance on thermodynamically efficient (but very energy intensive) heavy industrial activities. Third, we extend our useful work analysis to estimate China’s future primary energy demand, and find values for 2030 that are significantly above mainstream projections.

3.2 Introduction

As the world’s economic powerhouse and largest energy consumer (International Energy Agency (IEA), 2013a), much effort is spent understanding China’s historical energy consumption (e.g. (International Energy Agency (IEA), 2012; Letschert et al., 2010; Energy Foundation China, 2001)) and future energy demand (International Energy Agency (IEA), 2010; International Energy Agency (IEA), 2013b; Organisation for Economic Co-operation and Development (OECD), 2012). However these studies typically examine primary or final energy data, rather than useful work values obtained using an exergy analysis based technique. This is the research gap that this paper seeks to address. Exergy analysis takes a broader, whole system approach to energy analysis, giving “a measure of the thermodynamic quality of an energy carrier” (Hammond, 2007, p.686), thereby enabling a robust view of useful work consumed in provision of energy services. Exergy analysis also has the benefit of taking into account more aspects of the energy supply chain than traditional energy analysis, and in a more consistent way. A flow visualisation of primary exergy to useful work is given in Figure 3-1:

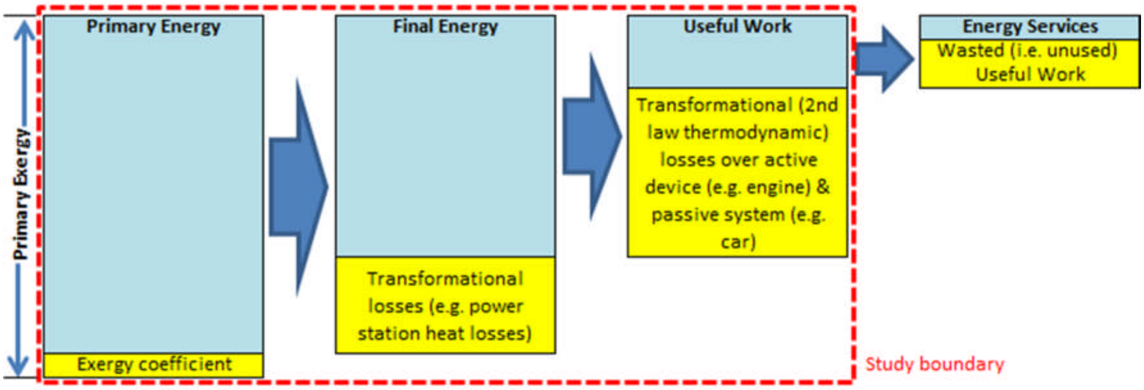

Figure 3-1 Conceptual diagram of primary exergy to useful work

A key assumption in this study is that useful work is a better 'energy parameter' than primary energy on which to analyse end energy use and economic activity, since - as Figure 3-1 shows - it is the last thermodynamic place where energy is measured before it is exchanged for energy services. We are not alone in this view. Numerous authors (e.g. (Hammond, 2007; Rosen et al., 2008; Groscurth et al., 1989)) suggest exergy analyses can help understand national-scale energy use. For economic insights, Percebois suggested in 1979 that energy intensity metrics (i.e. energy consumption relative to GDP) were better undertaken at the energy output stage, since it "allows us to analyse structural change in energy supply and situates our analysis at the level of satisfied needs" (1979, p.148). Serrenho et al's (2014) recent work on useful work intensity supports this assertion. Meanwhile, Warr and Ayres (2010), Santos et al (2014) and Guevara et al (2014), all found empirical evidence suggesting useful work is a better candidate as a factor of production (than primary energy) to explain economic growth. This gets us to the crux of our argument: if it is useful work and not primary energy that supplies economic needs, then we should conduct energy and economic analyses at that level.

The few published time-series studies of useful work accounting have focussed largely on industrialised countries including the US, UK and Japan (e.g. (Ayres & Warr, 2005; Williams et al., 2008; Warr et al., 2010) and later all EU-15 countries (Serrenho et al., 2014). Somewhat curiously, these country-scale analyses typically focus on economic implications and linkages, rather than energy-based conclusions. Brockway et al (2014) set out to address this imbalance, by undertaking a 50 year time-series analysis (1960-2010) of the US and UK. They found the US and UK may no longer be increasing their aggregate exergy efficiency, as increases in process level efficiencies are offset by efficiency dilution taking place (Brockway et al., 2014), following the case of Japan (Williams et al., 2008). In short: individual technology gains in efficiency are being overtaken by using increasing amounts of less efficient processes, such as air-conditioning. This raises the question: could the same be happening in China?

Numerous Extended Exergy Accounting (EEA) studies have been published on China (e.g.(Chen & Chen, 2007; Chen & Chen, 2009; Dai & Chen, 2011; B. Chen & Chen, 2006; Dai et al., 2014b; Dai et al., 2014a; Chen et al., 2014; Dai et al., 2012; Jiang & Chen, 2011; Ji & Chen, 2006; Chen et al., 2006; B Chen & Chen, 2006; Chen & Qi, 2007)). EEA is a biophysical exergy analysis method, developed largely by Wall and Sciubba in the 1990s (e.g.(Wall, 1990; Wall et al., 1994; Sciubba, 2001)) to examine the embedded exergy of all natural resources inputs (e.g. energy, natural materials) and associated outputs of the economy (e.g. food, materials, wastes). This valuable technique helps understand societal exergy consumption. It is complementary to the useful work accounting method applied here, which is based on an “energy carriers for energy use” approach (Ertesvag, 2001, p.254) introduced at a national-scale by Reistad (1975), which examines the exergy destruction of energy conversion processes from primary exergy to end useful work. The key distinction is that EEA is akin to a mass-balance analysis (except it studies exergy content not mass) whereas Reistad’s approach estimates the thermodynamic work done by the energy system to deliver energy services. It is the latter approach we require for detailed energy system analysis – and such national-scale useful work accounting studies for China are rare (e.g. (Ma et al., 2012)), and none to date examine a long time-series.

To address the lack of exergy-based analyses in China which examine time-series results through an energy demand lens, we pose the following research question: *What new insights can useful work analysis provide for historical and future energy demand in China?* In response, we provide three novel, linked analyses. To start, we undertake the first historical exergy efficiency and useful work analysis for China, covering the period 1971-2010. Next, we adopt an index decomposition analysis to identify the key drivers of change in China’s useful work. Last, we develop a useful work based method for projecting China's primary energy demand to 2030, and also test implications of potential future declines in the rate of exergy efficiency improvement.

The paper proceeds as follows. After the Introduction, Section 3.2 contains Methods and Data, Results and Discussions are in Section 3.3, with Conclusions in Section 3.4.

3.3 Methods and Data

3.3.1 Historical useful work analysis (1971-2010)

3.3.1.1 Method Summary

Reistad (1975) defined exergy as 'available energy'. As depicted in Figure 3-1, at a country-scale, primary exergy of energy carriers (e.g. coal, oil, gas, renewables, food and feed) is transformed into ready to use 'final energy' (e.g., diesel or electricity), which is then used to provide 'useful work' (i.e. through heat, mechanical drive, manual labour or electrical devices), to ultimately provide energy services (e.g. warmth, light, cooling, sustenance). Carnahan et al (1975, p.37) defined task-level 'useful work' (U_{ij}) as "the minimum available work [exergy input] to perform the task". For our purposes, task-level means sub-class (j) (e.g. diesel road transport or low temperature heat) levels nesting within overall main classes (i) of energy use (i.e. heat, muscle work, transport, mechanical drive). Task-level exergy efficiency (ε_{ij}) represents the second law thermodynamic efficiency of the energy conversion from primary exergy to end useful work, defined by Carnahan et al (1975) as equation 3-1:

$$\varepsilon_{ij} = \frac{Useful\,work, Uij}{Primary\ Exergy, Eij} = \frac{The\ minimum\ exergy\ input\ to\ achieve\ that\ task\ work\ transfer}{Maximum\ amount\ of\ reversible\ work\ done\ as\ system\ reaches\ equlibrium} \quad \textbf{(3-1)}$$

Primary exergy values at task-level (E_{ij}) are then multiplied with their associated task-level exergy efficiencies (ε_{ij}) to give an estimate for task-level useful work (U_{ij}). When summed, we derive an overall estimate for the total national-scale useful work ($U_{tot} = \sum U_{ij}$) via equation 3-2. Finally, national exergy efficiency (ε_{tot}) is given by equation 3-3, which - following Carnahan et al (1975) - we adopt as a country-scale measure of energy efficiency, and use it as a term throughout this paper for consistency. Equation 3-2 also reveals the obvious (but important, as we see later) observation that useful work changes are supplied by changes in primary exergy and/or exergy efficiency.

$$\Sigma\, U_{ij} \;=\; \Sigma\,(E_{ij}\,\varepsilon_{ij}) \tag{3-2}$$

$$\varepsilon_{tot} \;=\; \frac{\Sigma\, U_{ij}}{\Sigma\, E_{ij}} \tag{3-3}$$

Our country-scale useful work accounting approach follows the "energy carriers for energy use" (Ertesvag, 2001, p.254) method of exergy and useful work analysis, as developed by numerous authors including Reistad (1975), Wall (1986), Ayres et al (2003). More recently Serrenho (2014) developed useful work accounting using a consistent International Energy Agency (IEA) based input energy mapping framework. Brockway et al (2014) made further advances to electricity applications and mechanical drive classes, which is also used in this study for consistency and comparability. We apply these advances to produce a first time-series analysis of China. Figure 3-2 gives an overview of the basic stages:

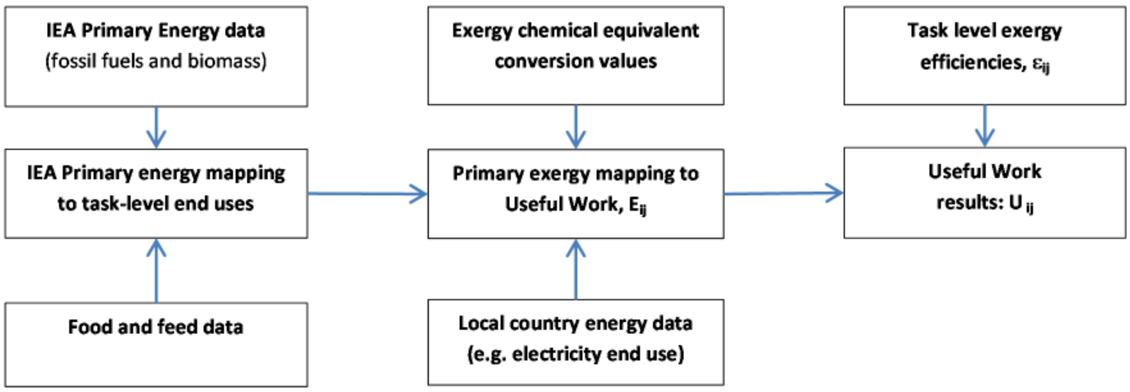

Figure 3-2: Useful work analysis flowchart

3.3.1.2 Input data

Primary exergy inputs, E_{ij}, are first derived. IEA energy datasets 1971-2010 (International Energy Agency (IEA), 2013a) for fossil fuel and biomass (combustible renewables) provided much of the base data. IEA primary energy values are converted to primary exergy inputs using chemical exergy coefficients (Szargut et al., 1988). At an aggregate level, total primary exergy is around 5%

higher than the IEA's Total Primary Energy Supply (TPES) values. The inputs E_{ij} are then mapped to three main classes (heat, mechanical drive and electricity) and to task-levels where possible (e.g. Low Temperature Heat (LTH)), following recent approaches (Serrenho, 2014; Brockway et al., 2014). The task-levels are listed in Appendix A. In some cases, we extend the IEA end energy use breakdown to more granular levels (e.g. road fuel split between transport modes) by supplementing Chinese end consumption data in three key areas: buildings (Letschert et al., 2010; Amecke et al., 2013; Murata et al., 2008; Lawrence Berkley National Laboratory (LBNL), 2013; Pachauri & Jiang, 2008; Catania, 1999); transport (Hao et al., 2012; Huo et al., 2012; He et al., 2005; Qunren & Yushi, 2001; Wang et al., 2006); and industry (Hasanbeigi et al., 2011; He et al., 2013; Price et al., 2002; Hasanbeigi, Jiang, et al., 2013; Hasanbeigi, Price, et al., 2013).

Next, task-level exergy efficiencies (ε_{ij}) for transport, heat, and electricity are added. Previous US-UK values (Brockway et al., 2014) are modified by Chinese data as follows. For transport, local fuel economy data was used for road and rail (Qunren & Yushi, 2001; Wang et al., 2006; Hao et al., 2011; Teter, 2014). For calculating Carnot efficiencies (for heat exergy efficiencies), we used 1971-2010 China monthly air temperature data (National Climatic Data Centre, 2014). Indoor temperatures (for LTH efficiencies) are weighted for China's city/rural split and assume a 20 year lag in comfort levels versus UK data (Department of Energy & Climate Change (DECC), 2013). LTH first law efficiencies are based on Warr et al (2010), Chen et al (2006) and Edwards et al (2004). Steel and ammonia industries are adopted (as with US-UK study) as representative of High Temperature Heat (HTH) efficiencies, by virtue of having the two highest proportions of Chinese industrial energy use (Hasanbeigi, Price, et al., 2013). First law (GJ/tes) efficiency data for steel (He et al., 2013; Price et al., 2002; Hasanbeigi et al., 2011; Hasanbeigi, Jiang, et al., 2013; Ross & Feng, 1991; Phylipsen et al., 2002) and ammonia (taken as 75% of UK values, based on average values from Phylipsen et al (2002)) and the IEA (Saygin et al., 2009) are combined with temperature data to calculate time-series exergy efficiencies. For electricity application efficiencies, values of 80% of those from the US-UK analysis were typically used, based on evidence that China's average devices were 10-20 years behind US-UK values across industry, commerce and residential sectors (Letschert et al., 2010; Fridley et al., 2012).

Then, we calculated primary exergy and useful work values for a fourth main class: muscle work. For human labour, estimates follow Brockway et al's (2014) approach: using manual labour population (Laux et al., 2003; Brooks & Tao, 2003), food intake data (Wirsenius, 2000; Food and Agricultural Organisation of the United Nations (FAOSTAT), 2013), and Smil's estimated 13% conversion efficiency of food to human useful work (Smil, 1994). For draught animals, we assumed 100 million draught animals in China in 1990 (Ramaswamy, 1994), and a 1% annual decline in numbers from 1971 to 2010, mirroring India (Down to Earth, 2004). For animal useful work outputs, we assumed 400W average power output for a 5 hour working day over 120 working days/year, based on published data (Wilson, 2003; O'Neill & Kemp, 1989; Ramaswamy, 1994). Estimates of intake feed requirements were based on Ramaswamy (1994) and Krausmann et al. (2007).

Last, a note on data quality. For input energy data, two systematic discrepancies mean our national-level datasets underestimate actual primary energy use. First, at a national-scale, IEA-based TPES values are ~5% lower than those of Lawrence Berkeley National Laboratory (LBNL) China Energy Databook (LBNL, 2013). Second, reported aggregate primary energy consumption in China is ~10% higher from aggregated regional versus national datasets (Guan et al., 2012). However, these differences are expected to be systematic, and thus have limited overall effect for our trends analysis. For task-level efficiencies, whilst the China data sources are weaker in many instances than the previous US-UK studies (Brockway et al., 2014), overall trends and comparison to US-UK results remain valid.

3.3.1.3 Useful work accounting outputs

Appendix A shows the task-level outputs of useful work, primary exergy and exergy efficiency. This data serves as task-level as inputs to the Logarithmic Mean Divisia Index (LMDI) decomposition analysis, or is summed to give useful work or exergy efficiencies at main class level (i.e. heat, mechanical drive, electricity and muscle work) and country-scales.

3.3.2 LMDI decomposition (1971-2010)

LMDI decomposition is now the mainstream Index Decomposition Analysis (IDA) technique for analysing drivers of changes in CO_2 emissions (e.g. (Wang et al., 2005; Xu et al., 2014)) and sectoral energy use such as manufacturing and transport (e.g.(Liu et al., 2007; Zhang et al., 2011)). Using the LMDI approach, we develop a new approach to reveal the relative contribution of energy and efficiency drivers to China's historical useful work (U). First, we expand equation 3-2 (U = $\Sigma E_{ij}\ \varepsilon_{ij}$) to yield equation 3-4, which is based on task-level useful work (U_{ij}) and primary exergy (E_{ij}), enabling the historical results to act as the input data for the LMDI analysis. Equation 3-5 to 3-9 give the four drivers of useful work changes: Input Exergy (D_{ex}); Main class structure (D_{Str}); sub-class (i.e. task) level structural change (D_{dil}); and task-level efficiency (D_{eff}). This shows how LMDI decomposition can be used to breakdown the overall exergy efficiency changes (from the main analysis results in Section 3.1) into three parts.

$$\boldsymbol{U} = \sum_{ij} \boldsymbol{U_{ij}} = \sum_{ij} \boldsymbol{E} \frac{\boldsymbol{E_i}}{\boldsymbol{E}} \frac{\boldsymbol{E_{ij}}}{\boldsymbol{E_i}} \frac{\boldsymbol{U_{ij}}}{\boldsymbol{E_{ij}}} \tag{3-4}$$

$$\boldsymbol{D_{tot}} = \frac{\boldsymbol{U^T}}{\boldsymbol{U^0}} = \boldsymbol{D_{eX} D_{Str} D_{diL} D_{eFF}} \tag{3-5}$$

$$\boldsymbol{D_{eX}} = \mathbf{exp}\left(\sum_{ij} \hat{\mathrm{w}}_{ij} \, \mathbf{ln}\left(\frac{\boldsymbol{X^T}}{\boldsymbol{X^0}}\right)\right) \tag{3-6}$$

$$\boldsymbol{D_{Str}} = \mathbf{exp}\left(\sum_{ij} \hat{\mathrm{w}}_{ij} \, \mathbf{ln}\left(\frac{\boldsymbol{S_i^T}}{\boldsymbol{S_i^0}}\right)\right) \tag{3-7}$$

$$\boldsymbol{D_{diL}} = \mathbf{exp}\left(\sum_{ij} \hat{\mathrm{w}}_{ij} \, \mathbf{ln}\left(\frac{\boldsymbol{L_{ij}^T}}{\boldsymbol{L_{ij}^0}}\right)\right) \tag{3-8}$$

$$\boldsymbol{D_{eFF}} = \mathbf{exp}\left(\sum_{ij} \hat{\mathrm{w}}_{ij} \, \mathbf{ln}\left(\frac{\boldsymbol{F_{ij}^T}}{\boldsymbol{F_{ij}^0}}\right)\right) \tag{3-9}$$

$$\hat{\mathrm{w}}_{ij} = \left(\frac{(\boldsymbol{U_{ij}^T} - \boldsymbol{U_{ij}^0})/(\mathbf{ln}\,\boldsymbol{U_{ij}^T} - \mathbf{ln}\,\boldsymbol{U_{ij}^0})}{(\boldsymbol{U^T} - \boldsymbol{U^0})/(\mathbf{ln}\,\boldsymbol{U^T} - \mathbf{ln}\,\boldsymbol{U^0}))}\right) \tag{3-10}$$

Where

- E = Primary exergy input to economy
- E_i = Main class exergy input
- E_{ij} = Task-level exergy input
- U_{ij} = Task-level useful work output
- $\hat{w}_{ij}$ = log mean weighting function
- X = Exergy input
- S = Main class share of exergy input (E_i/E)
- L = Task-level share of exergy input within main class (E_{ij}/E_i)
- F = Task-level exergy efficiency(U_{ij}/E_{ij})
- D_{eX} = change in overall exergy input (E)
- D_{Str} = change in share of exergy inputs between main classes (E_i)
- D_{diL} = change in task-level shares (E_{ij}) of exergy inputs within main classes
- D_{eFF} = changes in task-level exergy conversion efficiencies (U_{ij}/E_{ij})

3.3.3 China energy demand scenarios 2010-2030

After conducting the historical and decomposition analyses, we develop and trial a new useful work-based methodology to estimate primary energy demand to 2030, based on projections of GDP and extrapolations of exergy efficiency under illustrative constant and declining exergy efficiency growth rate scenarios. Four steps were required. The first estimates China's useful work requirement for 2010-2030. To do this, 1971-2010 overall useful work energy intensity (UW/GDP) - calculated from historical GDP data (World Bank, 2014) – is extrapolated using a best-fitting curve to 2030. Using World Bank forecasts of GDP for 2011-2030 (World Bank & The Development Research Center of State Council the People's Republic of China, 2012) – see also Appendix B, China's total useful work (to deliver that GDP) in 2030 is then estimated.

Second, total projected useful work to 2030 is allocated to task-levels. To start, useful work proportions from main classes are estimated based on historic trend comparison in UK, US and China. China and US allocations are shown in Figure 3-3. Then, task level allocations are derived, also based on comparisons to previous US-UK values, which place China as ~40 years behind US-UK allocations. These results at task-level are given in Appendix B.

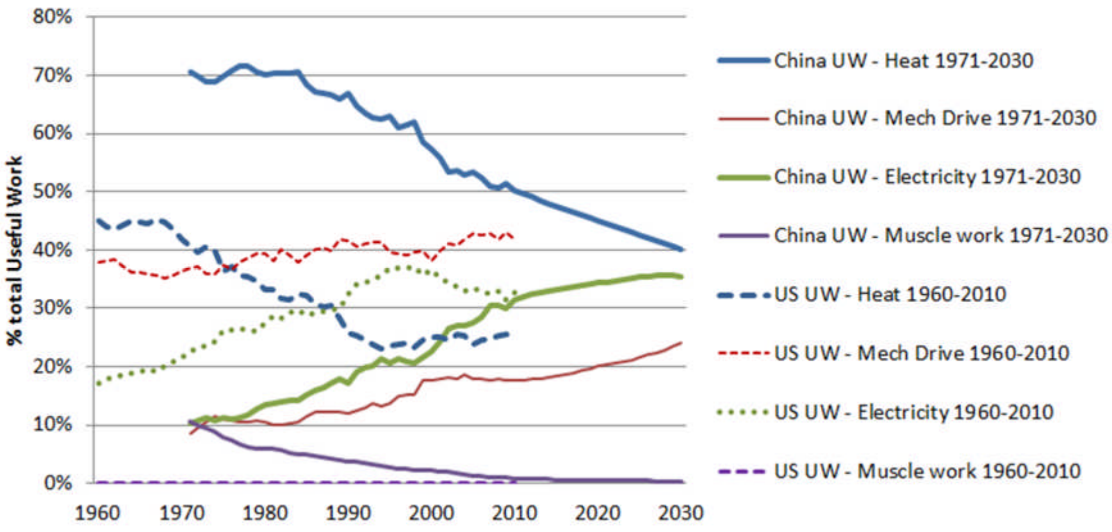

Figure 3-3: China (1971-2030) & US (1960-2010) useful work allocations

Third, task-level exergy efficiencies are projected to 2030 under two illustrative scenarios which have different efficiency gains assumptions. In Scenario 1 (constant efficiency gains), China's 1990-2010 task-level exergy efficiency changes are extended to 2010-2030. Typically this places China's task-level efficiencies in 2030 as those of average US-UK values in 2010. In Scenario 2 (declining efficiency gains), only half of China's 1990-2010 efficiency gains are extended to 2010-2030, with two thirds of these reduced gains assumed to occur in 2010-2020. There is some justification for the declining gains scenario, as Brockway et al (2014) found that efficiency gains in important task-levels (e.g. residential electricity and LTH) slowed or reversed in 1990-2010 (versus 1970-1990). Assuming an average 20 year lag for China, this could mean similar effects exhibited in China by 2030. More detailed efficiency results at task-level are given in Appendix B. Whilst other efficiency scenarios are possible (and indeed probable), our two selected cases are intended to represent the possible envelope of task-level efficiencies for 2010-2030, and are thus valid to study the effects of declining efficiency gains.

Fourth, estimates of total primary energy demand for 2010-2030 are made at task-level (equation 3-11) and aggregate level (equation 3-12). Suffix 1 and 2 refer to Scenario 1 and 2. Finally, the chemical exergy conversion ratios (Szargut et al., 1988) are removed to reveal primary energy (i.e. TPES) projections to 2030 under these two scenarios, with differences suggesting impacts of declining exergy efficiency gains on primary energy demand.

$$E_{1ij} = \frac{U_{ij}}{\varepsilon_{1ij}} \; ; \quad E_{2ij} = \frac{U_{ij}}{\varepsilon_{2ij}} \qquad \textbf{(3-11)}$$

$$E_1 = \Sigma E_{1ij}; \qquad E_2 = \Sigma E_{2ij} \qquad \textbf{(3-12)}$$

3.4 Results and Discussion

3.4.1 1971-2010 useful work accounting results

Table 3-1 summarises useful work, primary exergy and exergy efficiency results for 1971-2010, with task-level results given in Appendix B for 1971 and 2010. China's end useful work has increased 10 fold since 1971, with electricity applications and HTH industrial uses growing from 30% to 53% of total useful work. Conversely, muscle work and low temperature heat have together declined from 40% of total useful work to 8%.

Table 3-1: Useful work analysis results 1971-2010

Useful work analysis: output category		1971		1980		1990		2000		2010	
Useful work	**Main category end use**	**PJ**	**% of total**	**PJ**	**% of total**	**PJ**	**% of total**	**PJ**	**% of total**	**PJ**	**% of total**
	Direct heat	1,087	71%	1,848	71%	2,787	68%	3,901	59%	7,602	51%
	Mechanical Drive	126	8%	268	10%	477	12%	1,140	17%	2,633	18%
	Electricity end uses	154	10%	343	13%	684	17%	1,460	22%	4,665	31%
	Muscle work	157	10%	151	6%	148	4%	137	2%	127	1%
	Total	**1,524**	**100%**	**2,610**	**100%**	**4,096**	**100%**	**6,638**	**100%**	**15,027**	**100%**
Primary Exergy	**Main category end use**	**PJ**	**% of total**	**PJ**	**% of total**	**PJ**	**% of total**	**PJ**	**% of total**	**PJ**	**% of total**
	Direct heat	15,370	54%	21,560	56%	28,271	55%	31,504	49%	51,983	43%
	Mechanical Drive	1,090	4%	1,971	5%	2,988	6%	5,625	9%	12,720	11%
	Electricity end uses	1,592	6%	3,519	9%	6,283	12%	13,951	22%	42,507	35%
	Muscle work	10,661	37%	11,760	30%	13,489	26%	13,398	21%	13,159	11%
	Total	**28,713**	**100%**	**38,810**	**100%**	**51,032**	**100%**	**64,478**	**100%**	**120,369**	**100%**
Exergy efficiency (useful work / primary exergy)	**Main category end use**	**% efficiency**		**% efficiency**		**% efficiency**		**% efficiency**		**% efficiency**	
	Direct heat	7.1%		8.6%		9.9%		12.4%		14.6%	
	Mechanical Drive	11.6%		13.6%		16.0%		20.3%		20.7%	
	Electricity end uses	9.7%		9.7%		10.9%		10.5%		11.0%	
	Muscle work	1.5%		1.3%		1.1%		1.0%		1.0%	
	Total	**5.3%**		**6.7%**		**8.0%**		**10.3%**		**12.5%**	

Aggregate exergy efficiency has grown almost linearly from 5.3% to 12.6%.Table 3-1 (together with Appendix B) suggests one factor is the structural shift from lower to higher efficiency classes, i.e. the decline in share of muscle work and low temperature heat (20°C) versus the rise in HTH. Figure 3-4 illustrates a second reason: the strong growth in mechanical drive and heat class efficiencies – which make up over half of total primary exergy inputs. The question of whether this linear aggregate efficiency trend can continue is considered via the future scenario analysis in Section 3.3.

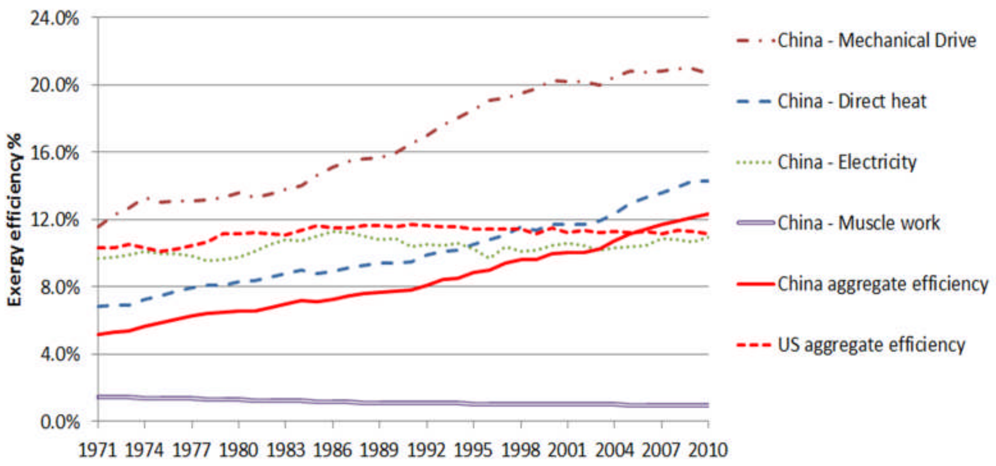

Figure 3-4: China's exergy efficiency by end use 1971-2010, compared to US aggregate efficiency

Figure 3-4 also compares China's aggregate efficiency growth to the stable US (10%-11%) values from the previous US-UK study (Brockway et al., 2014). China's exergy efficiency overtakes the US by around 2004. At first, it is tempting to see China's overtaking of the US's aggregate efficiency as 'technological leapfrogging' (e.g.(Goldemberg, 1998)) – i.e. rapidly adopting high-efficiency technologies without having to deal with the legacy of past low efficiency capital stock. In fact this is not the case, since task-level exergy efficiencies are generally lower than the US (except mechanical drive, which is a small component of China's energy use). This result implies structural differences make a significant contribution to China's increasing efficiency: i.e. its production-focused industrial economy uses more high temperature heat and industrial processes versus the US's mature consumer economy. The index decomposition results in Section 3.2 support this view. In turn, this implies as China's economy also matures and its structure shifts towards that of the US, that this may have a diluting effect on future overall exergy efficiency, as seen later in Section 3.3.

Few comparative studies are available of other estimates of aggregate Chinese efficiencies. Chen et al (2006) calculate a value of 20%, twice that of our 10% value for China in 2000. The main reasons are due their exclusion of muscle work, and higher industry efficiency (e.g. 78% for the chemical sector).

Nakicenovic et al (1996) estimated reforming countries (e.g. China) exergy efficiencies in 1990 to be ~10%, of a similar order to our 8% estimate for 1990.

Figure 3-5 shows how China's 10-fold useful work growth was supplied by a 4-fold increase in primary energy coupled to a 2.5-fold gain in aggregate exergy efficiency: from 5% to 12%. In other words, if China's exergy efficiency had stayed at 5%, a 10-fold gain in primary exergy would have been required to achieve the same useful work supply level.

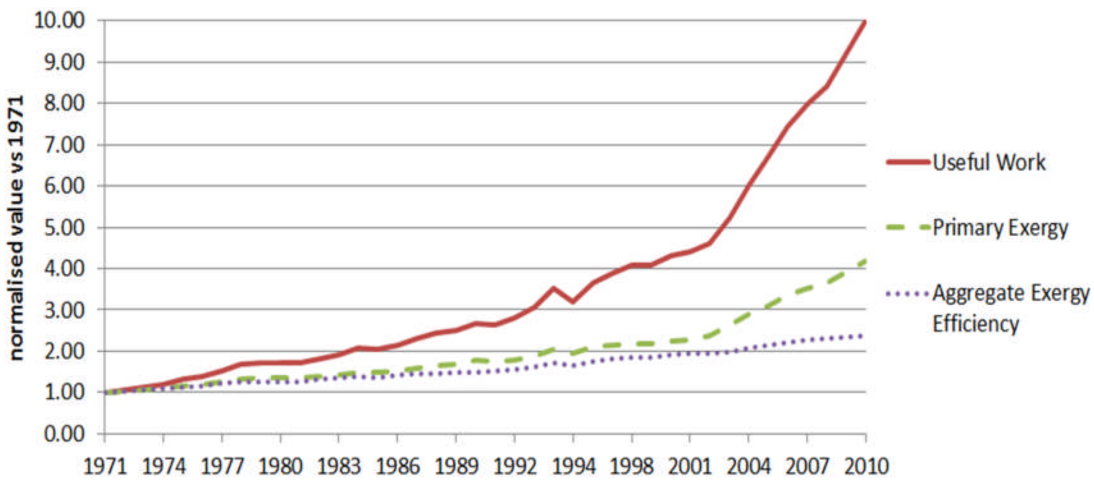

Figure 3-5: China 1971-2010 useful work analysis results vs 1971 datum

Finally, to understand the overall flow of exergy to end useful work, and the exergy losses that occur during the various conversion processes, useful work-based Sankey diagrams of China are constructed for 1971 and 2010, as shown in Appendix B. They show the transformation of China in 40 years from a largely agricultural to industrial economy. By 2010, China is dominated by energy dense fossil fuel inputs (versus food and feed for muscle work) and energy intensive end uses, particularly in industry, which underpins the rise in overall exergy efficiency.

3.4.2 LMDI decomposition results 1971-2010

The multiplicative factors are summarised in Table 3-2 for the period 1971-2010, comparing three countries: China, the UK and US. For China, the largest contribution to useful work growth is primary exergy, confirming the result of Figure 3-5. Importantly, the overall efficiency gain factor (2.5) is now split into three parts. First, the main class structural change (1.39) tracks the move from less efficient (i.e. muscle work) to more efficient (i.e. heat) main classes. Second, we find sub-class structural change (1.19) is above 1.00, which means that within each main class there has also been an efficiency ‘concentration’ effect. This is due to China’s transition from agricultural society to industrial powerhouse, causing structural shifts within main classes from lower to higher efficiency categories (e.g. LTH to HTH). Third, task-level efficiency gains (1.48) are the largest of the three efficiency gain factors.

Table 3-2: LMDI decomposition factors 1971-2010 for China-US-UK

Country	U Useful work	Dex Primary Exergy	Dstr Main class structural change	Ddil Sub-class structural change	Deff Task-level efficiency
China	9.76	3.96	1.39	1.19	1.48
US	1.53	1.32	1.03	0.88	1.29
UK	1.43	1.01	1.04	0.87	1.58

Country	U Useful work	Dex Primary Exergy	Dstr*Ddil Overall structural change	Deff Task-level efficiency
China	9.76	3.96	1.66	1.48
US	1.53	1.32	0.90	1.29
UK	1.43	1.01	0.90	1.58

The value of using the LMDI approach is also highlighted by Table 3-2. Firstly, it confirms and quantifies the assertion stated in Section 3.2: that overall structural change (1.66) is at least as important to overall efficiency gains as task-level efficiency gains (1.48). Secondly, we can directly compare factors to other countries. In this case, we see that China has not reached the point of efficiency ‘dilution’ that can be seen in the US and UK – where D_{dil} would be below 1.00 – as found earlier by Williams et al (2008) for Japan. China’s improvements to task-level efficiencies (1.48) are similar to US (1.29) and UK (1.58) values, confirming that instead of technological leapfrogging, it is overall structural change (1.66 for China versus 0.90 for US and UK) that has been responsible for China’s rise in overall aggregate efficiency to overtake the US.

3.4.3 Future exergy efficiency: impacts on primary energy projections

3.4.3.1 Step 1 – Useful work projection to 2030

China’s useful work and primary energy intensities (of economic activity) are shown in Figure 3-6, based on constant price GDP. It shows a 66% reduction in useful work intensity from 12.0 (GJ/2005$US) in 1971 to 3.9 (GJ/2005$US) in

2010, compared to an 86% reduction in primary energy intensity (210.7 to 29.8 GJ/2005$US) – the standard metric for energy intensity (e.g. (Liddle, 2010)) – over the same period. The greater stability of useful work intensity suggests useful work is more closely linked to GDP than primary energy – supporting the key assumption noted earlier. Useful work and primary energy intensities are projected to 2030 using best-fitting trendlines also shown in Figure 3-6.

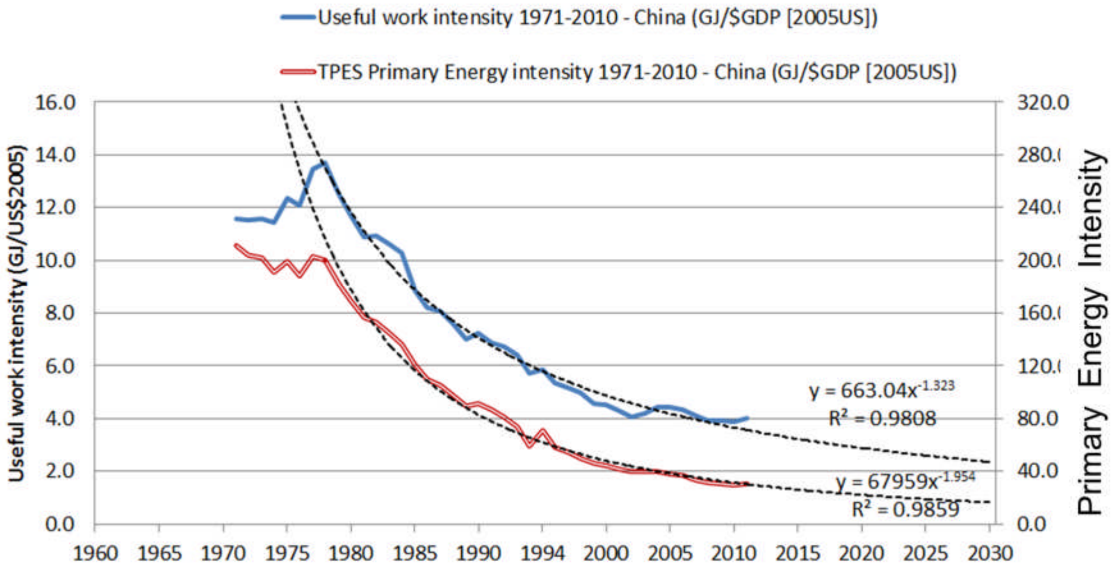

Figure 3-6: Comparison of China primary energy and useful work intensities

The World Bank's GDP forecast for China in 2030 (World Bank & The Development Research Center of State Council the People's Republic of China, 2012) is $13.5Trillion(US2005), a 3.5-fold increase from the $3.8Trillion(US2005) value in 2010. Using the useful work intensity projection of 2.45 (GJ/US$2005) for 2030, this gives a useful work estimate of 33.1EJ in 2030 (just over double the 15.0EJ consumed in 2010) – to deliver that level of GDP.

3.4.3.2 Step 2 – Allocation of task-level useful work

Figure 3-7 shows the projected annual useful work growth to 2030 is almost linearly ~ 27-28Mtoe/year. This is due to two effects cancelling each other out: a slowdown in GDP growth mirroring useful work intensity reductions. At a main class level, as China's economy matures, a slowdown in heat's contribution to useful work is offset by growth in electricity and mechanical drive (mainly transport) classes. This appears broadly consistent with other economic forecasts for China used in energy modelling (e.g. (International Energy Agency (IEA), 2013b)).

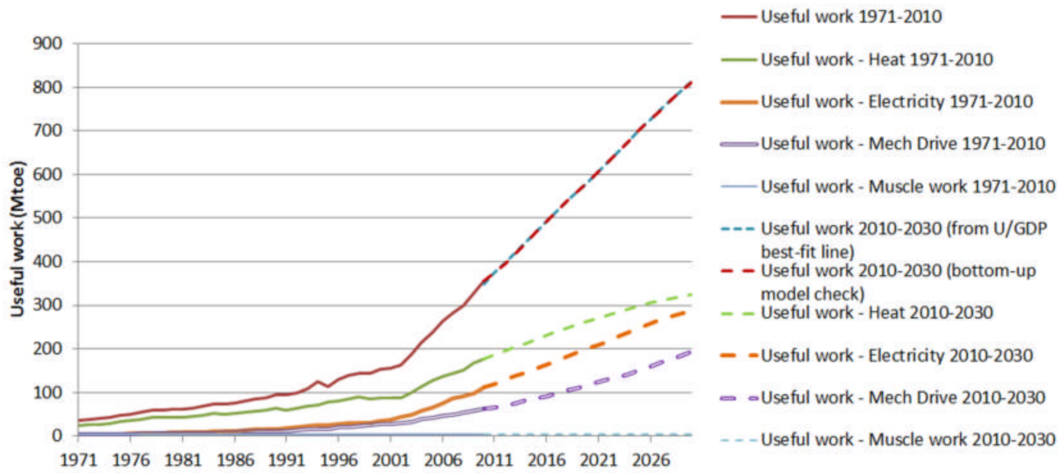

Figure 3-7: China – useful work projection to 2030

3.4.3.3 Step 3 – Task-level exergy efficiencies

Next, task-level exergy efficiencies are projected based on the linear and declining gains scenarios described earlier – see Appendix B. The results at main class level are shown in Figure 3-8. In Scenario 1, stable gains in task-level exergy efficiencies are combined with structural change in China in 2011-2030 – moving towards a more service sector-based economy, with associated decreases in higher efficiency processes (e.g. high temperature heat) and increases in low-efficiency activities (e.g. residential and commercial electricity), as shown earlier in Figure 3-3. This results in only a small increase in national aggregate exergy efficiency to 13% in 2030. The green wedge in Figure 3-8 illustrates the effect of this structural change, compared to a simple extrapolation of China's 1990-2010 aggregate efficiency, which would result in aggregate exergy efficiency of around 17% in 2030. In Scenario 2, which includes both structural change and slowing of task-level efficiency gains, aggregate exergy efficiency peaks at 12.8% before 2025, then reduces to 12.5% by 2030. Therefore most of the reduction in overall efficiency is due to assumed structural change than the difference in task-level efficiencies under the two scenarios.

For heat and mechanical drive classes, the projected efficiency dilution is so strong (i.e. less industrial usage and more consumer / commercial use), their efficiencies decline by 2030 under both efficiency scenarios. As electricity provides an increasing share of useful work by 2030, this accelerates the slowdown (scenario 1) and decline (scenario 2) in overall exergy efficiency. Mechanical drive efficiency stagnates in this analysis under both scenarios, since it had task-level efficiencies that were increasing (e.g. static motors and aviation) and decreasing (e.g. road transport – due to more cars / less motorcycles, and more heavy duty-trucks). However, as the smallest of the three main classes, this effect has limited impact on the aggregate exergy efficiency.

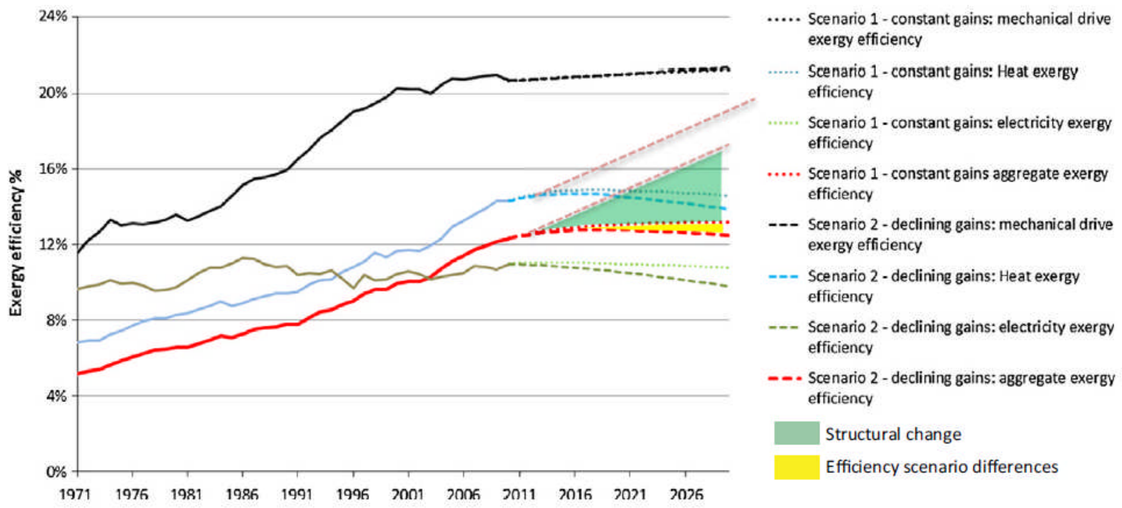

Figure 3-8: China – exergy efficiency scenario results

3.4.3.4 Step 4 –Primary end demand in 2030

Finally, the useful work-based primary energy estimates are calculated based on the assumed efficiency scenarios. The results are compared in Figure 3-9 to five published reference (i.e. current policies) scenarios (International Energy Agency (IEA), 2013c; US Energy Information Administration (USEIA), 2014; British Petroleum (BP) Ltd, 2014; IIASA, 2014; Fridley et al., 2012) and a top-down primary energy intensity (TPES/GDP) based estimate (derived econometrically via the best-fit TPES/GDP projection shown earlier in Figure 3-6). By 2030, our Scenario 1 (6,000Mtoe/year) requires 900Mtoe/year more primary energy than the econometric estimate, whilst Scenario 2 – due to assumed declining efficiency gains – requires an additional 300Mtoe/year (compared to Scenario 1). The TPES/GDP derived primary energy estimate (as with the other five reference projections) slows over time, following the assumed slow-down in GDP growth. In contrast, our useful work derived projections show more linear increases, as with flat overall exergy efficiencies (shown earlier in

Figure 3-8), the linear projected growth in useful work required (see earlier Figure 3-7) is passed on to required primary energy inputs.

Our useful work-based projections are significantly higher than the five reference cases. The three reference scenarios using a 2010 base year (US Energy Information Administration (USEIA), 2014; International Energy Agency (IEA), 2013c; British Petroleum (BP) Ltd, 2014) produce estimates of 4,300-5,000Mtoe/year in 2030, whilst the two scenarios with a 2005 base year (IIASA, 2014; Fridley et al., 2012) estimate primary energy consumption as 3,200Mtoe in 2030. A key aspect therefore appears the choice of base year, with the 2005 base year models missing China's step up in energy consumption, and so undercut the projections of later base year models. Perhaps this illustrates how tricky energy forecasting is, as Smil notes: "long-range energy forecasters have missed every important shift of the past 2 generations..[and they]..will continue to be wrong" (2000, p262).

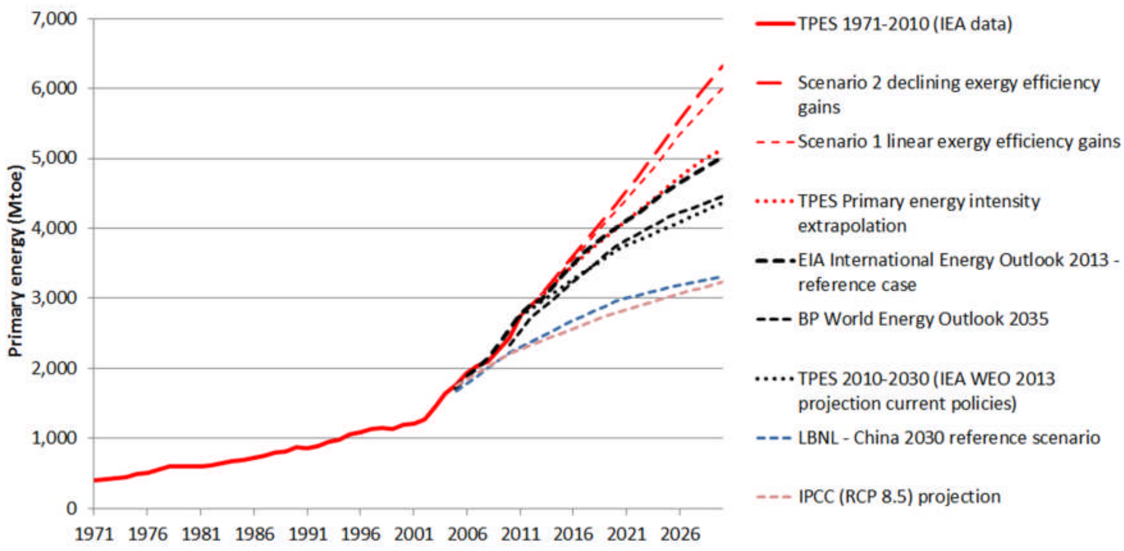

Figure 3-9: China – Primary energy (TPES) forecasts to 2030

Nevertheless, the fact remains the traditional energy models give lower estimates of primary energy than our simple useful work-based approach – so it's worth reflecting on this. Most importantly, we base our projections on a different energy intensity metric versus mainstream models – ours is based on useful work (U/GDP), as this measures the energy level delivered to economic activities, rather than on primary energy (E_{prim}/GDP) entering the economy. Moreover, our E_{prim}/GDP based projection is 20% below our U/GDP based projections – showing that this distinction is an important one. The GDP projections that we use are consistent with other models (e.g. (International Energy Agency (IEA), 2013b)). Our methodology is also top-down: it starts from an aggregate demand estimation, and then builds up its constituent elements from task-share trends. Other energy models tend to be bottom-up, using demand and technology trends of various sectors. We attach more detailed scenario data in the Appendix B.

Whilst we believe the useful work based approach to primary energy forecasting is justified by the observed links between aggregate economic activity and useful work, significant caveats around the accuracy of the underlying data to our energy projection conclusions. For the useful work calculations for 1971-2010, though the primary exergy data is relatively robust (relying mainly on IEA energy balance data), the task-level efficiencies have greater uncertainty, being based on often partial data. In turn, projecting task-level useful work allocations and exergy efficiencies to 2030 amplifies any data inaccuracies. However the driving rationale of the paper was to develop a new technique based on useful work. The result highlights the possible importance of this method and thus mandate for further study.

3.5 Conclusions

To address the lack of time-series exergy analyses for China which examine energy demand drivers and implications, we set the following research question: *What new insights can useful work analysis provide for historical and future energy demand in China?* First, our historical analysis found China's exergy efficiency grew linearly from 5.3% (1971) to an impressive 12.5% (2010), placing it between the US (11%) and the UK (15%). In addition, a striking 10-fold rise in China's useful work occurred from 1971 to 2010, supplied by a 4-fold increase in primary exergy and a 2.5 fold increase in exergy efficiency. Second, using LMDI decomposition we found efficiency growth was split evenly between task-level efficiency gains and structural change (e.g. moving from muscle work to mechanical drive). Third, a new useful work-based energy forecasting technique is developed and trialled, which – based on two illustrative exergy efficiency scenarios – projects China's 2030 primary energy demand in the range of 6,000-

6,300Mtoe, significantly higher than the 4,500-5,200Mtoe estimates from published sources using traditional energy models which use the same 2010 baseline year.

The results allow several key insights. Firstly, if China's exergy efficiency had stayed at 5%, a 10-fold (rather than 4-fold) gain in primary exergy would have been required to achieve the same useful work supply level. Through the mechanism of the macro-economic rebound effect, however, as Ayres et al (2007) and Schipper and Grubb (2000) established, lower efficiency gains may in fact translate to lower economic growth, and hence lower required useful work. Second, the application of LMDI decomposition to useful work results provided robust insights: revealing China's efficiency rise above the US was not due to technological leapfrogging, but greater use of energy intensive (yet more exergy efficient) industrial processes. Third, in common with the US and UK, China may approach an asymptotic exergy efficiency maximum by 2030, as its economy matures and efficiency dilution starts. Such dilution is already forecast: the modal shift to cars (Fridley et al., 2012) will reduce mechanical drive exergy efficiency; a rapid increase in residential electricity (Letschert et al., 2010); and a peaking in the share of HTH allied to a shift to greater residential LTH. Fourth, our extension of useful work based technique projects higher primary energy demand in China by 2030 versus traditional bottom-up energy model estimates (i.e. based on primary or final energy). Further studies investigating the possible reasons (e.g. differences in assumed future energy efficiency savings, structural consumption, energy rebound and efficiency dilution) would therefore be beneficial.

Overall, the useful work method appears a valuable technique to give new insights into Chinese energy consumption and efficiency – past, present and future. Given the implications to future energy demand and associated policies, further research is encouraged. First, work to improve the consistency of the useful work method would be of benefit – such as the treatment of renewables, non-energy use, active/passive system efficiencies, or extending the analysis boundary to include energy services, as others suggest (Ma et al., 2012; Nakicenovic et al., 1996; Ayres, 1998). Second, contrast the construction of traditional (primary and final energy) versus useful work energy models, to uncover the reasons for energy projection differences. Third, undertake further economic analysis to test the key assumption underpinning this work: that useful work is a more suitable parameter for energy and economic analysis than primary energy. Lastly, policy implications could be explored – such as how to meet higher (than expected) primary energy demand, or how to amend micro-efficiency policies to capture energy savings before rebound occurs.

3.6 Acknowledgments

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Chapter 4

Energy-augmented nested CES aggregate production functions: aspects of their econometric estimation

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Highlights

- Energy-augmented nested CES aggregate production functions have become popular
- They play a key role in macroeconomic models which inform energy-emissions policy
- Thus we summarise and discuss key current aspects of their empirical estimation
- Function specification and estimation methods significantly impact results
- Strengthened statistical reporting will improve robustness of estimated parameters

4.1 Abstract

Constant Elasticity of Substitution (CES) aggregate production functions are overtaking the Cobb-Douglas (C-D) function in usage, and play an increasingly key role in macroeconomic models. The two conventional factors of production in these functions – capital and labour – are being augmented by energy, allowing macroeconomic models to inform not just economic but also energy and environmental policies. This in turn places a due weight of responsibility on the empirical studies which estimate the unknown CES function parameters, since

their outputs then become inputs to the macroeconomic models. However, undertaking empirical CES studies are far from straightforward: the flexibility offered by the CES function comes with a broad set of aspects to be considered in their specification and parameter estimation.

And herein lies the issue: given the prominent use of energy-augmented CES aggregate production functions in important macroeconomic models, a coherent collation of key current aspects relating to their empirical estimation is required. We find the diverse choices regarding functional form and solution methods have a significant impact on parameter estimation values. In addition, the use of statistical methods and reporting of parameter precision is a weak area of current studies, which by strengthening will improve robustness of the estimated parameters. This paper serves as a timely navigational aide to those either undertaking empirical energy-augmented CES studies or using their results in energy-economy models.

Keywords: production function; econometrics, estimation, macroeconomics, CES, elasticity of substitution; energy

JEL Classification Code (suggested): C10; C51; D24; E23; O47; Q43

4.2 Introduction

4.2.1 The growing use of CES aggregate production functions

Production functions seek to explain economic output arising from input factors of production, and are central to growth accounting (i.e. the study of the components of economic growth) and macroeconomic modelling. For our purposes, we define aggregate production functions as those applied at sector (Dissou et al., 2012; Smyth et al., 2011) or economy-wide (Solow, 1957; Nelson, 1964; Kander & Stern, 2014) levels.

The two most common aggregate production functions are the Cobb-Douglas (C-D) and Constant Elasticity of Substitution (CES) functions (Duffy & Papageorgiou, 2000; Felipe & Adams, 2005), as illustrated by Figure 4-1. Their central role in macroeconomic models mean they are “an important instrument in [Government] economic forecasts and policy” (Miller, 2008, p.1).

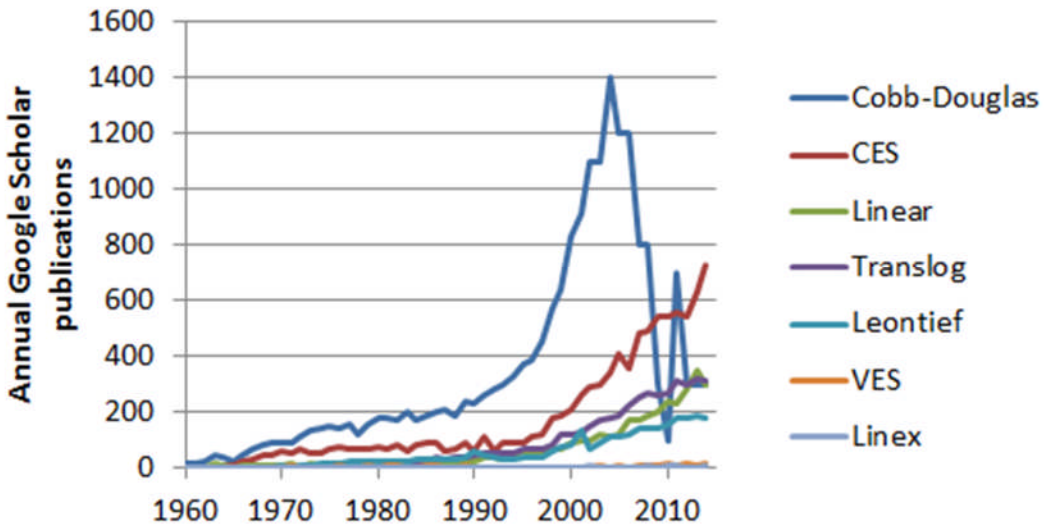

Figure 4-1: Google-Scholar search[15] of publications that reference each production function

The C-D function in its famous 1928 Cobb and Douglas formulation[16] (Cobb & Douglas, 1928) is given in equation 4-1, which according to conventional economic theory ascribes economic output (Y_t) to two primary factors – capital (K_t) and labour (L_t):

$$Y_t = \theta A K_t^{\propto} L_t^{\beta} \qquad A \equiv e^{\lambda t} \tag{4-1}$$

where α and β are the elasticities of output (Y_t) with respect to capital and labour respectively (noting also typically $\alpha + \beta = 1$ to meet constant returns-to-scale assumption), θ is a scale parameter, A is Total Factor Productivity (TFP) – the exogenous share of output not explained by the endogenous factors of production, and t is time relative to an initial year. λ is the Solow residual, equal to the rate of change in TFP, defined by equation 4-2, where $\dot{A}$, $\dot{Y}$, $\dot{K}$, $\dot{L}$ are time derivatives of A, Y, K, L respectively.

15 Google Scholar search (excluding citations) on 5 March 2015 for 7 common types of production function: “CES production function”; “Cobb-Douglas Production function”; “Linear production function”; “Translog production function”; “Leontief production function”; “VES production function”; “LINEX production function”.

16 Whilst the function is named after Cobb and Douglas, Lloyd (Lloyd, 2001) suggests the C-D origins can be traced earlier to von Thünen in the 1840s and Wicksell c. 1900.

$$\lambda = \frac{\dot{A}}{A} = \frac{\dot{Y}}{Y} - \propto \frac{\dot{K}}{K} - \beta \frac{\dot{L}}{L} \quad \textbf{(4-2)}$$

An important parameter in growth accounting is the elasticity of substitution (σ), a measure of the ease by which one production factor (e.g. labour) may be substituted by another (e.g. capital). For aggregate production functions, it is most commonly measured by the Hicks Elasticity of Substitution (HES)[17], as given in equation 4-3, where π_i is the marginal productivity $(\partial Y/\partial X_i)$ of input X_i and π_j is the marginal productivity $(\partial Y/\partial X_j)$ of input X_j. The HES is thus a measure of the curvature of the production function isoquant.

$$HES_{ij} = -\frac{\partial ln\,(X_i/X_j)}{\partial ln\,(\pi_i/\pi_j)} \quad \textbf{(4-3)}$$

In a C-D function, the elasticity of substitution has a fixed unity value. This significant constraint is overcome by the CES function, introduced in 1956 by Solow (1956), but most famously associated with Arrow et al (1961). The CES function in equation 4-4 has δ as a share parameter, ρ as a substitution parameter (leading to the HES, $\sigma = 1/(1+\rho)$), ν as a returns-to-scale parameter, θ as a scale parameter, A as TFP. The CES is therefore more flexible than the C-D function, with several special cases depending on the value of σ as noted by Arrow et al (1961): Leontief ($\sigma = 0$); C-D ($\sigma = 1$) and Linear ($\sigma = \infty$) functions.

$$Y_t = \theta\, A\left[\delta K_t^{-\rho} + (1-\delta)\, L_t^{-\rho}\right]^{-\frac{\nu}{\rho}}; \qquad A \equiv e^{\lambda t} \quad \textbf{(4-4)}$$

In an empirical study, historical time-series data (of the factors of production and economic output) is added to the functional form (e.g. equation 4-4) to form an analytical model: whose econometric solution estimates values for the unknown CES function parameters. Solow's 1957 US study (Solow, 1957) using the C-D function was the first time-series empirical study of its kind and "a landmark in the development of growth accounting" (Crafts, 2008, p.1), and was followed by others including Arrow et al (1961) and Denison (1962). Whilst many studies follow this neo-classical C-D approach (Desai, 1985; Nelson, 1964; Chow & Li, 2002), many researchers – famously including Solow (Solow, 1957) - found that

17 Other elasticity of substitution definitions are also in use, particularly for cost functions, such as the Allen Elasticity of Substitution (AES), Cross-price elasticity (CPE), Morishima Elasticity of Substitution (MES). A broader discussion is given in Sorrell (2014).

increases in capital and labour factors of production commonly explained only a minority of output growth, with the remainder ascribed to exogenous TFP. As a result, a focus on TFP and the Solow residual has remained a priority for researchers, including Jorgenson (1967), Denison (1979) and Hulten (2001).

4.2.2 Adding energy as a factor of production

Neo-classical capital-labour aggregate production functions ignore the possible role of energy as a factor of production, since it is viewed as an intermediate product (of capital and labour), rather than a primary input. The 1970s oil crises focussed attention on the role of energy in economic growth, and thus provided an opportunity for researchers to add energy (E) as an input (Rasch & Tatom, 1977; Renshaw, 1981; Berndt & Wood, 1975), typically amending the C-D function in equation 4-1 to that shown in equation 4-5:

$$Y_t = \theta A K_t^{\alpha} L_t^{\beta} E_t^{\gamma} \qquad\qquad A \equiv e^{\lambda t} \qquad \textbf{(4-5)}$$

where γ is the elasticity of output with respect to energy, and $\alpha + \beta + \gamma = 1$ to meet constant returns to scale assumption.

More recently, adding energy as a factor of production in aggregate production functions has regained popularity (van der Werf, 2008). One possible reason is practicality, in that "increasing attention on the energy and environmental issues has evoked a revival of the relevant macroeconomic modelling" (Zha & Zhou, 2014, p.793) - in other words, the effects of energy in an energy economic model cannot be studied unless it is included as a variable. Another possible reason is the growing evidence base that energy is tightly linked to economic growth (Stern, 1993; Bruns et al., 2014; Kalimeris et al., 2014), providing a mandate for its inclusion.

Energy (E) can be placed inside a nested CES function by augmenting equation 4-4 as shown in equation 1-11, with capital and labour in an inner (K-L) nest, and energy in an outer (KL_E) nest, giving equation 4-6:

$$Y_t = \theta\, A[\delta_1[(\delta\, K_t^{-\rho_1} + (1-\delta)L_t^{-\rho_1}]^{\rho/\rho_1} + (1-\delta_1)E_t^{-\rho}]^{-\frac{\nu}{\rho}} \;\; ; \;\; A \equiv e^{\lambda t} \qquad \textbf{(4-6)}$$

where ρ and ρ_1 are substitution parameters which lead to σ_1 within the inner (K-L) nest and an outer nest σ between the inner (K-L) composite and energy (E).

4.2.3 Aim and scope of paper

Three propositions provide the rationale for our paper. First, energy-augmented nested CES aggregate production functions are important to macro-economic models which inform climate and economic policy. Second, as a result, empirical studies which estimate the CES parameters are also important, and aspects of their econometric specification and estimation deserve close examination. Third, though single aspect literature of CES production function theory and empirical usage (Saunders, 2008; Henningsen & Henningsen, 2011; Klump & Preissler, 2000; Shen & Whalley, 2013; Kander & Stern, 2014; Zha & Zhou, 2014; Temple, 2012) exists, what is required for the practitioner is a succinct collation of the most important issues and options, to help avoid analytical blindspots which may have significant impacts on the estimated parameters.

Therefore, this paper addresses the following question: "*what are the important aspects to consider in the empirical estimation of energy-augmented CES aggregate production functions?*" The paper starts with a broader review the applications of C-D and CES aggregate production function studies in Section 4.2. This provides the context for the narrowing of focus in Section 4.3 to consider the specification of the empirical CES model: comprising the design of the function form and the input time-series datasets. Next, parameter estimation techniques are examined in Section 4.4, before conclusions are given in Section 4.5.

Finally, a note on our study boundary. First, our aggregate production function focus is predominantly at the economy-wide scale, though many aspects considered are also suitable for sectoral-level functions. Second, we exclude further discussion on 1. Less popular aggregate production functions (i.e. translog (Pavelescu, 2011), variable elasticity of substitution (VES) (Fare & Yoon, 1981), linear exponential (LINEX) (Warr & Ayres, 2012), linear (Thurston & Libby, 2002) and Leontief (Li & Rosenman, 2001) functions); 2. computational general equilibrium (CGE) based studies (Punt et al., 2003; Sajadifar et al., 2010) - since these only use - not estimate - CES parameters; and 3. cost functions - which are a popular price-based alternative to production functions (Bentzen, 2004; Saunders, 2013; Pavelescu, 2011; Adetutu, 2014).

4.3 Applications of C-D and CES aggregate production functions

To provide context for later sections, we briefly review the various applications of C-D and CES aggregate production functions. We start with a sample survey, and then move a wider literature search.

4.3.1 Sample survey

We studied a small sample of Figure 4-1's Google-Scholar results, seeking to identify similarities and differences in applications. Whilst Google-Scholar returned results for all production function types (i.e. firm level to sectoral to economy-wide scales), it nevertheless provides a guide as to the context and application of production function studies. We reviewed 46 studies (Feldstein, 1967; Fisk, 1966; Nelson, 1964; Rasch & Tatom, 1977; Hayami & Ruttan, 1970; Prais, 1975; Ulveling & Fletcher, 1970; Desai, 1985; Uri, 1984; Renshaw, 1981; Khan & Ahmad, 1985; Mankiw et al., 1990; Finn, 1995; Dougherty & Jorgenson, 1996; Kalirajan et al., 1996; Hall & Jones, 1999; Garcia-Milà & McGuire, 1992; Kalaitzidakis & Korniotiis, 2000; Chow & Li, 2002; Caselli, 2005; Vouvaki & Xepapadeas, 2008; Autor et al., 2006; Martin & Mitra, 2001; Fernald & Neiman, 2010; Long & Franklin, 2010; Hájková & Hurník, 2007; Yuan et al., 2009; The Conference Board, 2012; Daude, 2014; Kotowitz, 1968; Zarembka, 1970; O'Donnell & Swales, 1979; Desai & Martin, 1983; Rusek, 1989; Easterly & Fischer, 1995; Kemfert, 1998; Gohin & Hertel, 2001; Bonga-Bonga, 2009; Duffy & Papageorgiou, 2000; Szeto, 2001; Kemfert & Welsch, 2000; van der Werf, 2008; Cantore et al., 2014; Dissou et al., 2012; Koesler & Schymura, 2012; Wang, 2012), with the 29 C-D and 17 CES studies, in proportion with their prevalence in the total returned results. To make the best of the tiny, biased sample (0.1% of 40,000 Google-Scholar references obtained for Figure 4-1), we selected studies based first on highest returned relevance[18], second by filtering studies to only include empirical studies at an aggregate (sector or economy-

[18] According to the Google Scholar website, the 'relevance ranking' takes into account the full text of each source as well as the source's author, the publication in which the source appeared and how often it has been cited in scholarly literature.

wide) scale, and third selecting C-D and CES studies in proportion with the number of CES and C-D studies in each decade found by Google-Scholar.

Figure 4-2 shows a histogram of the different purposes driving the C-D and CES sample studies. Their focus on economy-wide issues is reflective only that nearly all studies selected were at that scale. For C-D studies, the most common purpose was analysing historical changes in exogenous TFP, and studying new factors of production in addition to capital and labour. As the CES studies allow non-unity elasticities of substitution, and are weighted towards more recent studies, this helps explain their focus on elasticities of substitution and computational methods (e.g. use of new solution algorithm).

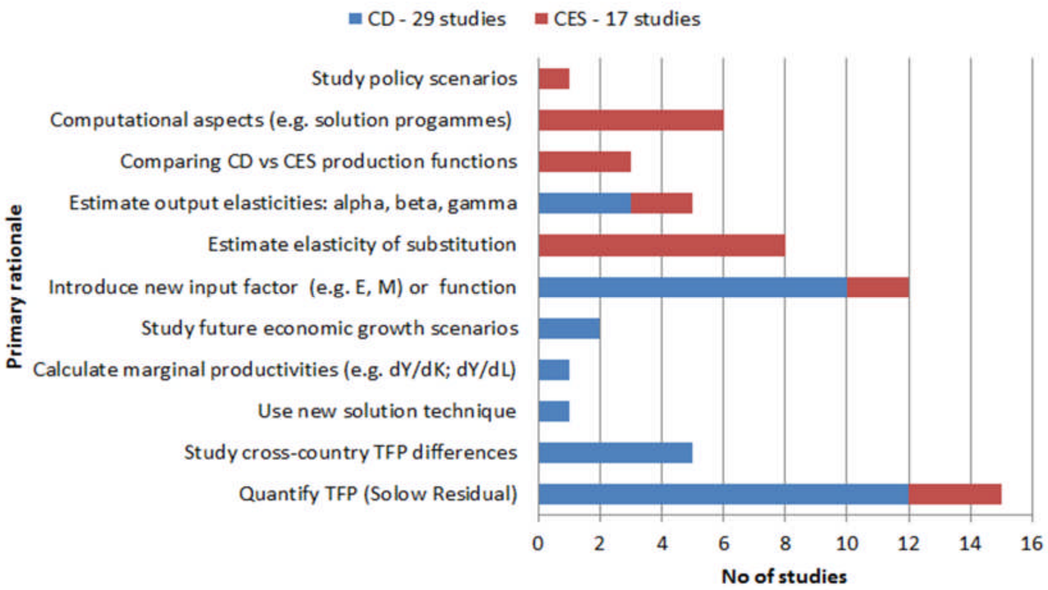

Figure 4-2: Primary study rationale in the sample

For output measure, since nearly all selected studies were the economy-wide scale, output was almost exclusively classified as GDP, with the key differentiator being whether it was GDP in constant prices (30No.) or GDP per worker (14No.).

Figure 4-3 shows the wide variation for choice of factors of production. For the conventional factors of production of capital and labour, capital stock and number of workers were the most common variable. Energy was the most popular additional factor of production, appearing first in the post oil-crises 1970s (Rasch & Tatom, 1977; Renshaw, 1981), and reappearing in our sample in the 1990s (Finn, 1995; Kemfert, 1998; Kemfert & Welsch, 2000; Dissou et al., 2012; van der Werf, 2008; Vouvaki & Xepapadeas, 2008).

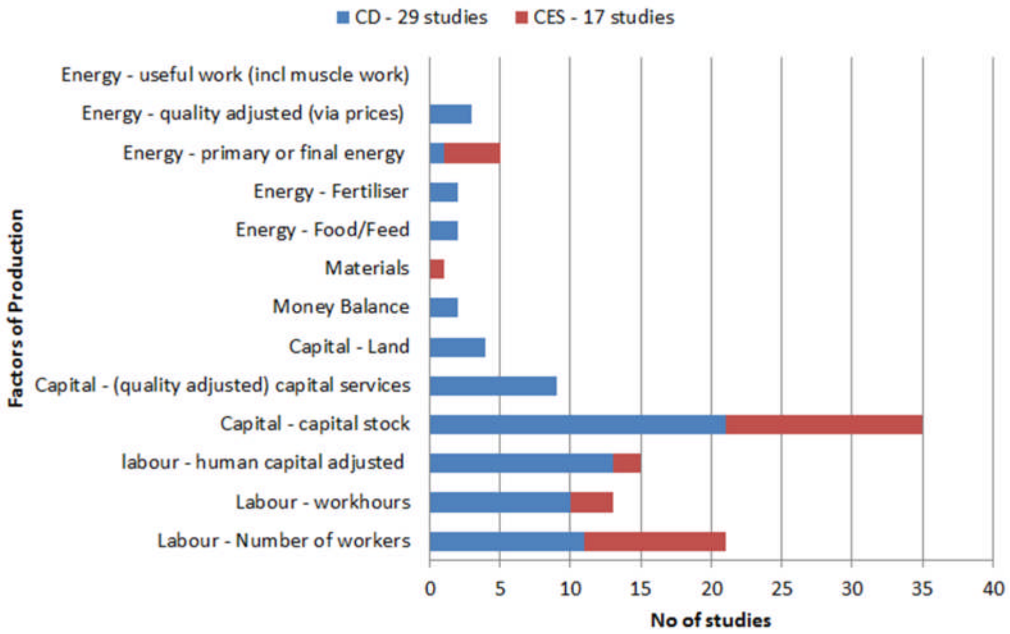

Figure 4-3: Factors of production in the sample

4.3.2 Wider literature search

Including energy as a factor of production starts from the idea that variables in addition to labour and capital - such as energy (Rasch & Tatom, 1977; Renshaw, 1981; Yuan et al., 2009), materials (Capalbo & Denny, 1986; Koesler & Schymura, 2012) or money balance (Prais, 1975; Khan & Ahmad, 1985) - help explain economic output. Binswanger and Ledergerber (1974) as far back as 1974 that “the decisive mistake of traditional economics... is the neglect of energy as a factor of production”. However, including energy as a factor of production remains controversial. One argument is that energy is not an independent, primary input, but instead as an intermediate quantity made by labour and capital is thereby redundant (see Dales’ Biophysical GEMBA model as an example reflecting this argument (Dale et al., 2012a; Dale et al., 2012b)). To counter, the same argument could be applied to capital (i.e. you cannot make capital without labour), and authors including Stern (2011) advocate energy as an independent factor of production. Some authors go further: Kümmel (1982) suggests energy is the only factor of production, with capital and labour therefore intermediate products (of energy). Denison (1979) suggests a second argument: that energy’s low ‘cost-share’ (typically below 10% of GDP (US Energy Information Administration (US EIA), 2011; Platchkov & Pollitt, 2011)) means it can only make a correspondingly small contribution to economic growth. However, authors including (Stresing et al., 2008) have sought to debunk this argument, whilst Aucott and Hall (2014) show how – despite its low ‘cost-share’ - small variations in energy prices have significant impacts on economic output.

Aggregate production functions themselves are not without criticism. Indeed Mishra suggests they are “the most turbulent area of research in the economics of production” (2010, p.20). Criticism occurs on three main fronts. First is the accounting identity critique (Shaikh, 1974; Felipe & Holz, 2001), which infers the C-D function can be derived from an income accounting identity: output equals wages plus profits. This is held to explain the excellent historical fits, with observed correlation coefficients (R^2) commonly above 0.99 (Desai, 1985; Chow & Li, 2002). Later, Felipe and McCombie (2001) extended the accounting identity argument to include the CES function. Second, are concerns about measuring capital: Robinson (1953) and Fisher (1969) were among a group involved in the 1950s-1970s ‘Cambridge-controversy’, who suggested aggregate capital could not be measured, thereby invalidating the use of aggregate production functions. Third are empirical concerns, since factors of production typically explain only a minority of economic growth, leading Solow to remark “it takes something more than the usual “willing suspension of disbelief” to talk seriously of the aggregate production function” (1957, p.312).

Despite ongoing critiques (Felipe & McCombie, 2010; Felipe & McCombie, 2014; Felipe & Fisher, 2003), the practical reality is that 1. “economists have continued using the aggregate production function in both theoretical and applied works” (Felipe & Holz, 2001, p.262), and 2. that energy is increasingly used as a factor of production by a wide set of studies beyond academia, with Government agencies (Miller, 2008; Ravel, 2011; Long & Franklin, 2010; Szeto, 2001) and Central Banks (Groth et al., 2004; Fernald & Neiman, 2010; Baier et al., 2002; Klump et al., 2011; Growiec, 2010) funding and publishing studies. Several reasons may explain this. First, is the ‘pull’ from energy-related questions including macro-economic energy rebound (Saunders, 2015; Wei, 2007), the contribution of energy to reducing TFP (Fröling, 2011), and climate and economic implications of energy transitions (Kander & Stern, 2014; Lu & Stern, 2014). Second, since the elasticity of substitution (σ) is an important parameter in economics (Chirinko, 2008; Palivos, 2008), significant effort in energy-augmented CES empirical analysis is directed to estimate values of σ (Kemfert & Welsch, 2000; Koesler & Schymura, 2012; Dissou et al., 2012; Shen & Whalley, 2013). Third, the comparison between CES and C-D functions is an important study focus – whether for cross country comparisons (Duffy & Papageorgiou, 2000), specific countries (Bonga-Bonga, 2009), sectors (Ravel, 2011) or business cycles (Cantore et al., 2014). Fourth, general equilibrium models are an important application of the empirical CES study results, as highlighted by van der Werf (van der Werf, 2008), and are widely used to assess the impact of policy (Turner, 2009; Bor & Huang, 2010). CGE models are the most popular, and are commonly CES-based (Bor & Huang, 2010; Henningsen & Henningsen, 2011; Sancho, 2009; Sajadifar et al., 2010) since this allows non-unity elasticity of substitution values, but may also include C-D modules (Annabi et al., 2006; Punt et al., 2003; C. Sanchez, 2004). Dynamic Stochastic General Equilibrium (DSGE) models are less common, but also use CES functions (Cantore et al., 2014; Klump & Saam, 2006).

Overall, energy-augmented CES aggregate production functions have emerged into widespread usage, serving as a good compromise between complexity (of the analysis) and flexibility (i.e. wider range of available parameters). For example, Kander and Stern noted their choice of CES over translog production function was because “we decided that it was better to model some of the main features more reliably or believably [in a CES function] than to attempt to model many features of the data less reliably [in a translog function]” (2014, p.58).

4.4 Empirical CES model - specification

4.4.1 Economic output (Y)

It seems initially straightforward (at an economy-wide level) to select economic output (the dependent variable, Y) as Gross Domestic Product (GDP). However, three choices need to be made before arriving at a selection, and each will result in different parameter estimates. First, is whether to use GDP (Kemfert & Welsch, 2000; Dissou et al., 2012) or Gross Value Added (GVA) (van der Werf, 2008; Stern, 2011; Guarda, 1997). Since GVA excludes any distorting GDP effect of subsidies and taxes, it is arguably a more accurate – but less used - measure of aggregated economic output in CES analysis. Second, is whether to specify output in (more common) constant prices (Hájková & Hurník, 2007; Yuan et al., 2009; Desai, 1985; Zarembka, 1970) or Purchasing Power Parity (PPP) prices (Szeto, 2001; van der Werf, 2008). Since PPP places a higher weight on GDP in non-OECD countries - one $US Dollar in China buys more goods than in the US - PPP may be useful in cross-country studies (Liddle, 2012; Steinberger et al., 2010) by providing a more level playing field for comparisons. Third, is whether to use aggregate (Y) values (Shen & Whalley, 2013; Sun, 2012; Bonga-Bonga, 2009) or output per person[19] (Y/L) values (Duffy & Papageorgiou, 2000; Caselli, 2005; O'Donnell & Swales, 1979; Daude, 2014; Chow & Li, 2002). The choice may be influenced by the motivation for the study: typically aggregate output (Y) studies focus on whole economies of individual countries (Kemfert & Welsch, 2000; Bonga-Bonga, 2009; Szeto, 2001), whilst output per worker (Y/L) studies enable more comparable inter-country (Easterly & Fischer, 1995; Duffy & Papageorgiou, 2000) and regional/sectoral comparisons (O'Donnell & Swales, 1979; Kotowitz, 1968).

4.4.2 Factors of production (K,L,E)

4.4.2.1 Unadjusted (basic) factors

Studies commonly adopt capital stock (K), labour (L) and primary energy (E), which we can consider as unadjusted (or basic) factors of production: i.e. are measured and aggregated without taking into account qualitative differences. Capital stock (the estimated market value, in currency units, of assets involved in production) is most commonly derived via the Perpetual Inventory Method (PIM), where an assumed initial capital stock valuation changes each year via additions (new stock) minus subtractions. Gross capital stock (GCS) defines subtractions as retirements of existing assets; whilst Net Capital Stock (NCS) is equal to GCS less depreciation of existing assets. With NCS and GCS data published by statistical agencies ((ONS) UK Office of National Statistics, 2014; Schreyer et al., 2011), CES studies have adopted both NCS (Zarembka, 1970; Schreyer, 2004) and GCS (Rasch & Tatom, 1977; van der Werf, 2008) datasets. For labour, three options for unadjusted values of workforce labour exist, listed here in descending accuracy as a measure of labour input: workhours (Rasch &

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[19] 'per person' depends on how Labour (L) is defined – see section 3.2 – and could mean per worker, per capita or per quality-adjusted worker.

Tatom, 1977; Kotowitz, 1968), numbers of workers (Ravel, 2011; Shen & Whalley, 2013), or population (for economy-wide studies only) (Wang, 2012). Unadjusted energy - typically given in energy units as terajoules (TJ) or million tonnes of oil equivalent (mtoe) – can be based on primary energy values or final (purchased) energy. Economy-wide studies most commonly use primary energy (Shen & Whalley, 2013), whilst sector-level studies only use final energy (van der Werf, 2008; Koesler & Schymura, 2012; Dissou et al., 2012) since primary energy values are not reported at that level.

Overall, these unadjusted variables remain very popular for empirical production function analysis, due to the availability of national and international time series across countries and sectors (International Energy Agency (IEA), 2013; Feenstra et al., 2015; British Petroleum (BP) Ltd, 2014; Department of Energy & Climate Change (DECC), 2013).

4.4.2.2 Quality adjusted factors

Quality adjusted values for capital (K*), labour (L*) and energy (E*) seek to better represent the productive effect of the basic factors of production (K, L, E) on economic output (Y). Since quality adjustment typically increase unadjusted values (Schreyer, 2004), the use of quality adjusted variables at an economy-wide scale assigns more of the increase in economic output to the growth in factors of production, and less to exogenous technical change (i.e. Solow residual).

Quality adjustment of capital is achieved by estimating ‘capital services’, defined as “the flow of productive services provided by an asset that is employed in production”.[20] Consider a machine in a factory: its capital service can be measured by multiplying the price of the goods by the amount of goods produced by the machine in each year. As national-level time-series of capital services emerge (Wallis & Oulton, 2014), their use and application in empirical CES studies is increasing (Schreyer, 2004; Hájková & Hurník, 2007). A less common alternative is capital utilisation: which estimates how productively capital equipment is used following economic cycles (i.e. less in recessions, more at other times), as shown in the Paquet and Robidoux (2001) Canadian study.

[20] OECD glossary of statistical terms https://stats.oecd.org/glossary/detail.asp?ID=270

Quality adjustment of labour multiplies (unadjusted) work-hours by a quality index – commonly of worker schooling or skills. As international datasets of such quality metrics - such as Barro and Lee (2001) – have become more available, quality-adjusted labour appears more widely used in CES studies (Autor et al., 2006; Dougherty & Jorgenson, 1996; Daude, 2014; Nilsen et al., 2011).

Two main methods are used for quality-adjusting energy: on a physical or economic basis, as highlighted by Cleveland et al (2000) and later Stern (2010). Physical approaches consider the energy content of fuels as typically either heat content or amount of exergy (available energy) of the energy carrier. This can be at the start of the energy conversion chain as primary exergy (Cleveland et al., 2000), or nearer the end of the energy conversion stage as useful work (Ayres & Warr, 2005). Regarding economic approaches, Cleveland et al (2000) suggest higher fuel prices or marginal products are indicators of higher quality, whilst Stern introduces a substitution method whereby quality can be measured by "how much of one fuel is required to replace another" (2010, p.1474). Weighting can range from simple aggregation to Divisia indices. Including quality adjusted energy in empirical aggregate production function studies are rare: Ayres and Warr used the physical approach by including useful work data in economy-wide C-D and LINEX functions (Ayres & Warr, 2005; Warr et al., 2010), whilst Kander and Stern (2014) provide an economic-based CES example, using a Divisia weighted price based method for energy quality.

Despite the apparent merits of quality adjustment (Caselli, 2005), caution is needed. For capital services, Inklaar (2010) raises concerns about the accuracy of the methodology, such that the Penn World Tables (PWT) retains capital stock for its capital data (Inklaar & Timmer, 2013). For energy, economic approaches can be problematic – for example energy price data varies with sector and end use and may be distorted by taxes and subsidy effects, whilst simple price weighting is biased as it assumes no restrictions on substitutability between energy inputs (Berndt & Wood, 1975). As for physical approaches to energy quality, few national datasets exist of thermodynamic 'useful energy', leaving researchers to time-consumingly construct their own datasets (Berndt, 1990; Warr & Ayres, 2010). The result is that most CES empirical studies continue to use unadjusted energy, i.e. primary or final energy datasets (Kemfert & Welsch, 2000; van der Werf, 2008).

Interestingly, empirical studies involving only capital and labour expend significant effort to quality adjust at least one variable (Burda & Severgnini, 2014; Finn, 1995; Klump et al., 2011; Wang, 2012), but those introducing energy as a third variable typically use unadjusted values for capital and labour (Prywes, 1986; Kemfert, 1998; van der Werf, 2008; Dissou et al., 2012). This seems surprising, but perhaps instead reflects the significant effort required to develop or obtain time-series of quality adjusted variables.

4.4.3 Nesting and elasticity of substitution

Nesting, and elasticity of substitution, are interlinked aspects of CES function specification: the choice in one affects the other - so they are presented and discussed together in this section.

4.4.3.1 Nesting

Once the CES function has more than two factors of production, the issue of whether - and how - to nest them, arises. To see why, let us view the non-nested CES function introduced by McFadden (1963), and used by Edenhofer et al (2005). It is given in equation 4-7, using the notation of the nested equation 1-11:

$$Y_t = \theta\, A[K_t^{-\rho} + L_t^{-\rho} + E_t^{-\rho}]^{-\frac{\nu}{\rho}} \quad ; \qquad A \equiv e^{\lambda t} \tag{4-7}$$

As Broadstock et al (2007) note, the assumption that all factors of production are equal substitutes ($\sigma = 1/(1+\rho)$). Is both highly restrictive and appears unlikely in practice. As a result, the non-nested structure is giving away some of the flexibility sought (versus its C-D rival), and so various authors (van der Werf, 2008; Lecca et al., 2011; Zha & Zhou, 2014) report this structure is rarely used.

Thus a more common approach is to ‘nest’ the factors of production, which is more flexible because it allows different elasticities of substitution to exist between production factors. A nested three-factor format is shown in Figure 4-4, with two factors of production are placed within an ‘inner’ nest and one in an ‘outer’ nest. Figure 4-4 portrays the KL(E) nesting structure of equation 1-11, where capital-labour is in the inner nest, and energy sits in the outer nest.

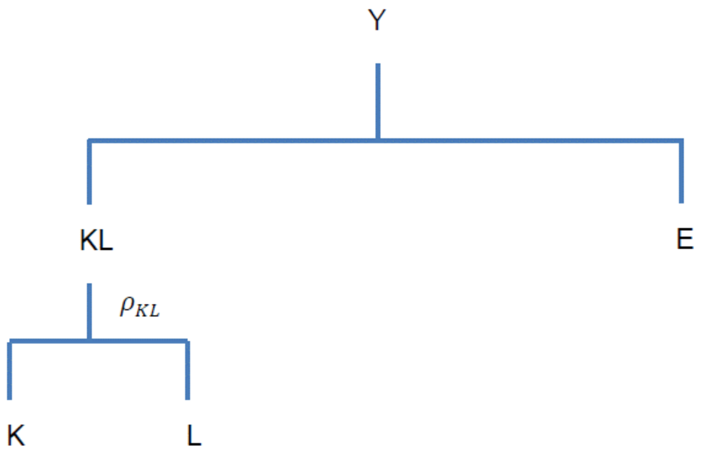

Figure 4-4: KL(E) nesting for the CES function, adapted from Lecca et al (2011)

With three factors of production (K,L,E), the CES function has two other possible nests in addition to the KL(E) structure in equation 1-11: EK(L) in equation 4-8 and LE(K) in equation 4-9.

$$Y_t = \theta\, A[\delta_1\big[(\delta\, E_t^{-\rho_1} + (1-\delta)K_t^{-\rho_1}\big]^{\rho/\rho_1} + (1-\delta_1)L_t^{-\rho}]^{-\frac{\nu}{\rho}} \quad ; \quad A \equiv e^{\lambda t} \qquad \textbf{(4-8)}$$

$$Y_t = \theta\, A[\delta_1\big[(\delta\, L_t^{-\rho_1} + (1-\delta)E_t^{-\rho_1}\big]^{\rho/\rho_1} + (1-\delta_1)K_t^{-\rho}]^{-\frac{\nu}{\rho}} \quad ; \quad A \equiv e^{\lambda t} \qquad \textbf{(4-9)}$$

Van der Werf (2008) reviewed numerous energy-augmented (i.e. KLE or KLEM) production functions used in climate-based models. He found whilst most studies analysed a single, KL(E) nest - a view supported by Zha and Zhou (2014), there was also considerable variation in nesting structure. This presents two routes forward for analysts. The first is to decide on a single nesting structure, based on theoretical or other considerations. For example, Saunders (2008) suggests the KL(E) nesting is the only nesting structure that permits the full range of energy rebound (R_e), from hyperconservation (R_e <0) to backfire (R_e >1). The second, less common approach is to report on all three types of nesting (Dissou et al., 2012; Kemfert, 1998; van der Werf, 2008; Shen & Whalley, 2013), though care is needed in interpretation, since certain solution aspects (such as elasticity of substitution) will not be comparable between different nestings.

4.4.3.2 Elasticity of substitution, σ

Interwoven with the issue of nesting is the elasticity of substitution, σ, which tells us the ease by which one factor of production (e.g. labour) is substitutable by another (e.g. capital). Taking the CES function in equation 1-11, we previously noted the special cases where capital and labour have zero substitutability (i.e. are complements) in a Leontief function ($\sigma = 0$); some substitutability in a C-D function ($\sigma = 1$), and are perfect substitutes in a linear function ($\sigma = \infty$). Chirinko's 2008 paper (Chirinko, 2008) highlights the importance that conventional economics places on the elasticity of substitution between capital and labour - which appears borne out by Thomas Picketty's recent work (Picketty, 2014) and the subsequent flurry of academic debate (Rognlie, 2014; Rowthorn, 2014; Semieniuk, 2014). (Yet it also reveals how orthodox economists continue with capital-labour aggregate production functions which ignore energy as a factor of production).

With multiple factors of production several key issues are raised by nesting regarding the elasticity of substitution. The first – following on from the previous section - is how the nesting structure effects the elasticity of substitution. Sato's (1967) two-level nest CES function in equation 1-11 permits separate values for inner-nest (K-L) elasticity $\sigma_1 = \sigma_{KL}$ and outer-nest (KL-E) elasticity $\sigma \quad = \sigma_{KL,E}$, - which he tells us can be used to justify nesting choice:

"Introspection tells us that the [inner-nest] elasticities of substitution should be substantially higher than the [outer-nest] elasticity. After all, we justify the aggregation by the fact that aggregated factors are similar in techno-economic characteristics. One of such similarities is obviously the ease of substitution". (ibid, p.203)

Sorrell picks up the implication of this important point, suggesting "estimates of substitution elasticities are likely to be biased if separability is assumed where not supported by the data" (2014, p.2861). This means that the choice of nesting structure matters (e.g. KL(E) versus EK(L)), and amounts to imposing separability on the factors of production - since they are forced into nesting structures that may not match the data. Van der Werf (2008) continues; illustrating how the estimated elasticity between two factors of production (e.g. K-L) vary significantly depending on the nesting structure.

Second, numerous definitions of elasticity of substitution exist, as noted earlier, and Sorrell (2014) highlights the confusion (and ignorance) that follows. In particular, CGE models based on production function equations require HES values, whereas commonly the cost-function derived Allen Elasticity of Substitution (AES) values are incorrectly used (Chang, 1994; Prywes, 1986; Thompson, 2006). Van der Werf continues the CGE critique, arguing that even if HES values are chosen, they are likely to be incorrect since “in most applied dynamic climate policy models, neither the production structure nor the accompanying elasticities of substitution have an empirical basis” (2008, p.2965).

Third, some studies set (pre-analysis) elasticity of substitution values for the inner nest, which thereby constrains the available values for the parameters to be estimated, including the outer nest elasticity of substitution. An example is the restricted CES function based on Hogan and Manne (1977), where the capital-labour inner-nest is assumed as a Cobb-Douglas function ($\sigma = 1$), as given in equation 4-10. Saunders (2008) adopts this approach, as do some CGE models (Bosetti et al., 2007; Manne et al., 1995).

$$Y_t = \theta\, A\Big[(\delta\, K_t^{\alpha} + L_t^{(1-\alpha)})\Big]^{\rho} + (1-\delta)E_t{}^{\rho}]^{\frac{1}{\rho}} \quad ; \qquad A \equiv e^{\lambda t} \qquad \textbf{(4-10)}$$

All of this matters, since estimated parameters – such the elasticity of substitution in empirical CES studies (Zha & Zhou, 2014; Koesler & Schymura, 2012; Sorrell, 2014; van der Werf, 2008) - can have a large influence on macroeconomic model results. For example, with a KL(E) nest, Jacoby et al (2006) found changes to the elasticity of substitution was the main driver of differences in their CGE model results, whilst Saunders (2015) suggested variations in elasticity of substitution had a significant impact on the size of estimated energy rebound.

4.4.4 Other CES function parameters

4.4.4.1 Productivity / technical change coefficients

Exogenous TFP (as measured by the parameter *A* in CES equation 1-11) can also be defined as Hicks-neutral technical change. This means productivity changes are neutral – rather than biased - across factors of production. Whilst many studies employ this assumption (Kemfert, 1998; Kemfert & Welsch, 2000), it is restrictive since it assumes the productivity of labour, energy and capital all increase at the same rate, which may simply not be true.

To overcome this restraint, separate productivity coefficients (α_K, α_L, α_E) can be introduced and estimated for each factor of production, modifying equation 1-11 to become equation 4-11. The productivity coefficients represent technological changes of each production factor while leaving the productivity of the others unchanged. Sorrell (2014) describes this as giving the separate coefficients' ability to assign bias in technical change to specific production factors. Note if α_K = α_L = α_E, equation 4-11 returns to the Hicks-neutral equation 1-11.

$$Y_t = \theta\, A[\delta_1\big[(\delta\, \alpha_K K_t^{-\rho_1} + (1-\delta)\alpha_L L_t^{-\rho_1}\big]^{\rho/\rho_1} + (1-\delta_1)\alpha_E E_t^{-\rho}]^{-\frac{\nu}{\rho}};\ \ A \equiv e^{\lambda t} \qquad \textbf{(4-11)}$$

In an energy-augmented CES production function context, van der Werf (2008) and Dissou et al (2012) provide examples of this method, estimating directly the technical change parameters assigned to the factors of production. Papagerogiou et al (2015) extend this approach, by splitting fossil fuel and renewables adopting separate technical productivity coefficients.

4.4.4.2 Returns to scale, (ν).

Empirical CES studies almost exclusively assume unity returns-to-scale (ν = 1.0), which is a conventional economic assumption. However it is econometrically possible to estimate ν: Szeto (2001) who estimated ν = 1.09, and Duffy and Papageorgiou (2000) – who estimated ν=0.97-1.00, provide rare CES examples. Curiously – though perhaps since the values were close to 1.0 - both their economy-wide studies then returned to ν = 1.0, since as Szeto noted "theory suggests that there are constant returns to scale in production, we will impose this restriction in the remainder of our empirical analysis" (2001, p.7).

Thus, it seems sensible to first run an unrestricted empirical analysis, and then re-run with a unity returns-to-scale parameter (i.e. ν = 1.0). The results will indicate how well the model supports the unity returns-to-scale assumption – although since an unrestricted analysis has fewer degrees of freedom, the parameter estimates will be less precise.

4.4.4.3 Output share parameters, $\boldsymbol{\delta, \delta_1}$

In a classical capital-labour C-D function (which is a restricted CES), the partial output elasticity associated with a given factor of production (α_K, α_L) is commonly equated to the respective cost-shares of aggregate output (typically around 0.3

for capital, 0.7 for labour). This has been called by some the cost-share theorem (Warr & Ayres, 2012; Giraud, 2014; Kümmel et al., 2010; Casten, 2013), but let us label it more accurately as a cost share principle (CSP), since it is based on empirical evidence (Kaldor, 1961) and is not a mathematical theorem.

In an energy-augmented CES function, the CSP is not possible to apply, since output elasticities for a three level CES function are not constant with respect to time. Taking a KL(E) nest as an example, equation 4-12 - adapted from Santos et al (2016) - shows how output elasticities vary because they are depending on the time-varying factors of production (k, l, e), except in the limiting C-D case where ρ = 0. Thus it is not possible to follow the CSP in the case of the general three input CES function.

$$\alpha_E = \frac{\frac{\partial Y}{\partial E}}{\frac{Y}{E}} = \frac{1-\delta}{\delta E^{\rho}[\delta_1 K^{-\rho 1}+(1-\delta_1)L^{-\rho 1}]^{\frac{\rho}{\rho 1}}+1-\delta} \qquad \textbf{(4-12)}$$

4.4.4.4 Normalisation

A historical complaint about aggregate production functions is that they combine different units: e.g. capital ($); labour (hrs); and energy (TJ), generating “production function parameters [that] have no economic interpretation” (Klump et al., 2011, p.5). One method is to normalise the factors of production prior to estimating the unknown parameters, as advocated by La Grandville, Klump, and co-authors (Klump & Preissler, 2000; Klump et al., 2011; La Grandville & Solow, 2009). This method indexes time-series data to the base year, so $y = Y_t/\, Y_0$; $k = K_t/\, K_0$; $l = L_t/\, L_0$; $e = E_t/\, E_0$; with the resultant normalised (lower case) version of equation 1-11 shown as equation 4-13:

$$y_t = \theta\, A[\delta_1\big[(\delta\, k_t^{-\rho_1} + (1-\delta) l_t^{-\rho_1}\big]^{\rho/\rho_1} + (1-\delta_1) e_t^{-\rho}]^{-\frac{\nu}{\rho}} \quad ; \quad A \equiv e^{\lambda t} \qquad \textbf{(4-13)}$$

For CES functions, this seemingly minor adjustment is actually a major change, since by converting production factors to normalised values, different values for all estimated parameters are obtained (Klump et al., 2011). Advocates suggest this also allows a more comparable basis to study elasticities of substitution between different studies (Shen & Whalley, 2013; Palivos, 2008). Shen and Whalley (2013) provide a rare example of energy-augmented normalised CES empirical study.

However, despite growing support for normalisation, it is not yet a mainstream technique, and some have cautioned against its use beyond its reach: Temple suggests that "the normalisation approach is not enough to allow a meaningful comparison of economies that differ ''only'' in the elasticity of substitution" (2012, p.301).

4.5 Empirical CES model - parameter estimation

4.5.1 Estimation methods

The C-D function (equation 4-5) is typically estimated as a linear equation by ordinary least squares (OLS), after first taking logarithms. This simple, linear solution method is one reason for its enduring popularity. However, the CES function (equation 1-11) cannot be transformed in the same simple manner to a linear equation without approximation, and so numerous other techniques have been developed, as evidenced by the CES sample studies shown in Figure 4-5.

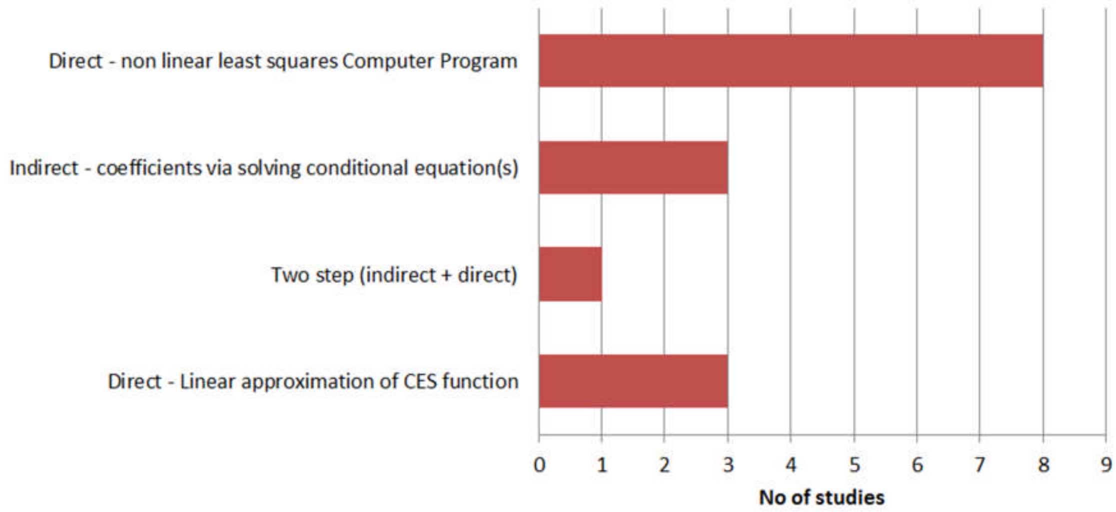

Figure 4-5: CES estimation method in sample papers

The most popular technique in the sample – used by over half the sample (Rusek, 1989; Easterly & Fischer, 1995; Kemfert, 1998; Kemfert & Welsch, 2000; Dissou et al., 2012; Koesler & Schymura, 2012; Duffy & Papageorgiou, 2000; Szeto, 2001) - is direct non-linear estimation. Though complex, its popularity appears to be increasing, which may be due to the increased availability of econometric guidance (Greene, 2010), off-the-shelf programmes (Henningsen & Henningsen, 2011), and advances in computing power.

A second method indirectly estimates the parameters, since the solution to the non-linear function is not directly estimated. Instead, three linear conditional simultaneous equations - one for each factor of production – are derived based on applying Shephard's Lemma[21] to the overall CES function. This method is a common approach where the sole parameter of interest is the elasticity of substitution, σ, as Van der Werf (2008) and Dissou et al (2012) show.

Third, is a hybrid indirect-direct method, based on Nerlove's two-step process (Nerlove, 1967). Bonga Bonga (2009) provides a rare, recent example, which in the first step estimates the elasticity of substitution (σ) and distribution parameter (δ), based on the estimated ratio of marginal productivities under perfect competition, and then in the second step inserts σ and δ in a back into the CES equation, reducing it to a linear equation which is then directly estimated.

A fourth method used is direct linear approximation, based on equation 4-14: Kmenta's simplification of the non-linear CES equation (Kmenta, 1967). However, since the Kmenta approximation cannot be used to linearise CES functions with more than two factors of production (Henningsen & Henningsen, 2012), it is found only in our samples for two factor (capital-labour) studies (Zarembka, 1970; Duffy & Papageorgiou, 2000; Wang, 2012).

$$\begin{aligned}\log X_i = \log \gamma + \nu\delta \log K_i + \nu(1-\delta)\log L_i \\ - \frac{1}{2}\rho\nu\delta(1-\delta)[\log K_i - \log L_i]^2 + u_i\,. \end{aligned} \tag{4-14}$$

4.5.2 Statistical reporting

Statistical reporting in empirical CES studies is an important aspect because it provides context for the empirical results. Whilst noting there may be an inherent difference between statistical testing completed in the analysis, versus that which is reported, a different groups of reporting are considered here. The first group we shall label 'standard statistical reporting' - the most common statistical testing reported on the fitted function and its econometrically estimated coefficients.

[21] Shephard's Lemma can be defined as "the cost minimising demand for any input can be obtained from the partial derivative of the cost function with respect to the price of that input"

From the sample, the majority report goodness-of-fit via the coefficient of determination (R^2) (Zarembka, 1970; O'Donnell & Swales, 1979; Easterly & Fischer, 1995; Kemfert & Welsch, 2000) and the Durbin-Watson D-W value - testing for autocorrelation of the residuals of the regression (Kemfert & Welsch, 2000; Kotowitz, 1968; Rusek, 1989; van der Werf, 2008), as shown in Table 4-1. The overall F-test - giving the statistical significance of the overall relationship – was less commonly reported (Bonga-Bonga, 2009; Rusek, 1989; O'Donnell & Swales, 1979). Within our sample, only Easterly and Fischer (1995) and Duffy and Papageorgiou (2000) reported tests for heteroskedasticity in the error term (i.e. the fitted residual).

Table 4-1: Example of overall goodness-of-fit statistical reporting, from Kemfert (1998)

Durbin-Watson (d) and R^2 values

	R^2	DW-statistic (d)
KE/L	0.9996	1.44656
KL/E	0.786	1.8585
EL/K	0.9986	1.87970

Reporting of p-values on the statistical significance of individual coefficients is also common (Rusek, 1989; Duffy & Papageorgiou, 2000; Szeto, 2001; van der Werf, 2008), though as we see from Table 4-2 it should be used (and viewed) with caution. This is because p-values are a measure of the evidence against a null hypothesis, with small p-values indicate overwhelming evidence against the null. Statistical fitting software typically assumes the null hypotheses that fitted parameters are zero. That may not be a meaningful null hypothesis for some parameters of the CES production function. For example, a study that endeavours to assess whether (or not) energy should be included in the CES production function via the (kl)e nesting structure should use a null hypothesis of delta = 1 (energy should not be included) and test whether there is overwhelming evidence against the null hypothesis (thereby indicating that energy should be included). For this example study, the reported p-values from fitting software will be unhelpful: the p-value will tell the analyst whether delta is likely to be different from zero, not whether it is likely to be different from 1.0. Thus, authors should be very careful that reported p-values accord with the purposes of a study. this practice is at best questionable since it tells us nothing in this case.

Table 4-2: Example of parameter p-value statistical reporting, from Zha and Zhou (2014)

Estimated results of nested CES production function.[a]

Nested structure	Estimated results				
	a	b	α	β	γ
(KL)E	0.6270 (0.0401)	0.9312 (0.0091)	−0.4139 (0.0065)	−0.0568 (0.0015)	0.2004 (0.0009)

[a] Figures in parentheses are p values.

Thus, reporting of standard errors (as shown in Table 4-3) will add further information for readers interested in the precision with which parameters are estimated. For example, in a study examining the substitutability of energy for the capital/labour composite in a (kl)e nesting structure (Equation 4), the value of sigma is central. If sigma is reported as 0.5 with standard error of 0.3, it will be hard to claim whether kl and e are substitutes or complements. If, instead, sigma is found to be 0.95 with standard error 0.02, it could reasonably be claimed that kl and e are substitutable. But even here, standard errors should be used with caution if confidence intervals are the endgame – as for example, a confidence interval on delta might extend from 0.90 to 1.02, but 1.02 is not economically-meaningful in the CES production function.

Table 4-3: Example of parameter standard errors, from Van der Werf (2008)

Estimated elasticities of substitution

	(KL)E		(LE)K		(KE)L	
	$\sigma_{KL,E}$	$\sigma_{K,L}$	$\sigma_{LE,K}$	$\sigma_{L,E}$	$\sigma_{KE,L}$	$\sigma_{K,E}$
Industry σs						
Basis metals	0.6454**	0.6190**	0.4990**	0.8889**	0.8866**	0.9606**
	(0.0639)	(0.0212)	(0.0198)	(0.0179)	(0.0417)	(0.0132)
Construction	0.2892**	0.2242**	0.1796**	0.5127**	0.9496**	.9931**
	(0.0566)	(0.0312)	(0.0308)	(0.0442)	(0.1112)	(0.0026)
Food and tob.	0.3990**	0.4597**	0.4240**	0.8454**	0.9231**	0.9920**
	(0.0585)	(0.0226)	(0.0223)	(0.0253)	(0.0716)	(0.0051)
Transport eq.	0.1705*	0.4638**	0.3927**	0.8167**	1.0126**	1.0022**
	(0.0818)	(0.0319)	(0.0323)	(0.0378)	(0.0800)	(0.0008)
Non-metal. min.	0.2546**	0.4541**	0.3925**	0.8204**	0.9465**	1.0001**
	(0.0653)	(0.0242)	(0.0238)	(0.0262)	(0.0650)	(0.0038)
Paper etc.	0.4489**	0.4103**	0.3518**	0.7997**	0.8907**	0.9945**
	(0.0684)	(0.0220)	(0.0215)	(0.0291)	(0.0706)	(0.0076)
Textiles etc.	0.2944**	0.2737**	0.2320**	0.7852**	1.0440**	0.9987**
	(0.0649)	(0.0192)	(0.0187)	(0.0323)	(0.0728)	(0.0018)

Note: Standard errors in parentheses. */** indicates that coefficient differs from zero at 5/1% level of significance.

A second reporting group examine economic assumptions imposed from the orthodox literature, done through the specification of the production function. For example, specifications can be set to test input separability (via different nestings - (Kemfert, 1998)); unity returns-to-scale (by estimating it directly - (Szeto, 2001)), and the standard assumption of Hicks-neutral technical progress (via separate productivity coefficients - (Dissou et al., 2012)).

Relating to statistical reporting is the application of statistical techniques as part of the estimation process. For example, five of the sample (Duffy & Papageorgiou, 2000; Szeto, 2001; Dissou et al., 2012; Bonga-Bonga, 2009; Wang, 2012) reported using cointegration techniques to test the variables and error terms (all since 2000). This is an appropriate technique for the indirect CES estimation method which requires evaluation of linear conditional equations. By conducting unit root and augmented dickey-fuller (ADF) tests on the time-series datasets before proceeding with the analysis, Szeto (2001) modified the analysis to use first differences (instead of aggregate values) to correct for autocorrelation problems. Dissou et al (2012) followed a similar approach, and as their data passed the ADF tests on level variables, deemed the data was appropriate for their analysis. Another example is checking the correlation between the Solow residual with the production factors (Daude, 2014) or other exogenous macroeconomic variables (Magalhães, 2005). This helps assessment of the extent to which the Solow residual contains other valuable information, or just consists of ‘noise’. Statistical ‘bootstrapping’ is also within this field - using resampling techniques to determine with greater precision the standard errors of the estimated parameters. Whilst none of the sample studies used this technique, it is entering the wider growth accounting literature (Growiec, 2010; Papageorgiou et al., 2015; Giraud, 2014), and could be applied to empirical CES analyses, as shown by Santos et al (2016).

Last, also related to statistical reporting, is the issue of boundary solutions, and their impact on results, which may keenly affect the estimated parameters. Santos et al (2016) discuss two aspects: first, solutions that exist on boundaries can shield the estimation of certain parameters of interest. For example, if the distribution parameter δ_1 in the KL(E) nested equation 1-11 is estimated to be 1.0, then energy makes no contribution to output. In this case the value for the elasticity of substitution between KL and E cannot be estimated. Second, solutions that exist very close to boundaries can return unstable results, i.e. small movements away from one parameter value cause significant changes to other estimated parameters.

Overall, statistical reporting can strengthen the empirical results, and provide better context for comparison of results between studies. However, it seems an aspect of the estimation process that is under-reported at present.

4.6 Conclusions

Based on our findings, we reach three separate conclusions. First, a transition from C-D to CES aggregate production functions is underway, and in parallel energy is being added as a third factor of production. This may be due to various ‘pulls’ from modelling (e.g. CGE models demanding energy-augmented elasticity of substitutions), increased practicality of estimating CES functions (e.g. greater computational power and off-the-shelf nonlinear solution programmes) or theoretical critiques of the C-D function gaining weight, causing a switch to the more flexible CES function.

Second, both the specification of the energy-augmented CES aggregate production functions and the parameter estimation technique have real impacts on the values of the estimated coefficients. Modelling choices made are therefore important, including the values of output (Y) and factor of production (K, L, E), the functional form to use (e.g. nesting), which other parameters to include (e.g. returns-to-scale), and whether to normalise – or not - the function. Given this diversity of choice and impact, it seems sensible to report where possible on a range of options. An example is to estimate and report on all nesting options, since it adds interpretative value to the study itself and enables improved inter-study comparisons.

Third, the observed trend towards the sophisticated direct non-linear estimation of the CES parameters has not been matched by increased breadth of statistical reporting. For example, bootstrapping to report standard errors is more common in other fields but has merit for empirical CES production functions, whilst the more detailed study of solutions adjacent to boundary models is important, but absent from current studies.

Overall, the estimation of energy-augmented nested CES aggregate production functions is a growing, important field of study, since their results are input to macroeconomic models which inform climate and economic policy. By collating the key current aspects of their empirical estimation, we hope this paper provides a succinct and accessible navigation roadmap for the practitioner: being forewarned is forearmed.

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Chapter 5

A new approach to estimating total economy-wide energy rebound: An exergy efficiency based study of the UK, US and China

5.1 Abstract

In 1865, William Stanley Jevons wrote "It is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth"'. Thus Jevons introduced the notion of energy rebound: that some or all of energy efficiency savings may rebound via higher energy use. Efforts to estimate rebound have focussed mainly on one part of the puzzle - consumer-sided 'respending' rebound - which evidence suggests is around 25-50%. However, whilst empirical analyses of total rebound - which includes producer and long term macroeconomic effects - are rare, those that do exist suggest total rebound may be over 50%, and in some cases over 100% (backfire). The continued reliance on energy efficiency – a major part of global carbon reduction strategies - without including rebound in energy models and policy, may have serious implications for meeting climate change mitigation targets.

One hundred and fifty years later, we know that rebound exists, but do not have a common understanding of its magnitude. Four weaknesses are found in existing total rebound studies: differences in energy efficiency definitions, differences in the location of rebound in the energy chain, inconsistent analysis boundaries, and methodological flaws. A central limitation is the lack of a thermodynamic, economy-wide basis for adopted energy efficiency: typically physical or economic metrics are used as proxies for real economy-wide thermodynamic efficiency. However, such a measure already exists: exergy efficiency. Based on the first and second law of thermodynamics, and the consideration of exergy as 'available energy', it has already been applied at a national-level to energy use and economic growth studies, but not energy rebound.

In response, we develop a thermodynamic 'exergy' based analysis to estimate total long term rebound for the UK, US and China: completing the first multi-country, multi-method study of total energy rebound. The results suggest that China's industrial based economy is in a state of 'backfire' – with energy rebound higher than that of the energy savings induced by energy efficiency, due to its producer-sided economic structure. For the UK and US, their more mature economies exhibit limited (partial) rebound.

Overall, we find exergy efficiency is a viable national energy efficiency measure for energy rebound analysis, one that could contribute to the evidence base for energy rebound. That said, policy makers should not wait for a resolution to the Jevons paradox – since it may never arrive – but instead should include rebound based on best available evidence according to the precautionary principle.

5.2 Introduction

5.2.1 Energy rebound and the Jevons paradox

2015 was the 150th anniversary of the Jevons paradox (Jevons, 1865), where William Stanley Jevons suggested that contrary to expectation, the introduction of energy efficiency technologies to the Scottish coal mining industry had increased – not reduced - fuel consumption. This is the concept of energy rebound: the idea that not all theoretical energy savings (from energy efficiency) may be realised. Stern defined energy rebound as occurring "if energy-saving innovations induce an increase in energy consumption that offsets the technology derived saving" (2011, p.40). Saunders (2008) provides a mathematical definition of energy rebound, R_e, as in equation 5-1, where η_τ^F is the elasticity of fuel use (F) with respect to efficiency gain (τ).

$$R_e = 1 + \eta_\tau^F = 1 + \frac{Change\ in\ fuel\ use\ (\%)}{efficiency\ gain\ (\%)} \qquad \textbf{(5-1)}$$

Thus a 1% efficiency gain and 0.5% reduction in fuel use would yield R_e = 0.5, which is partial rebound. Actually from equation 5-1 five states of energy rebound can occur, as shown in Table 5-1:

Table 5-1: States of energy rebound

Change in energy use from 1% efficiency gain	Energy rebound $\boldsymbol{R_e}$
<-1%	Super-conservation (R_e< 0)
-1%	Zero (R_e= 0)
-0.01% to -0.99%	Partial (e.g. R_e= 0.01-0.99)
0%	Full (R_e= 1)
>0%	Backfire (R_e> 1)

Total economy-wide energy rebound can be split into the three components in Figure 5-1. These are direct rebound ('respending' on same product/energy use), indirect rebound ('respending' on other product/energy use), and macroeconomic rebound (e.g. economy-wide structural and growth augmenting effects). The sum of the three components add up to total rebound.

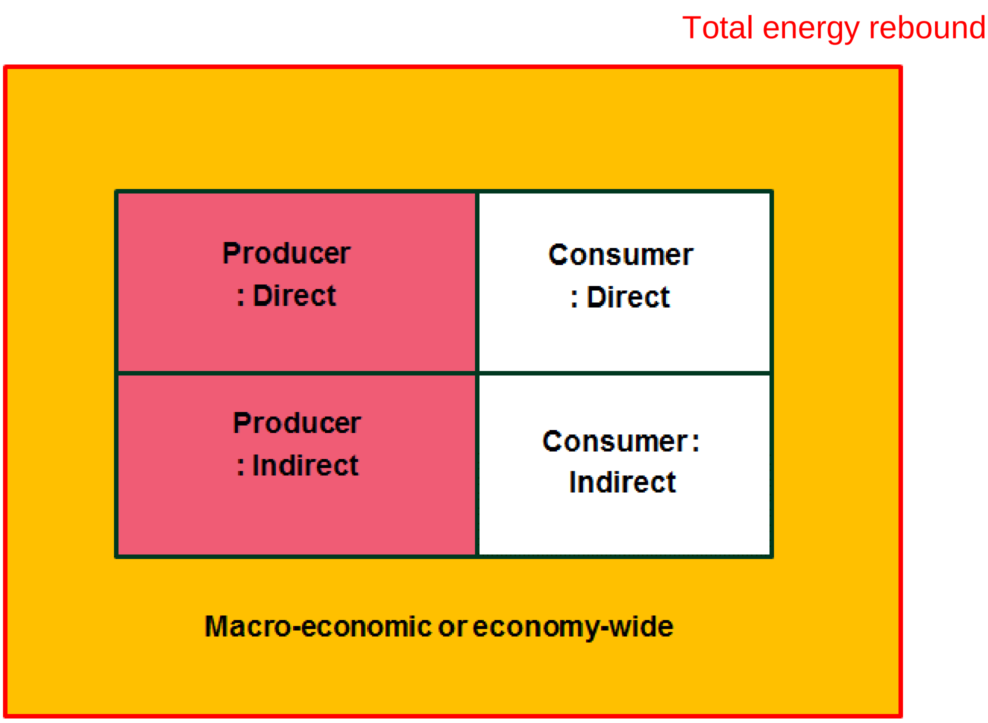

Figure 5-1: Components of total energy rebound, based on Jenkins et al (2011) and Saunders (2015)

Alcott (2005) asserts Jevons' theoretical justification (for his empirical observations) was that energy efficiency increases productivity via a cycle of greater profitability, reducing prices of goods, and increasing demand. Subsequently, the recent debates over rebound have split into two schools of thought. One school follows the 'Khazzoom-Brookes postulate' (Saunders, 1992), and advocates rebound is significant (Brookes, 1979; Khazzoom, 1980; Saunders, 1992; Alcott, 2005), whilst the Grubb-Gillingham school suggest rebound is not significant (Schipper & Grubb, 2000; Gillingham et al., 2013). Exchanges between the two schools sometimes occur, such as between Brookes and Grubb in the early 1990s (Brookes, 1990; Grubb, 1990; Brookes, 1992; Grubb, 1992; Brookes, 1993).

5.2.2 Current state of knowledge

Whilst detailed studies of the status of energy rebound exist (Alcott (2005), Sorrell and co-authors (Sorrell & Dimitropoulos, 2007a; Broadstock et al., 2007; Allan et al., 2007; Sorrell & Dimitropoulos, 2007b; Sorrell, 2007), and Jenkins et al (2011)), a recap of the main points and very recent progress is relevant to set the contextual background for this paper. Three strands are presented: concepts, estimation and policy.

First, the conceptual strand has made recent progress in identifying rebound effects from different types of energy efficiency improvements. Ayres (2005) suggests radical "macro" innovations (e.g. steam engines) have large rebound effects versus "micro" innovations (i.e. existing technology improvements). Sorrell and Dimitropolis concur, and suggest understanding energy efficiency improvements associated with the larger general purpose technologies (GPTs) are "perhaps the key to unpacking the Khazzoom-Brookes postulate" (2007b, p.135). Relevant to climate policy is Gillingham et al (2014), who distinguish between rebound effects from 'Zero-Cost Breakthroughs' (ZCBs) – i.e. device-level efficiency improvements – and 'Policy-Induced Improvements' (PIIs). Other suggested ways of splitting total rebound include short versus long term rebound (Saunders, 2008); rebound from macroeconomic growth versus macroeconomic price changes (Gillingham et al., 2013), and consumer versus producer sided rebound (Saunders, 2015).

Second, in terms of estimation of energy rebound, referring to Figure 5-1, much of the analysis is focussed on consumer-sided rebound (e.g. transport or residential sectors), either direct rebound (Small & van Dender, 2007) or indirect rebound (Chitnis et al., 2013; Turner, 2009). The Intergovernmental Panel on Climate Change (IPCC) (2014) suggests consumer sided rebound may be of the order of 20-45%. Producer sided studies are conducted at industry-level and find a wide range of estimates from 24% (Bentzen, 2004) to backfire (>100%) (Saunders, 2013). Despite producer energy use being larger than consumer energy use, most studies are of consumer rebound (Saunders, 2015). Last, studies which of economy-wide or total rebound are rare: Sorrell and Dimitropoulos's (2007b, p.2) exhaustive review of the empirical work on energy rebound concluded that “despite the breadth of literature covered, very few of the studies reviewed in this report provide quantitative estimates for the size of the economy-wide rebound effect.” That said, more studies are emerging, including Zhang and Lin (2013), Fouquet (2014) and Saunders (2015), who estimate total energy rebound to be large - over 50% - and in some cases over 100% (backfire).

Third, are policy-sided discussions. Various authors suggest economy-wide energy rebound is not necessarily a bad thing. Gillingham et al (2014) suggest that total rebound appears to be 20-60%, thereby providing a net energy saving. Others, such as Saunders (1992) and Saunders and Tsao (2012), highlight the increases in economic welfare that have been delivered by energy efficiency, and that “policymakers should include these welfare gains in the tally of benefits of a policy” (Gillingham et al., 2014, p.26). Revealingly, as the IPCC advocate that “rebound effects cannot be ignored” (IPCC, 2014a, p.391) in future policy, this implies that energy rebound appears largely absent from current energy policies. Van den Bergh (2011), Azevedo et al (2013) and Sorrell (2015) among those who highlight the unintended consequences of energy efficiency policies which do not properly account for rebound.

Overall, we appear to know more - and yet less - at the same time: the refining of components and interrelations within rebound both clarifies and complicates the total rebound research space. The Breakthrough Institute highlights the importance of this complexity on the measurement of rebound itself: classing energy rebound as an ‘emergent phenomena’ because of the “higher order effects resulting from the complex interaction of multifold individual components and the combination of multiple non-linear and reinforcing effects” (Jenkins et al., 2011, p.9). In other words, the true size of rebound only becomes apparent when measured at scale, allowing these interactions to occur.

5.2.3 Total rebound: implications for estimation and energy policy

Two key points stand out from the literature reviewed. First, in terms of measurement, whilst the definitive answer to Jevons paradox remains elusive – and indeed may never be conclusively established – recent progress is being made. For example, whilst Madlener and Alcott stated in 2009 there is “at present no viable methodology for measuring indirect or economy-wide rebound” (2009, p.375), Chitnis and Sorrell (2015) illustrate advances in estimating indirect (consumer) rebound. Furthermore, literature published since 2010 (Jenkins et al., 2011; Tsao et al., 2010; Chitnis et al., 2014; Saunders, 2015; Fouquet, 2014; Zhang & Lin, 2013; Chitnis & Sorrell, 2015) suggests total energy rebound could be large and even over 100% (backfire) in some cases. However, a key impediment remains in that “some physical metric or metrics enabling a rigorous definition and measurement of macro-level energy efficiency change (e.g. at the national or global level) must be found.” (Madlener & Alcott, 2009, p.374).

Second, in policy terms, whilst energy rebound is known (if not quantified), it is largely absent from macroeconomic energy-economy models (HM Revenue and Customs, 2013; Barker et al., 2009; International Energy Agency (IEA), 2013) and energy and emissions reduction policies (European Parliament, 2012; Department of Energy & Climate Change (DECC), 2012). Indeed, rather than conservatively accounting for rebound, Arvesen et al (2011) discuss how models containing ‘unrealistic technology optimism’ negatively impact on climate mitigation policies. For example, policies under the EC’s Energy Efficiency Directive (European Parliament, 2012) are currently expected to only reduce EU energy use by 16% versus the 20% 2020 target (Fraunhofer Institute for Systems and Innovation Research et al., 2014). If such ‘low or no’ rebound optimism translates to an overestimate of the effectiveness of energy efficiency policies, this has serious implications for the 195 countries who agreed to emissions reduction plans under the 2015 Paris Agreement (UNFCCC, 2015).

For this paper, the focus is the first topic – the estimation of total rebound. To overcome the issue of definition of energy efficiency, we propose to use economy-wide exergy analysis, where exergy as ‘available energy’ is a thermodynamic measure of energy quality. To date it has been applied to energy and economics studies, but not in the area of energy rebound. Therefore, this paper addresses the following research question: “*can economy-wide exergy efficiency make progress in estimating total energy rebound?*” The structure of the paper is as follows: Section 5.3 gives a review of the current total rebound research frontier, Sections 5.4 and 5.5 present the methods and results, Section 5.6 then has a discussion based on the earlier sections, whilst Section 5.7 is conclusions.

5.3 Estimation of total energy rebound

In this section we set the background to the exergy-based rebound analysis, by exploring the current state of knowledge and debate relating to the estimation of economy-wide total energy rebound.

5.3.1 Current methods

Empirical studies which seek to estimate total energy rebound are placed here into three methodical approaches, based on the way energy efficiency is either defined or implemented in the method: economic, physical and thermodynamic. Studies typically use classify input energy data as the energy content (in Joules) of either primary energy (energy source, e.g. oil, coal, gas) or final energy (finished fuel, e.g. petrol, electricity).

5.3.1.1 Economic efficiency based methods

This is the most common method, and assumes an economic measure as a proxy for thermodynamic energy efficiency. It is split here into three sub-groups. The first is based on the price elasticity of demand, where the energy rebound (R_e) of energy demand is assumed to be equal to its own price elasticity as given in equation 5-2. For example, with an energy price change (due to energy efficiency improvement) of -1%, a 0.5% increase in energy use suggests R_e = -(0.5/-1.0) = 50%.

$$R_e = -P_e = -\frac{Change\ in\ energy\ use}{Change\ in\ price\ of\ energy} \tag{5-2}$$

Studies with this method are at consumer or industry levels. Consumer studies estimate energy demand (and thus rebound) in terms of energy services (e.g. lumens, passenger-kms) for domestic energy use (e.g. lighting, heating, transport). Sorrell and Dimitropoulous (2007a) collated an extensive set of studies using this approach, and found long run energy service rebound of between 10-30%. More recently, studies led by Fouquet (Fouquet & Pearson, 2011; Fouquet, 2012) found very long run (i.e. over 100 years) own-price elasticity of lighting and passenger transport is around -0.6 to -0.7. (i.e. rebound of 60% to 70%), whilst Chitnis and Sorrell (2015) apply a cross-price elasticity approach to find consumer-sided direct and indirect rebound to be 41% (heating) to 78% (transport). Industry level studies typically examine own-price final energy rebound using econometric cointegration approach. Examples include Bentzen (2004) who estimated US manufacturing rebound of 24% for 1949-1999, and Zhang and Lin (2013) who estimated China's 1994-2008 industrial sector rebound to be 69%.

A second group of studies examine primary energy rebound via primary energy intensity (GDP/energy use, measured in \$/GJ), and assess if primary energy rebound exists by studying if the greatest growth in output (ΔY) occurs at the same time as energy intensities (GJ/\$) decline the fastest. Schipper and Grubb estimated micro-rebound elasticities (for 1970s to 1990s) of 5–15%, and found "no evidence of *substantial* macro-rebounds within a sector, or of an economy-wide macro-effect" (2000, p.386). Figure 5-2 shows an example plot.

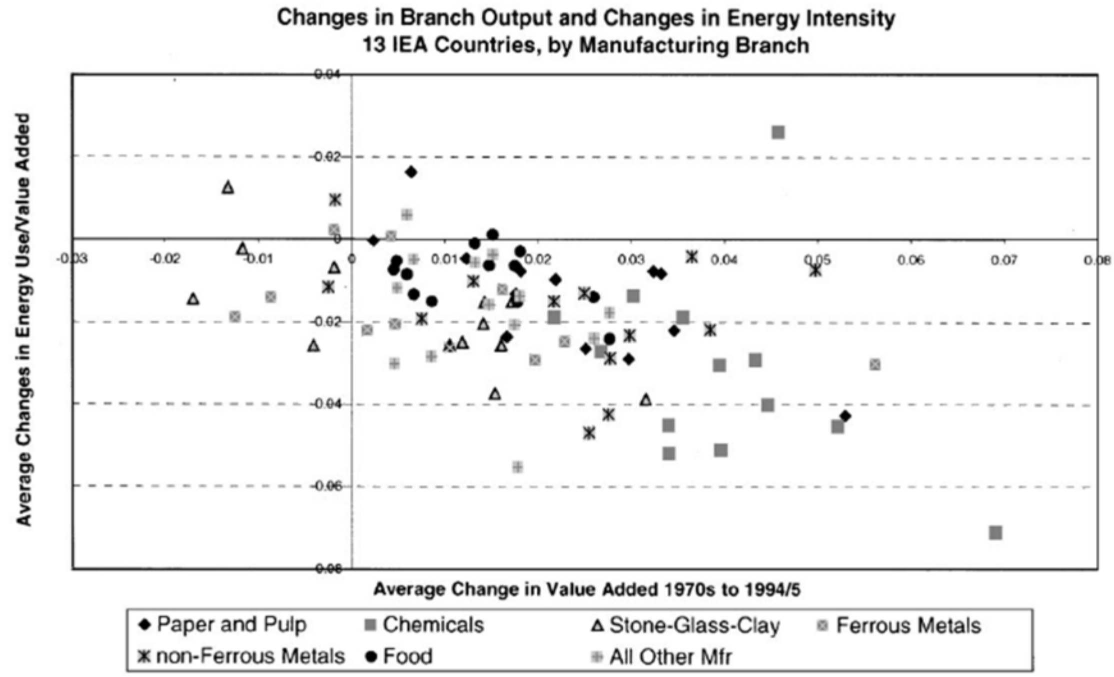

Figure 5-2: Macro-scale rebound study (Schipper and Grubb, 2000)

Sorrell and Dimitropolous are critical that Schipper and Grubb's "dataset does not allow [macro] rebound effects to be measured directly" (2007b, p.61). However Wei (2014) subsequently provided a basis for rebound estimation, using a general equilibrium framework and energy intensity as a measure of energy efficiency to estimate primary energy rebound as backfire (R_e > 1.0) for the case of China 1979-2010.

A third set of studies use macroeconomic models, such as computational general equilibrium (CGE) models (Turner, 2009; Turner & Hanley, 2011), or macroeconometric models (Barker et al., 2007; Barker et al., 2009). In both approaches, rebound is estimated by comparison of energy demand for a base case (no efficiency change) versus an improvement in energy efficiency. Since models are built either at sector or aggregate level, this dictates (due to availability of energy data at that level) if the estimates are for primary energy rebound (aggregate) or final energy rebound (sector-level). In the CGE framework, the effects of energy efficiency can be modelled through changes in prices, which then - under new equilibrium conditions – provide a new estimate of total energy consumed. Comparing the energy demand estimates therefore provides an estimate of energy rebound. Allan et al (2007) examined various

CGE studies, and found each reported rebounds of at least 37%. Barker et al (2009) provides a macroeconometric example, who estimated global economy-wide energy rebound of 52% by 2030, under a ‘no regrets’ IPCC energy efficiency scenario. The model assumed a direct energy demand reduction of 10% from energy efficiency savings, which altered the model through lower prices for goods, and higher economic output.

5.3.1.2 Physical efficiency methods

This method is specific to industry sectors, since it takes physical process efficiency (e.g. GJ/tonnes for steel industry - measured as final energy use in GJ versus tonnes of steel output) as a proxy for energy efficiency. By using industry-level final energy consumption data, final energy rebound is examined. Studies examine if energy efficiency improvements (i.e. reduction in GJ/tes) were larger than rates of increase in energy use. Two recent papers follow this approach. Dahmus studied global nitrogen, pig iron and aluminium sectors, and found “despite significant improvements in efficiency, the resources consumed by each of these activities .. has increased” (2011, p.887). Luke et al (2014) found a 40% increase in Chinese steel-making efficiency during 1990-2010 (assumed from 40% lower process efficiency) was much smaller than the 300% increase in steel sector energy use: evidence suggested as backfire (R_e > 1.0).

5.3.1.3 Thermodynamic efficiency methods

In this method, thermodynamic efficiency is used as the measure of energy efficiency. Two approaches are taken. The first uses aggregate production (or cost) functions to estimate energy rebound. Much of the theoretical framework for this is set by Saunders (1992; 2000; 2008). The basis is to collate variables which help explain economic growth: Capital (K), Labour (L), Energy (E), and insert these into an aggregate function such as that in equation 5-3. Saunders (2008) found that only the aggregate production function that allowed all cases of rebound in Table 5-1 was the CES function with a KL_E nesting structure (i.e. equation 5-3)

$$\mathrm{Y} = \left[a(K^{\propto}L^{1-\propto})^{\rho} + b(E)^{\rho}\right]^{\frac{1}{\rho}} \qquad \textbf{(5-3)}$$

By assuming that E is energy services (rather than primary energy), Saunders is able to provide the CES function in the format of equation 5-4. This is important, since it introduces (via $E = \tau F$) the separate components of fuel use (F), and energy efficiency (τ), where τ is the conversion efficiency from fuel to energy services (and is thus akin to our usage of exergy efficiency, ε).

$$\mathrm{Y} = \left[a(K^{\propto}L^{1-\propto})^{\rho} + b(\tau F)^{\rho}\right]^{\frac{1}{\rho}} \tag{5-4}$$

By applying equation 5-1 to equation 5-4, Saunders (2008) derives from a short term rebound equation where capital remains constant (equation 5-5), and a long term rebound equation which relaxes this constraint (equation 5-6), where σ is the elasticity of substitution (between KL and E), and S_F and S_L are the value shares of energy (fuel) and labour respectively.

$$R_{e\,(short\ term)} = 1 + \eta_{\tau}^{F} = \frac{\sigma}{1 - S_F} \quad ; \quad \eta_{\tau}^{F} = \frac{\tau}{F}\frac{\partial F}{\partial \tau} \tag{5-5}$$

$$R_{e\,(long\ term)} = 1 + \eta_{\tau}^{F} = 1 + \frac{S_F + (\sigma - 1)(1-\propto)}{S_L} \quad ; \quad \eta_{\tau}^{F} = \frac{\tau}{F}\frac{\partial F}{\partial \tau} \tag{5-6}$$

Rebound is then estimated by inserting the econometrically estimated parameters of the aggregate function into the derived rebound equation. Wei (2007; 2010) provides a similar (but arguably more complete) general equilibrium approach. Despite the depth of this theoretical background, few empirical studies of economy-wide primary energy rebound have been undertaken with this method. Wei (2007) uses a Cobb-Douglas framework to estimate rebound based on partial equilibrium (R_e ~ 1.0) and general equilibrium (R_e ~ 2.0) for a US type economy – however Saunders (2008) suggests the Cobb-Douglas function is an inappropriate choice of function as it will always exhibit backfire (R_e > 1.0). Zhang and Lin (2013) use a CES function to estimate China’s 1986-2009 short term primary energy rebound to be over 50% using equation 5-5, rather than long term rebound from equation 5-6. Saunders (2013) applies a cost function approach to industry sectors, to estimate final energy rebound for 30 US manufacturing sectors 1960-2000, finding substantial rebound (R_e~0.5) for energy specific gains and backfire (R_e>1) for all factors rebound.

A second method is based on estimating Actual Energy Savings (AES) versus Potential Energy Savings (PES), with rebound defined as equation 5-7. Hence if AES equals PES, then R_e = 0 (zero rebound), whilst if AES is zero, then R_e = 1.0 (total rebound). This can be applied at final energy level to industry sectors, or primary energy level to aggregate country scale.

$$R_e = \frac{Potential\ Energy\ Saved\ (PES)\ -\ Actual\ Energy\ Saved\ (AES)}{Potential\ Energy\ Saved\ (PES)} \quad \textbf{(5-7)}$$

Using the AES-PES framework, Saunders (2013) estimates final energy rebound for 30 US manufacturing sectors 1960-2000 to be over 50%. Whilst he states this is direct rebound only, given the length of the time-series, longer term macro-economic (restructure) aspects appear to be included. At an aggregate level, Saunders (2015) using this approach estimates 1850-2000 primary energy rebound of Sweden as over 50%.

Based on this AES-PES method, a hybrid economic-thermodynamic approach also exists, where energy rebound is estimated as equation 5-8, where λ is the estimated rate of technical progress (i.e. the Solow residual, estimated via aggregate production functions), Y is GDP output ($), EI is energy intensity (E/Y) (TJ/$).

$$Re_t = \frac{\lambda(Y_{t+1} - Y_t)(EI_{t+1})}{Y_{t+1}(EI_t - EI_{t-1})} \quad \textbf{(5-8)}$$

Empirical case studies using this hybrid method have recently focussed on estimating long term China primary energy rebound. In 2012, three studies (Li & Yonglei, 2012; Li & Lin, 2012; Lin & Liu, 2012) estimated energy rebound to be 53%-74% for periods between 1981-2009. In 2013, Zhang and Lin (2013) estimate 1986-2009 energy rebound as less than 10%, whilst in 2014 Shao et al (2014) estimate 1954-2010 China's national energy rebound of 39%.

5.3.1.4 Weaknesses of current estimation approaches

Looking across the current approaches to the estimation of total energy rebound, we observe four current weaknesses. The first is the lack of a common definition of energy efficiency. As Sorrell notes, "there is no consensus on the most appropriate definition [of energy efficiency] for the purpose of estimating rebound" (2009, p.1459). Madlener and Alcott (2009) suggest selecting a common energy efficiency measure (e.g. physical, thermodynamic or economic) is a priority for rebound studies.

The second weakness is the differing locations of rebound. Estimates of energy rebound can take place at different points in the energy conversion chain: primary energy, final energy, useful energy, or energy services level, as shown in Figure 5-3. Few estimate primary energy rebound, which is what Jevons observed and is most relevant to energy emissions policy. The implicit assumption that estimates at other points directly translates to primary energy rebound is unproven, and may be simply be incorrect.

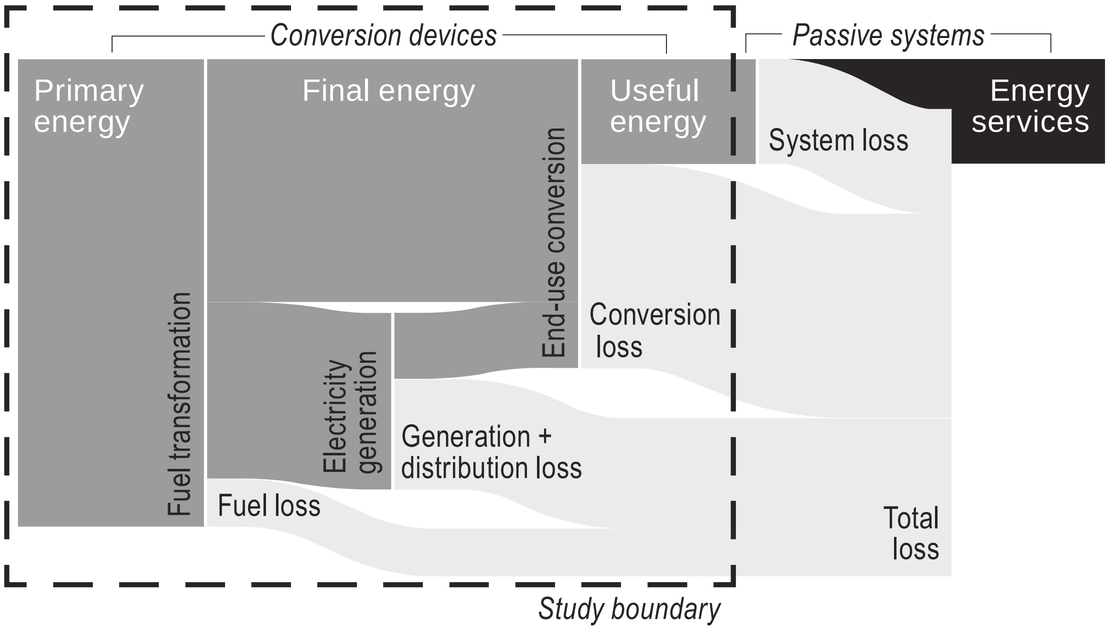

Figure 5-3: Energy conversion chain: from primary energy to energy services (adapted from Cullen et al., 2011)

The third weakness is inconsistent analysis boundaries. Whilst studies may claim or allude to being total rebound, in reality they may focus only on part of the economy. For example, consumer focused rebound studies (e.g. lighting or passenger transport) ignore producer energy use – thereby excluding the majority of energy use (Saunders, 2015). In addition, studies may ignore other macroeconomic effects (e.g. how much has economic output and non-lighting energy use increased due to increases to lighting energy services). Producer (i.e. industry sector) rebound studies are open to a similar critique: they study a subset of the overall economy and ignore wider macro-economic effects outside that sector (e.g. how much have rebound-driven increases in steel output increased energy use in other sectors?). In addition, time is a boundary issue: some studies examine short term (<10 years) and some longer term (>100 years), and longer studies may include greater macro-economic effects (Saunders, 2013).

The fourth weakness concerns flaws in the current methods. Take the commonly used price elasticity study methods: Sorrell et al (2009, p.1359) suggest "estimates of price elasticities should be treated with caution" since they are difficult to estimate, and subject to distortion from factors including demographics and policy. Meanwhile, for production function methods, Sorrell (2014) highlights the importance of the elasticity of substitution to quantify total rebound (e.g. in CGE models), and yet Saunders (2015) demonstrates that variations in the elasticity of substitution (i.e. from energy to capital-labour composite) has a significant effect on rebound results. In addition, whilst multi-method, multi-country studies would allow better comparisons, Zhang and Lin's (2013) China study is the only multi-method approach found.

Sorrell (2010) provides a fair summary of the current problems involved in estimation of total rebound:

"Rebound effects need to be defined in relation to particular measures of energy efficiency (e.g., thermodynamic, physical, economic), to relevant system boundaries for both the measure of energy efficiency and the change in energy consumption (e.g., device, firm, sector, economy) and to a particular time frame. Disputes over the size and importance of rebound effects result in part from different choices for each of these variables". (p.1786)

5.3.2 An alternative approach: The potential role of thermodynamic 'exergy efficiency' in energy rebound studies

The lack of a consistent energy efficiency definition appears a central barrier to estimate long term economy-wide primary energy rebound. Currently, using economic and physical based efficiencies is popular, but they remain proxies for thermodynamic-based energy efficiency, which is ideally what is required for the estimation of thermodynamic energy use and rebound. However, where thermodynamic efficiency approaches have been adopted, their values are not explicitly estimated prior to the rebound analysis.

To overcome this issue, appeal can be made to a tight, thermodynamic-based economy-wide energy efficiency definition. Such a definition exists, where aggregate 'exergy' efficiency may be taken as the thermodynamic measure for energy efficiency. Exergy can be considered as 'available energy' (Reistad, 1975), it is the usable part of energy. As it steps through the energy conversion chain in Figure 5-3, the usable part reduces in size until it is lost in exchange for energy services. This is useful work. Economy-wide energy efficiency as 'exergy' efficiency can be defined as the sum of useful work divided by input primary exergy, as given in equation 5-9:

$$Exergy\ efficiency\ = \frac{Sum\ of\ Useful\ Work}{Sum\ of\ Primary\ Exergy} \tag{5-9}$$

Studies to date have calculated exergy efficiency as an output from the analysis in order to generate useful work data for economic growth studies (Ayres & Warr, 2005; Warr & Ayres, 2012; Ayres & Voudouris, 2014), or to comment on the exergy efficiency trend itself for energy analysis purposes (Serrenho et al., 2014; Brockway et al., 2015). However, studies using exergy efficiency have not been applied to estimate economy-wide energy rebound, and this presents our research opportunity: examining whether exergy efficiency as the measure for energy efficiency may provide a more consistent basis for estimating total rebound, and overcoming current weaknesses.

5.4 An exergy efficiency based approach to estimate total energy rebound - Methods and data

Available exergy efficiency and useful work time-series datasets from previous studies by Brockway et al (2014; 2015) are applied to the two thermodynamic-based methodologies given in Section 5.2: the APF and AES-PES methods. Since both methods use the estimated CES function parameters, the estimation of this function is presented first. A more complete discussion of the choices and issues for specifying and solving the CES function is given in Chapter 4.

5.4.1 Econometric estimation of the CES aggregate production function

There are three econometric estimation steps. First, the CES function is specified. Saunders (2008) rebound flexible KL(E) nested CES function given in equation 5-4 is the obvious choice as the basis for our rebound analyses. We broaden equation 5-4 to allow non-unity substitutability between K and L in the inner (K-L) nest, with the resulting function is shown in equation 5-10:

$$Y = \theta\, A[\delta_1[(\delta\, K^{-\rho_1} + (1-\delta)L^{-\rho_1}]^{\rho/\rho_1} + (1-\delta_1)(\tau F)^{-\rho}]^{-\frac{1}{\rho}};\, A \equiv e^{\lambda t} \qquad \textbf{(5-10)}$$

where δ and δ_1 are share parameters (different from output elasticities), ρ and ρ_1 are substitution parameters (leading to Hicks elasticities of substitution of $\sigma_1 = 1/(1+\rho_1)$ within the inner (K-L) nest and $\sigma = 1/(1+\rho)$ between the inner (K-L) nest and outer (τF) nest, θ is a scale parameter, A is Total Factor Productivity (TFP). Whilst equation 1-11 allows the derivation of energy rebound for the APF method in Section 5.3, to estimate the parameters of the function, we can replace τF in equation 5-10 by a single, useful work (U) term (since $U = \varepsilon E = \tau F$), where ε is exergy efficiency, and E is primary exergy (primary energy measured as exergy). Thus for CES function estimation, equation 5-10 translates to a CES function of the form KL(U) as shown in equation 5-11:

$$Y = \theta\, A[\delta_1[(\delta\, K^{-\rho_1} + (1-\delta)L^{-\rho_1}]^{\rho/\rho_1} + (1-\delta_1)(U)^{-\rho}]^{-\frac{1}{\rho}} \quad ; \quad A \equiv e^{\lambda t} \qquad \textbf{(5-11)}$$

Second, the input data is assembled. In this case, these are annual time-series of Y, K, L, and U, for the UK (1980-2010), US (1980-2010), and China (1981-2010). The output measure (Y) is taken as GDP data in 2005 constant prices from the Penn World Tables 8.1 (Feenstra et al., 2015). Quality-adjusted labour (L) and capital (K) data are used, which as discussed by in Chapter 4 (Brockway et al (2016)) seeks to better account for the productive effect of raw labour (workhours) and capital (stock) inputs. As such, quality adjusted inputs are being more widely used in growth accounting studies (Nilsen et al., 2011; Daude, 2014; Hájková & Hurník, 2007). For labour, quality-adjusted total hours are obtained via a human capital indices from Barro and Lee (2014), multiplied by average hours worked per individual times engaged individuals for US and UK from

PWT8.1. (Feenstra et al., 2015) and for China from Wu (2014). For adjusted capital (i.e. capital services), the UK data was sourced from Wallis and Oulton (2014), the US data was assembled by splicing 1987-2010 data (US Bureau of Labour Statistics, 2015) and 1980-2001 data (Schreyer et al., 2003). For China, capital service data was obtained for 1981-2010 from Wu (2015). It is the availability of capital services data that constrains the time-period studied for the US and China. Annual useful work data for the UK, US and China was that obtained in previous analyses by Brockway et al (2014; 2015), i.e. Chapter 2 and 3 of this thesis.

Having obtained the input data, it is then normalised against base years of 1980 (UK), 1980 (US) and 1981 (China), in line with recommendations by Temple (2012). This enables data with different units to be combined in production functions. By convention, the parameters Y, K, L, U become lower case y, k, l, u when normalised, as shown in equation 5-12:

$$y = \theta\, A[\delta_1[(\delta\, k^{-\rho_1} + (1-\delta)l^{-\rho_1}]^{\rho/\rho_1} + (1-\delta_1)(u)^{-\rho}]^{-\frac{1}{\rho}} \quad ; \quad A \equiv e^{\lambda t} \qquad \textbf{(5-12)}$$

The normalised values of the data are shown in Figure 5-4 to Figure 5-7:

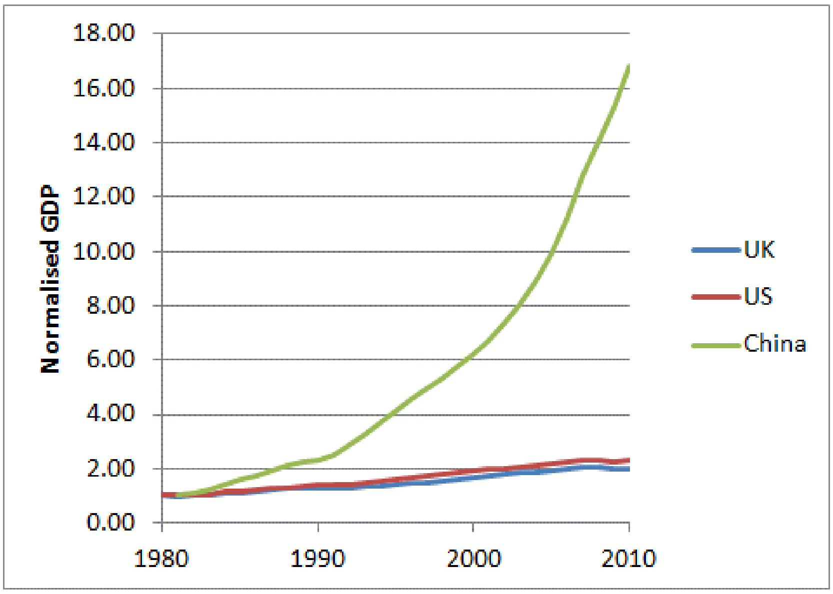

Figure 5-4: UK, US, China – normalised GDP (y)

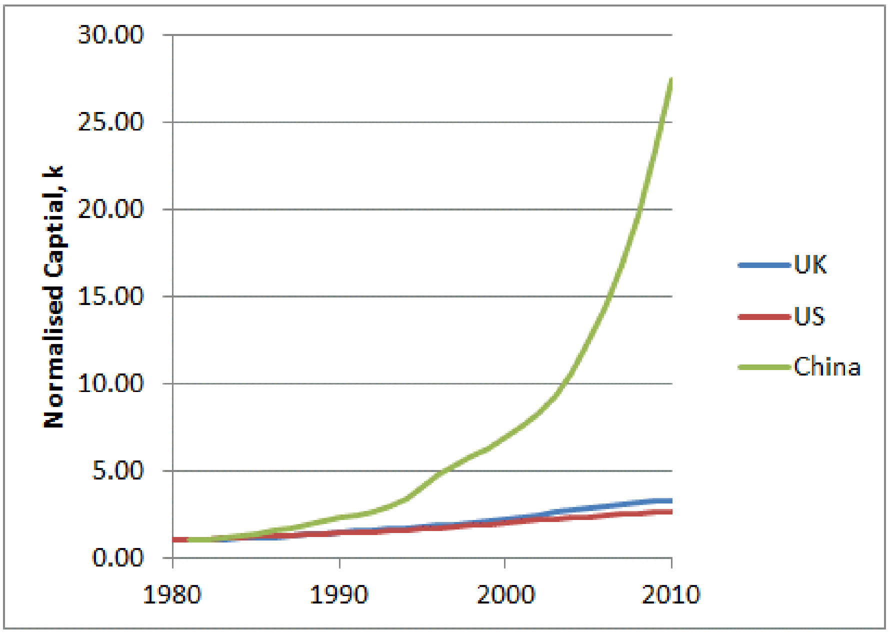

Figure 5-5: UK, US, China – normalised capital (k)

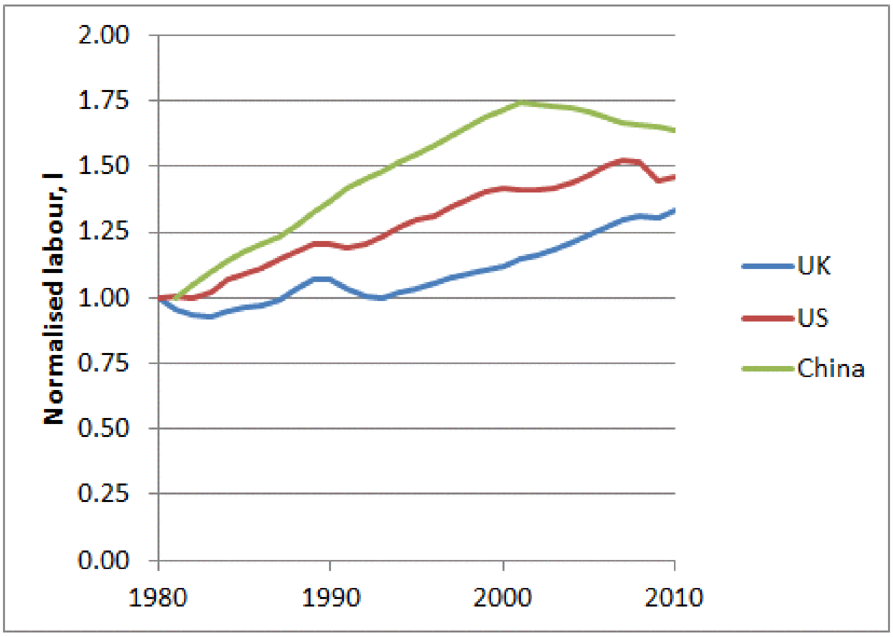

Figure 5-6: UK, US, China – normalised labour (l)

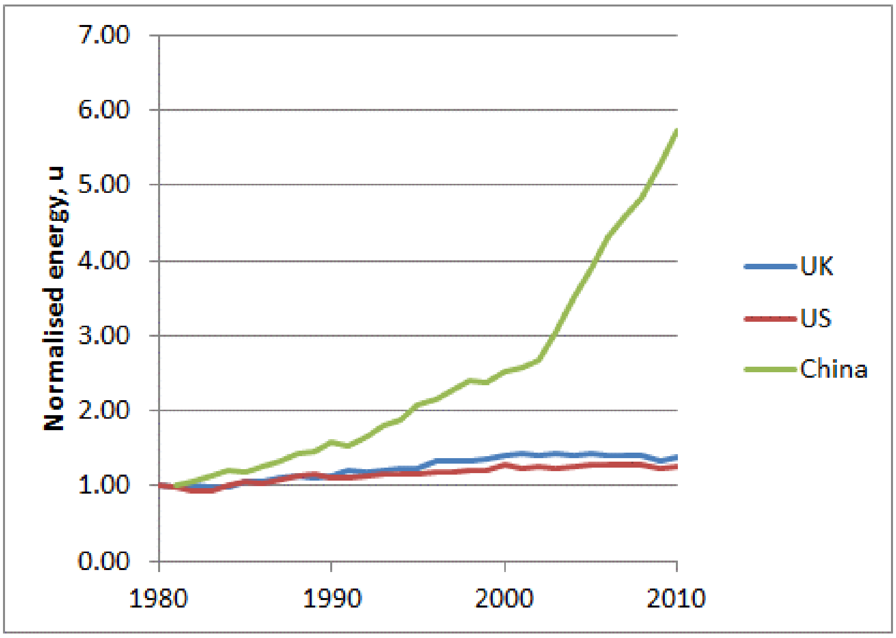

Figure 5-7 UK, US, China – normalised useful work (u)

The third step is to estimate values for the six unknown parameters: $\theta, \lambda, \delta, \delta_1, \rho, \rho_1$. In our case, it is performed on the normalised equation 5-12 using a non-linear technique developed by Henningsen and Henningsen (2011; 2012). This establishes base-fit estimates of the unknown parameters. To provide an estimate of their precision in the rebound calculations, we also estimate 95% resampling intervals for the key variables (λ, ρ), based on 1000 resamples in a bootstrapping technique. Since our sample is small (30 values from 1980-2010), we cannot assume normal distributions to estimate confidence intervals. Bootstrapping is ideal when such sample sizes are low. The technique takes a random resample of 30 points from the original sample data. Since it is random, some values may be included in the resample more than once. The solution is then estimated as before. This is repeated in our case 1000 times. The 2.5% and 97.5% values[22] therefore provide an estimate of the 95% confidence interval of the estimated parameters. A more detailed description is presented in Santos et al (2016).

[22] The 2.5% and 97.5% values are those of the 25th and 976th ranking in order of magnitude.

5.4.2 Exergy efficiency based estimation of energy rebound

In parallel to the CES function estimation, the two methods now derive their equations for long term primary energy rebound.

5.4.2.1 APF method

Using equation 5-10, the long term primary energy rebound equation was derived (as given in Appendix C), with the final equation given in equation 5-13.

$$Re = \frac{(1 + s_F + s_K)(1 + \rho) + (\rho(s_F - s_K - 1) + s_F)}{(1 + s_F + s_K)(1 + \rho)} \quad \textbf{(5-13)}$$

Where ρ is determined by the solution to the CES equation, and S_F and S_k are the value shares of fuel (energy) and capital respectively, given in equation 5-14 and equation 5-15:

$$s_F = \frac{p_F}{c}\frac{F}{Y} \quad \textbf{(5-14)}$$

$$s_K = \frac{p_K}{c}\frac{K}{Y} \quad \textbf{(5-15)}$$

where $\frac{p_F}{c}$ and $\frac{p_K}{c}$ are cost fractions, and $\frac{F}{Y}$ and $\frac{K}{Y}$ are output shares using normalised values of F, K and Y, as suggested by Saunders, (2015) p.45), who also notes to be consistent with duality theory[23], c = 1. The average cost fractions over the period analysed for energy for UK (Platchkov & Pollitt, 2011) and US (US Energy Information Administration (US EIA), 2011) are around 8%. For China, the energy cost fraction is unknown, but we take it as slightly higher (10%), based on the assumption that the economy is less competitive, and so energy will be relatively more expensive. The sensitivity of this assumption is evaluated in Section 5.5, by comparing estimates of rebound for energy cost fractions ranging from 0-20%. The capital/labour cost share was assumed to be a 30%/70% split based on Schneider (2011) using AMECO[24] data as shown in Figure 5-8:

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[23] Duality requires both primal (output maximisation) and dual (cost minimisation) requirements are met.

[24] AMECO is the European Commission's annual macro-economic database, available at http://ec.europa.eu/economy_finance/ameco/user/serie/SelectSerie.cfm

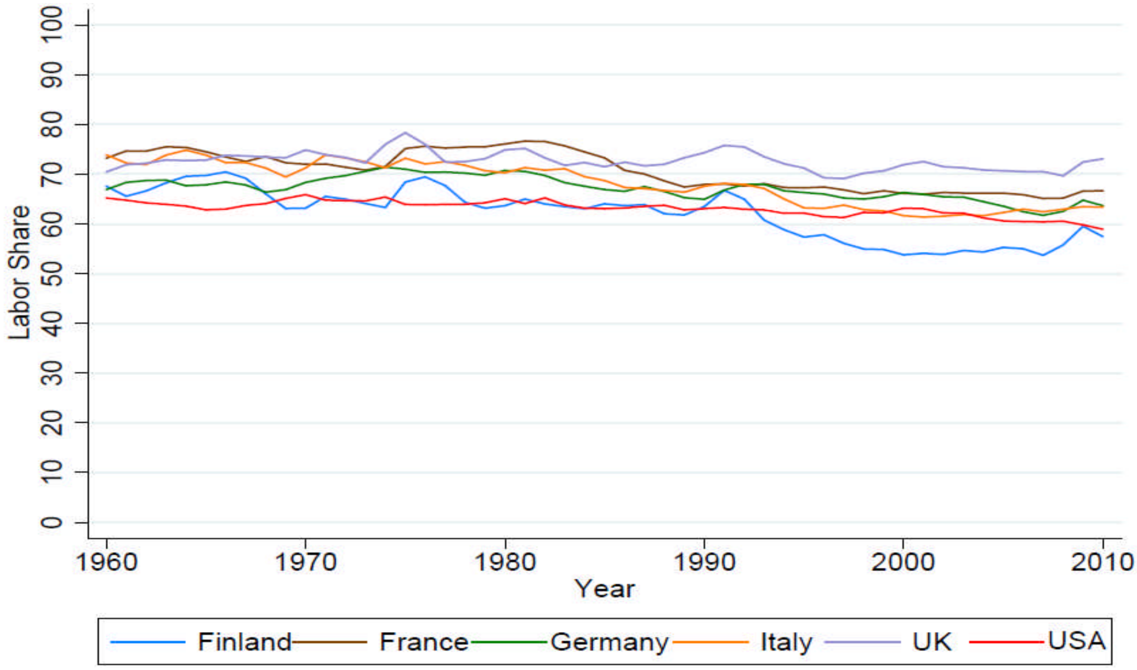

Figure 5-8: Labour shares for selected countries (Schneider, 2011)

For China, an average value of 50% is adopted, based on available data[25], as shown in Figure 5-9:

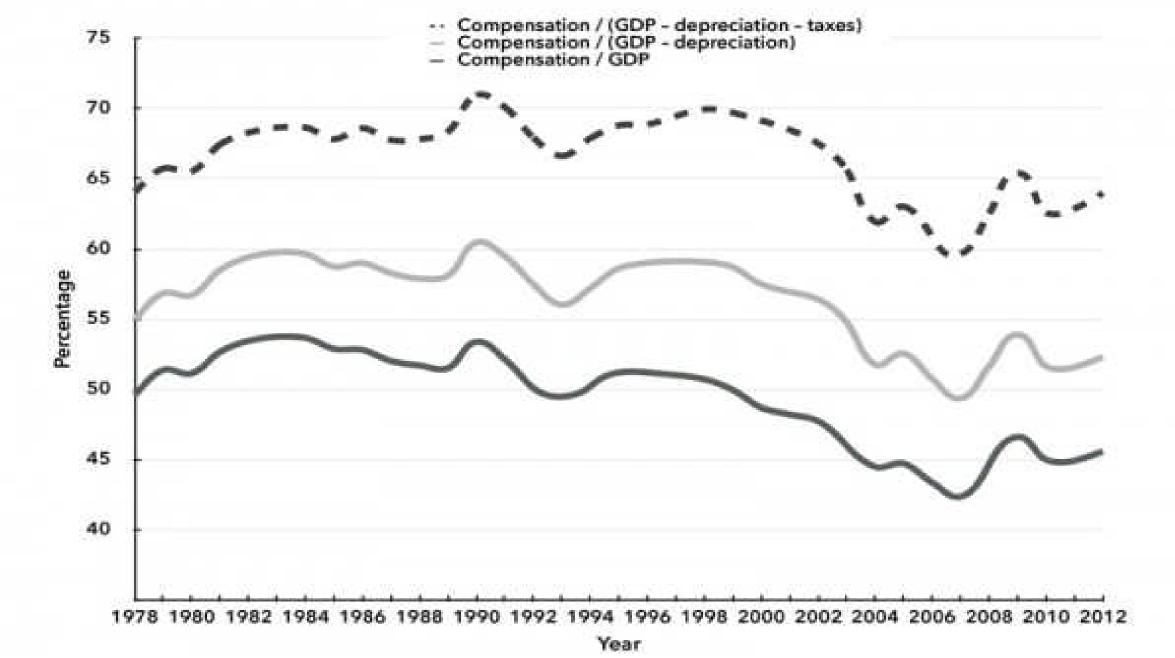

Figure 5-9: Labour shares for China (Schneider, 2011)

25 http://monthlyreview.org/2014/01/01/labor-share-question-china/

To account for the cost of energy, the cost fractions of energy, labour and capital add to 1.0. Finally, the average values for output shares, $\frac{F}{Y}$ and $\frac{K}{Y}$, are then used to calculate the value shares in Table 5-2:

Table 5-2: Calculated value shares, S_F, S_K

Country and time-scale	$\frac{p_F}{c}$	$\frac{F}{Y}$	S_F		$\frac{p_K}{c}$	$\frac{K}{Y}$	S_K
1980-2010 – UK	0.08	0.69	0.06		0.28	1.29	0.36
1980-2010 – US	0.08	0.75	0.06		0.28	1.06	0.30
1981-2010 - China	0.10	0.27	0.03		0.45	1.22	0.55

5.4.2.2 AES-PES method

The AES-PES method's expression for long term rebound is stated as equation 5-7, leading to the final derived format in equation 5-8. To move from equation 5-7 to equation 5-8, first let us find an expression for the denominator, PES. Taking Y_t as GDP in year t, and EI_t as Energy intensity (E_t /Y_t) in year t, the logic is as follows. In year t, the energy use is Y_t * EI_t, whilst in year t+1 it is Y_{t+1} * EI_{t+1}, If no technical change occurred from year t to t+1, the energy use in year t+1 would be Y_{t+1} * EI_t. Therefore the potential energy saving of technical change (energy efficiency) is given by equation 5-16:

$$PES = Y_{t+1} * (EI_t - EI_{t+1}) \quad \textbf{(5-16)}$$

Then, the expression for the numerator, PES-AES, can be found as the additional energy consumption due to technical progress (assumed from energy efficiency) is given by the change in energy use from year t to t+1 as shown in equation 5-17.

$$PES - AES = \lambda_{t+1} * (Y_{t+1} - Y_t) * (EI_{t+1}) \quad \textbf{(5-17)}$$

where λ_{t+1} is the Solow residual in year t+1, i.e. the fraction of economic growth which is exogenous (attributed to technical progress). The resultant expression for rebound (R_e = (PES-AES)/PES) is then obtained as given earlier in equation 5-8. The only variable used from the CES function solution is λ_{t+1}. A similar description of the logic is in Zhang & Lin (2013), but we replace their symbol σ with λ, to avoid confusion with σ as the elasticity of substitution.

5.5 An exergy efficiency based approach to estimate total energy rebound - Results

5.5.1 The CES aggregate production function results

The non-linear fitting procedure gives the following results for the six unknown parameters and overall fitting statistics in Table 5-3:

Table 5-3: CES function estimated parameters and statistics

Country	Value	Estimated parameter								
		γ	λ	δ_1	δ	ρ_1	ρ	σ_1	σ	R^2
UK	2.5% resampled	0.996	0.0120	0.018	0.000	-1.000	22.70	Inf	0.042	
	Base-fit	1.014	0.0129	0.053	0.013	-1.000	65.15	Inf	0.015	0.998
	97.5% resampled	1.029	0.0137	0.859	0.771	171.3	1254	0.006	0.001	
US	2.5% resampled	0.974	0.0034	0.262	0.675	-1.000	-1.00	Inf	Inf	
	Base-fit	0.987	0.0093	0.338	1.000	-1.000	84.78	Inf	0.012	0.999
	97.5% resampled	0.994	0.0109	1.000	1.000	16.51	113.3	0.057	0.009	
China	2.5% resampled	0.959	0.0462	0.036	0.310	-1.000	-1.00	Inf	Inf	
	Base-fit	0.980	0.0559	1.000	0.532	228.1	-0.52	0.004	2.082	0.999
	97.5% resampled	1.024	0.0606	1.000	0.724	548.5	1.07	0.002	0.484	

The two parameters which serve as inputs to the APF and AES-PES estimation methods are ρ and λ respectively. As we can see from Table 5-3, the value of λ is estimated with greater precision, versus that of ρ. In addition, the resampled values of ρ and λ generally provide highly asymmetric intervals of precision.

5.5.2 Exergy efficiency based estimation of energy rebound

5.5.2.1 APF method results

From the estimated values of ρ given in Table 5-3, we estimate from equation 5-13 the values of primary energy rebound (R_e), as shown in Table 5-4:

Table 5-4: APF method – total energy rebound results

Rebound value	UK (1980-2010)	US (1980-2010)	China (1981-2010)
$Re_{2.5\%\ resample}$	0.16	0.19	0.54
$\boldsymbol{Re_{basefit}}$	0.17	0.19	2.08
$Re_{97.5\%\ resample}$	0.20	INF	INF

The basefit results suggest that the UK and US have partial energy rebound (R_e ~ 0.2), whereas China exhibits backfire (R_e > 1.0). The UK results have a very tight banding between resampled values. Both the US and China have highly asymmetric resampled values, given their upper bound values are reported as infinite, since in equation 5-13 the value of ρ = -1 means the denominator is zero.

5.5.2.2 AES-PES method results

The results of the AES-PES method are shown in Table 5-5. This suggests that the UK-US have partial energy rebound (R_e = 0.3-0.5), whilst China exhibits higher rebound (R_e=0.9), but below backfire. The resampled bound values provide similar results, since they are close to the basefit values.

Table 5-5: AES-PES method – total energy rebound results

Rebound equation component		UK (1980-2010)	US (1980-2010)	China (1981-2010)
(A_1)	$\frac{\lambda_{2.5\% resample}}{GDP\ av\ growth}$	0.509	0.107	0.505
(A_2)	$\frac{\lambda_{basefit}}{GDP\ av\ growth}$	0.547	0.293	0.612
(A_3)	$\frac{\lambda_{97.5\% resample}}{GDP\ av\ growth}$	0.582	0.344	0.663
(B)	$\frac{Y_{t+1} - Y_t}{Y_{t+1}}$	0.022	0.026	0.093
(C)	$\frac{EI_t - EI_{t+1}}{EI_{t+1}}$	0.023	0.022	0.066
$Re_{2.5\% resample} = \frac{A_1 * B}{C}$		0.50	0.13	0.71
$\boldsymbol{Re_{basefit}} = \frac{\boldsymbol{A_2} * B}{C}$		0.53	0.35	0.86
$Re_{97.5\% resample} = \frac{A_3 * B}{C}$		0.57	0.41	0.93

5.6 Discussion

5.6.1 APF and AES-PES method results

5.6.1.1 Rebound estimates and comparison to other studies

First, the base-fit results[26] are given in Figure 5-10:

[26] For the purposes of comparison to other studies, the rebound results in this section are presented in % form

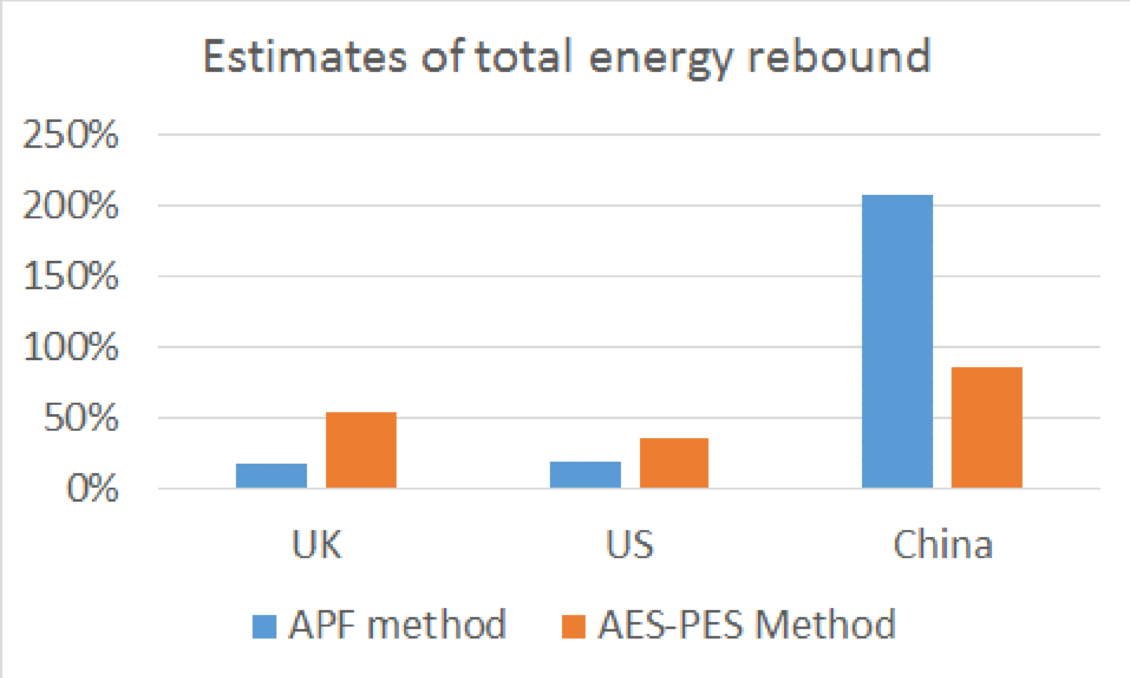

Figure 5-10: Summary of base-fit rebound results

From Figure 5-10, we can see that both methods give broadly similar results: partial rebound (R_e ~ 15%-50%) for the UK and US, but much higher rebound (R_e ~ 90%-210%) for China. These findings seem at least partly supported by the literature. For the UK and US, the estimates are similar to the 25-40% range suggested by Jenkins et al (2011) for developed countries, and estimates for OECD economies such as Barker et al (2007) and Saunders (2015), suggesting total rebound of 25-70%. Other estimates of rebound for developed economies such as the UK and US tend to focus on parts of the economy, such as households (rebound of 30-50%) (Chitnis & Sorrell, 2015; Thomas & Azevedo, 2013); energy services rebound up to 70% from lighting, heating and transport sectors (Fouquet, 2014); and 24% US manufacturing sector rebound (Bentzen, 2004).

Focussing on China, Table 5-6 presents six total rebound estimates found in the literature using the AES-PES or APF methods:

Table 5-6: Other long term total rebound estimates for China

Source (reference)	Time-series	Method *	Estimate of total rebound
Li & Yonglei, (2012)	1997-2009	AES-PES (CD)	74%
Lin and Liu (2012)	1981-2009	AES-PES (SRM)	53%
Li and Lin (2012)	1985-2008	AES-PES (CD)	67%
Zhang and Lin (2013)	1979-2004	AES-PES (CES)	41%
	1981-2009	APF (CES)	52% (short term)
Shao et al (2014)	1954-2010	AES-PES (LVA)	37%

Notes

* To estimate the value of λ - the estimated rate of technical progress (Solow residual) - for insertion in AES-PES rebound equation (5-8), the studies use four methods: CD (Cobb-Douglas), CES (Constant Elasticity of Substitution), SRM (Solow Remainder Method) and LVA (Latent Variable Approach).

The five AES-PES studies in Table 5-6 have broadly consistent results: estimating total energy rebound to be 37% to 74%. This is lower than our base-fit AES-PES estimate of 86%. If we assume that all AES-PES studies (including ours) contain broadly similar energy intensity (EI) values, it suggest our estimate of λ (Solow residual) is significantly higher than the other studies. Considering the APF method, only one study (Zhang and Lin, 2013) provides a comparable estimate. Their 52% estimation is for short term rebound - which Saunders (p.2208, 2008) suggests in such cases long term rebound is slightly higher. Our much higher APF method estimate of over 200% is based on the higher elasticity of substitution ($\sigma \sim 2.0$).

Therefore, in both methods, the impact of the key CES parameters (Solow residual and elasticity of substitution) can be clearly seen. Given such sensitivity, the resampling values provide further insight, and are given in Table 5-7:

:

Table 5-7: Total energy rebound results including resampling

Estimation method	Rebound value	UK (1980-2010)	US (1980-2010)	China (1981-2010)
APF method	$Re_{2.5\%\,resample}$	0.16	0.19	0.54
	$Re_{basefit}$	0.17	0.19	2.08
	$Re_{97.5\%\,resample}$	0.20	Inf	Inf
AES-PES method	$Re_{2.5\%\,resample}$	0.50	0.13	0.71
	$Re_{basefit}$	0.53	0.35	0.86
	$Re_{97.5\%\,resample}$	0.57	0.41	0.93

From the wider reported ranges in Table 5-7, we have less (statistical) confidence in the basefit values for the APF method. The APF values also suggest that that we have an indication for the US that there is partial rebound, but we can't rule out backfire based on the data at hand. For China, there is also considerable uncertainty, with a stronger indication of backfire – given this is reported for both the basefit and $Re_{97.5\%\,resample}$ values. Table 5-7 also highlights another issue: the upper bound ($Re_{97.5\%\,resample}$) APF results suggest infinite rebound for the US and China. As noted earlier it stems from the fact that $\rho = -1$ means the denominator in equation 5-13 becomes zero, and rebound is then infinite. As $\sigma = 1/(1+\rho)$, we see how such cases of infinite reported rebound occur when the elasticity of substitution is also infinite, i.e. savings in energy can be substituted without any restraint by capital-labour. As infinite rebound is obviously not possible - energy savings cannot lead to infinite energy use – we may view this result as both suggestive of backfire and also a limitation of the method.

5.6.2 Interpretation

The key results are the finding of partial rebound for UK-US and higher rebound (close to, or above backfire) for China. The literature relating to producer versus consumer rebound is relevant, since the UK-US economies are at a more developed, service-based stage, versus China, which is an industrialising nation. We might expect the UK-US to follow consumer-sided studies, whilst China might follow producer-sided studies. After reviewing available literature, the IPCC suggests consumer sided rebound may be of the order of 20-45% (IPCC, 2014) – a similar magnitude to our study results. Whilst quantitative studies of producer-sided rebound are much rarer - as noted by Saunders (2015) - Stern (2011) describes how producer rebound may be higher (than consumer rebound), as producer responses (i.e. increasing outputs) are not constrained by a fixed nominal income (as in the case for consumers). Van den Bergh (2011) advocates that developing (or in China's case - industrialising) countries would have higher rebound than a developed (mature) economy due to four factors: higher growth rates; highly intensive energy use; higher cost of energy; and lack of saturation in key energy services. All of these are true in the case of China. Ouyang et al (2010) also pick out the lack of energy service saturation as a key reason for China's higher energy rebound.

Our analysis also some support for this interpretation. First is the information from CES functions itself, especially the elasticity of substitution (σ_1) from the capital-labour composite to energy: found for the basefit results to be very low for the UK (0.02) and US (0.01), but high for China (2.08). Economic theory suggests where σ is low, energy is not easily substituted for capital-labour. This mean that energy savings (at low σ) would stay largely within the energy sector, with smaller rebound as a result. For larger σ, such as in China's case, energy is more easily substitutable for capital-labour, and so energy savings would be replaced by an increase in capital-labour, which in turn increases energy use. Thus rebound would be expected to be higher in such cases.

The sensitivity of the APF results to energy cost share is presented in Figure 5-11. This also shows two effects. First, China's rebound is essentially independent of fuel costs, as the value is governed by its high elasticity of substitution between energy and capital-labour. Second, on a related note, when the energy cost share approaches zero, energy rebound (R_e) tends to the value of the elasticity of substitution, σ.

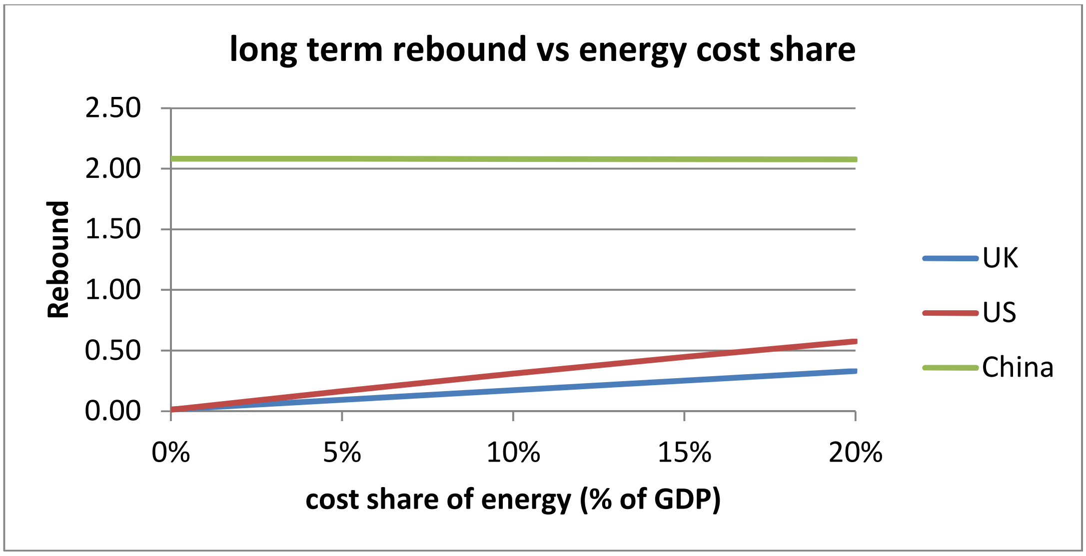

Figure 5-11: APF method: sensitivity of base-fit results to energy cost share

This makes sense as, if S_F= 0, then equation 5-13 reduces to equation 5-18:

$$Re = \frac{1}{(1+\rho)} = \sigma \qquad \textbf{(5-18)}$$

The APF method also allows us to split rebound in two parts - as shown by Saunders, p.2197 (2008). In the first part, equation 5-19 records the intensity (or substitution) effect, i.e. the relative change in energy use from input substitution, with output held constant. As Saunders notes, this is akin to reporting the change in energy intensity (F/Y) given a change in fuel efficiency ($\Delta\tau$), or more exactly: “the intensity effect describes the dynamic of the fuel/output ratio in response to τ” (Saunders, 2008, p.2197). In the second part, equation 5-20 depicts the relative change in energy use from changes in output, with intensity (F/Y) held constant.

$$\eta_\tau^{F_{Intensity}} = \frac{\tau}{F}\frac{\partial F}{\partial \tau} - \eta_\tau^{F_{Output}} = \frac{(\rho(s_F - s_K - 1) + s_F) - (s_F)(1+2\rho)}{(1+s_F+s_K)(1+\rho)} \qquad \textbf{(5-19)}$$

$$\eta_\tau^{F_{Output}} = \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} = \frac{s_F}{(1+s_F+s_K)}\left(\frac{1+2\rho}{1+\rho}\right) \qquad \textbf{(5-20)}$$

Table 5-8 presents the results in this form, i.e. splits the overall rebound for the APF method into two parts. To explain the values, consider rebound as occurring in two stages. First, is rebound from the intensity effect (i.e. rebound holding output constant). In this case we find partial rebound for the UK and US (R_{e1} = 0.1), but much higher rebound (backfire) for China (R_{e1} = 2.1). The second component (i.e. the output response) is then added to the first result, causing UK and US rebound to increase from 0.1 to 0.2, whilst remaining at 2.1 for China. Thus in our analysis, the two effects are similar for the UK and US, but are wholly dominated by intensity effects for China. The latter is a similar to that predicted by Saunders (Table 3, 2008), whereby rebound at high elasticity of substitution is governed by intensity effects.

Table 5-8: APF method rebound - output and intensity components

Country	Intensity effect $\eta_{\tau}^{F_{Intensity}}$	$R_{e1} = 1+\eta_{\tau}^{F_{Intensity}}$	Output effect $\eta_{\tau}^{F_{Output}}$	$R_e = 1+\eta_{\tau}^{F_{Intensity}} + \eta_{\tau}^{F_{Output}}$
UK	-0.91	0.09	0.08	0.17
US	-0.90	0.10	0.09	0.19
China	1.08	2.08	0.00	2.08

5.6.3 Wider discussion

There are three broader points to raise. First, is that our (and other) studies ignore the effect of energy (and thus rebound) embedded in trade: if China has a higher rebound value owing to its producer sided activities, this is due in large part to the demands for products manufactured in China from countries such as the UK and US. In other words, we are offshoring rebound, in the same way we offshore carbon emissions. So in a study based on a consumption based approach, we might expect the UK and US rebound to increase, and China's to reduce.

Second, is the idea that energy rebound may have a conflicting effect on energy and economic policy. For example, whilst significant rebound would hinder emissions reduction policies, the same rebound might stimulate increased economic growth, as advocated by the key 'engine of growth' arguments of Ayres and Warr (2010). In this case it also broadens the delivery of energy services, i.e. more people have access to more services such as lighting, transport, heating - which should be included in the balance sheet. Irrespective such conflicts, as Van den Bergh (2011) suggests, the sensible first step would be to include rebound in energy economic models and policy, since currently rebound is largely ignored. For example, he outlines how a ceiling to total energy consumption may prove an effective policy, enacted through a cap and trade system. Shao et al (2014) suggest for China, that further energy market liberalisation coupled to energy taxes will help to mitigate and reduce rebound effects. Jenkins et al concur, advocating taxes should be “sufficient to keep the final price of energy services constant despite improvements in energy efficiency, eliminating any net productivity gains from the efficiency measures” (2011, p.53).

Third, the provision of resampling results is an important advance on current studies, which provide only basefit estimates. The resampling distribution gives a sense for the precision with which we can determine the basefit rebound estimate: in our case with greater confidence for the UK, less so for the US and China. It also suggests greater precision with the AES-PES method versus the APF method. It also indicates how if further work gather more or improved data, this in turn might improve the precision of the rebound estimates by narrowing the uncertainty band.

5.6.4 Exergy efficiency – how well does it address the weaknesses of current methods?

5.6.4.1 Comparison to current approach weaknesses

First, the exergy efficiency values have provided the first empirical use of aggregate thermodynamic efficiency data in rebound calculations. Previously methods have typically used physical, economic or hybrid proxies. When thermodynamic efficiency has been used, it was estimated as part of the estimation process, i.e. it is an unknown CES function parameter. Given the key barrier of the diffusion of current energy efficiency proxies, the use an exergy efficiency based approach offers a possible route forwards.

Second, considering the location of rebound in the energy conversion chain, the APF and AES-PES methods used both estimate primary energy rebound. This is appropriate, and exactly the point in the energy conversation chain that rebound should be assessed given its impact on GHG emissions. But the analysis also has the benefit that it provides assessment of useful work and its link to economic growth. This is potentially important for economic policy, if stronger linkages between U-GDP than E-GDP are established. Thus the method offers an estimate of total energy rebound in the correct (primary energy) location, plus an assessment of the link between energy and economic growth at potentially a more meaningful place – i.e. useful work - as first suggested by Percebois (1979).

Third, considering boundary scale issue, the new exergy efficiency based methodology meets the core requirements that many studies do not meet, by providing country-scale assessments of total economy-wide energy rebound, over a long term timeframe of 30-50 years. Further refinement of the approach would allow other relevant boundary issues to be studied, for example splitting the analysis into producer and consumer rebound, and also to study separate time periods – such as pre and post 1990 for China, which would be very interesting given the changes in economic structure.

5.6.4.2 Limitations of approach

However, the exergy-based technique has several possible limitations, which are now set out. First is that both methods are based on the econometric estimation of the KL(E) aggregate CES production function. So any limitations in the CES aggregate function itself may be passed on to both APF and AES-PES methods. One example is the Solow residual (Lambda, λ), which is assumed as Hicks-neutral, meaning it is “unable to accurately reflect practical technological contribution to economic growth because it contains factors which are too broad” (Shao et al., 2014, p.239). In simple terms, the assumption that technical progress stems from energy efficiency gains may be incorrect: perhaps much of it is from labour productivity gains and not energy efficiency at all. In response, the CES function could be adjusted to split the components of efficiency gains between input factors of production to identify the contribution of efficiency to growth without recourse to the Solow residual. Another example is that the CES function is constructed based on the assumption of partial equilibrium, and thus ignore changes to the cost of economic output (c) that arise from efficiency gains (τ). Amending the approach to account for such general equilibrium effects along the lines of Wei (2010) may change the results.

Second, the exergy efficiency and useful work datasets used as inputs to the rebound analysis are based on an approach which lacks a universal, consistent methodology. This is discussed by Sousa et al (2016), who highlight several areas for improvement, which – once addressed – will strengthen the analysis and provide more robust exergy efficiency datasets. Therefore the estimation of the CES function and rebound will be affected by any methodological flaws in the exergy-based datasets.

Third, exergy efficiency is used in this analysis as an aggregated value, whereas previous work In Chapter 3 (Brockway et al., 2015) has decomposed the changes in the overall value into structural and device-efficiency effects. Incorporating an efficiency metric separate from structural changes may provide a more precise efficiency contribution for the estimation of rebound.

5.7 Conclusions

Current methods to estimate long term economy-wide energy rebound exhibit four key weaknesses owing to differences in their energy efficiency definitions, locations in the energy chain, analysis boundaries, and robustness of methods. In response, we advance a thermodynamic based approach using values of exergy efficiency and useful work, and apply this in a first empirical, multi-country, multi-method study, to estimate total long-term primary energy rebound for the UK, US and China.

Our key findings – in terms of estimated rebound – is that of partial rebound in the UK and US but higher rebound (close to, or exceeding backfire) in China. This is aligned to other studies, where higher rebound is expected in producer-sided economies (such as China), versus consumer-sided economies such as the UK. In addition, the resampled results add another layer of information and help build a more complete picture of the analysis results – for example the US economy may actually have much higher rebound than the basefit results suggest.

The exergy efficiency based methods advanced here to estimate total energy rebound can be taken as a step forward to help overcome flaws of assuming proxies for energy efficiency (such as price elasticity), by instead using empirical values of national-level thermodynamic efficiency. By mitigating some of the weaknesses in current methods, we edge closer to the desire of Madlener and Alcott, who state “the ultimate goal must be the measurement of total rebound” (2009, p.374). However, 150 years after Jevons, the practical reality is that we will never know with the true value of energy rebound, because the absence of a counterfactual will always mean that rebound will be modelled and not empirically measured.

Therefore the starting point for policy is to include rebound on a precautionary approach, taking the best available evidence to inform policy, since the Jevons paradox may never be resolved. Such evidence may include general trends, such as rebound for differing maturities of economy. For energy efficiency and emissions policies, individual policies should include rebound, and sum to more than the energy reduction targets. Last, a largely unaddressed but thorny issue is that of policy conflicts caused by rebound: such as how energy rebound may weaken emissions policies but enhance economic growth and welfare goals.

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Chapter 6
Synthesis and conclusions

6.1 Introduction

This Chapter first presents the main findings and insights for Research Objective A (Section 6.2), Objective B (Section 6.3) and Objective C (Section 6.4). Section 6.5 (as Research Objective D) then follows, synthesising the overall merits of UWA and exergy analysis as an alternative to mainstream energy analysis. Research Objective D is probably the most important of the four, because different insights emerge from the synthesis versus the separate objectives. For example, it allows a review of the key assumption underpinning the thesis: that it is useful work – and not primary energy – that has a closer linkage to economic growth. As set out in Table 1-3, the Research Objectives are delivered through sometimes more than one Chapter. This means that new analytical content is presented in each Section where required[27]. Finally, an overall assessment (including conclusions) is given in Section 6.6.

6.2 Research Objective A: use useful work method to understand historical energy use

Two papers (Chapter 2 and Chapter 3) provide the evidence base for this Objective, which are given in two parts: Section 6.2.1 UWA Methodology (Chapter 2 and 3); Section 6.2.2 historical aggregate results (Chapter 2 and 3).

6.2.1 Useful Work Accounting (UWA) methodology

An Excel-based model was developed to undertake the analyses for the UK-US and China papers, as described in Figure 1-27. The model was based on the

[27] Though perhaps uncommon, in this case it is - in part – a function of the alternative (journal paper) format PhD thesis.

“energy carriers for energy use” (Ertesvag, 2001, p.254) approach, most recently advanced by Ayres and Warr (2005; 2012) and Serrenho et al (2016) amongst others. In this method energy sources are mapped to four main end-use classes: 1. combustion-based heat, 2. combustion-based mechanical drive, 3. electricity end uses, and 4. muscle work – and combined with estimated exergy efficiencies to produce estimates of task-level useful work and (via equation 1-3) the overall economy-wide exergy efficiency.

For the UK-US study (Chapter 2), three advances to the Ayres-Warr-Serrenho method were undertaken, as part of the model development. First, granularity was added to the electricity end-use categories – particularly residential electricity. Second, the combustion-based mechanical drive efficiency was based on a novel, asymptotic ε-mpg relationship derived from powertrain data. Third, a correction was made to the electricity-based cooling efficiencies introduced by Ayres et al (2005), which had excluded losses from the Carnot temperature penalty. These methodological advances were carried through to the China study (Chapter 3).

Four points are worth discussing. First is that the methodological advances had significant impacts: it allowed the US efficiency dilution trend to be obtained as a key result in Chapter 2, and later via LMDI decomposition the same dilution effect was also found for the UK. The effect of the changes becomes clear in Figure 6-1, which shows the US model run with both Ayres et al (2005) and Brockway et al (2014) task-level exergy efficiencies. The stagnation in US efficiency is caused largely by the two changes to the electricity end use sectors: the combined effect of correcting the cooling efficiency, and refined granularity of electrical end uses combined to give greater weight to low efficiency sectors over time. These effects became more prominent over time as electricity use grows.

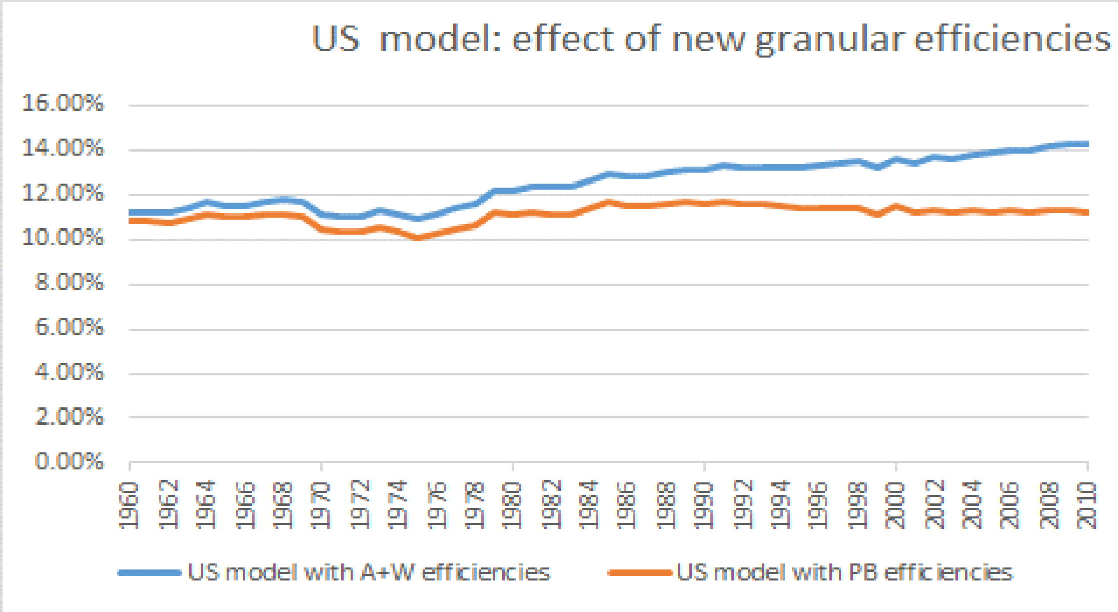

Figure 6-1: Comparison of US results with different efficiencies

Second, although formally simple, the modular Excel-based modelling approach allows sufficient granularity of analysis (e.g. for finding dilution) whilst overcoming common modelling pitfalls. It was built with separate stand-alone worksheets, and was totally self-contained: each sheet contained its own set of data references and assumptions, with no links to external files. This structure allowed enabled iterative amendments to components of the model: for example when greater electricity granularity was desired, it was done without affecting other sheets. In addition, the modelling approach was appropriate for assessment of aggregate trends and an overall view on the UWA technique, and widespread familiarity with Excel enables easier peer review.

Third, the methodological review undertaken in developing the UK-US models - i.e. comparing the approaches taken by previous studies - found numerous aspects of inconsistency (raised in Chapter 2), including front end mapping of energy sources to end uses, industrial heat efficiency, mechanical drive, electrical end uses, non-energy and manual labour. These are important, since they may significantly affect the results and applications, as shown by the effects of the changes made for the UK-US analyses. This broader list of major analytical differences has been compiled by Sousa et al (2016), of which I am a co-author.

Fourth, whilst such efforts to improve robustness and consistency in modelling approaches are desirable - and an important next step in advancing the credibility of UWA and exergy analysis - a significant amount of work remains to build a specific country model, and this is important to recognise. Whilst input energy can be largely automated (i.e. IEA mapping to task-level useful work categories), country-level data for task-level efficiencies are the key source of error, and therefore require – in my opinion - a detailed, and thorough approach to build in each case a bespoke model. The first (UK) model took around 6 months to complete, and the second (US) model around 4 months. Whilst the China model started with the structure of the US model, it still required several months of time-consuming detective work to build: and properly account for country-specific issues such as muscle work as a key sector (human and animal), and the residential energy use split between rural and city-based populations.

6.2.2 Historical analytical results

6.2.2.1 Aggregate exergy efficiency, ε

In terms of the aggregate efficiency results shown in Figure 6-2, the UK and US are similar in 1971 (~11%), but then have a divergent trend: whilst the US stays within a 11-12% banding, the UK increases close to 15% by 2010.

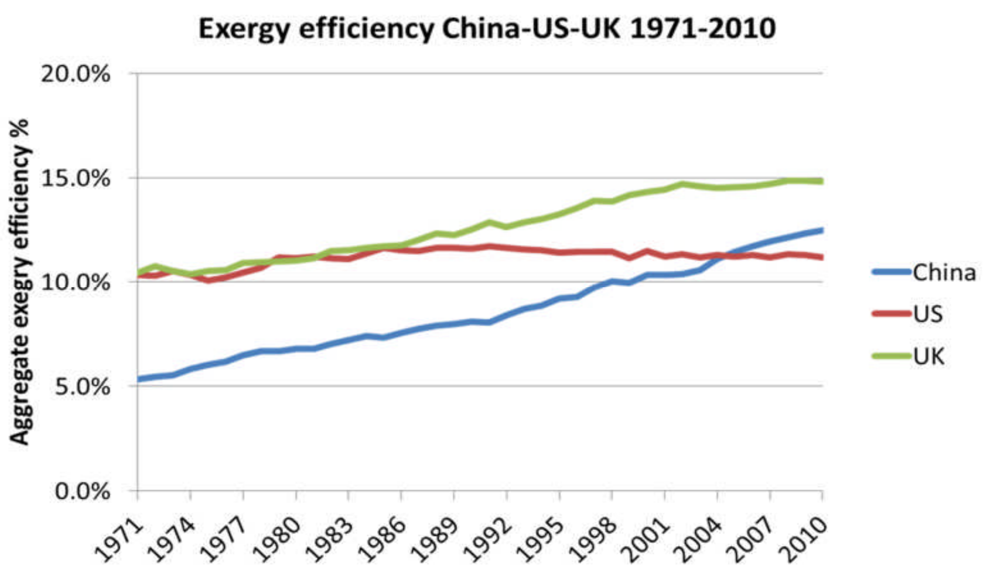

Figure 6-2: Exergy efficiency results for UK, US, China (1971-2010)

Efficiency dilution (as a key reason for the US's flat efficiency) was an important - but unexpected - finding, since it had not previously been identified for the US, and only once before in any study – in Japan (Williams et al., 2008). For the UK, the aggregate evidence for efficiency dilution in Chapter 2 was inconclusive, as although overall efficiency grew during 1960-2010, efficiency was flat in the last decade (2000-2010), perhaps suggesting the onset of dilution at an aggregate level. In comparison, China had an almost linear increase in efficiency, moving from 5% to 12.5% by 2010, overtaking the US, therefore showing no signs (in these aggregate results) of efficiency dilution.

Because the contributions of structural change versus efficiency gains could not be ascertained from the aggregate results, greater insights were found (in Chapter 3) by the novel application of LMDI decomposition to the field of useful work and exergy analysis. The decomposition results for China, US and UK are given in Table 3-2, reproduced here as Table 6-1:

Table 6-1: LMDI decomposition factors 1971-2010 for China-US-UK

Country	U	Dex	Dstr	Ddil	Deff
	Useful work	Primary Exergy	Main class structural change	Sub-class structural change	Task-level efficiency
China	9.76	3.96	1.39	1.19	1.48
US	1.53	1.32	1.03	0.88	1.29
UK	1.43	1.01	1.04	0.87	1.58

Country	U	Dex	Dstr*Ddil	Deff
	Useful work	Primary Exergy	Overall structural change	Task-level efficiency
China	9.76	3.96	1.66	1.48
US	1.53	1.32	0.90	1.29
UK	1.43	1.01	0.90	1.58

The key finding is that efficiency dilution is confirmed as occurring in both the US and UK – as D_{dil} is below 1.00 in both cases. This means that within main classes (e.g. electricity, mechanical drive, heating) there is a move to lower efficiency end uses. Whilst overall dilution did not occur for China, Table 6-2 also confirms that dilution has not occurred in any decade:

Table 6-2: Decadal LMDI decomposition results for China

LMDI factor	1971-1980	1980-1990	1990-2000	2000-2010
Dex	1.35	1.31	1.25	1.80
Dstr	1.10	1.06	1.09	1.11
Ddil	1.04	1.00	1.07	1.07
Deff	1.11	1.12	1.11	1.08

Also important was the finding that China's efficiency gain is driven mostly by structural changes and not Goldemberg's (1998) technological 'leapfrogging', as China's task-level efficiency gain (D_{eff} = 1.49) is between that of the UK and US, and is below that of overall structural change (D_{str}*D_{dil} = 1.66).

Three key insights follow from the UK-US-China historical efficiency results. First, is the validity and benefit from applying the LMDI decomposition technique to the useful work and exergy analysis results, as additional insights (e.g. dilution) can be gained. Second, the UK-US results suggest that there may be a natural - or rather practical – limit to aggregate national-level exergy efficiency of around 15% for mature economies. This may not be obvious from sight of China's linear growth to 12.5% in 2010, but is later confirmed by the future China analysis (discussed in Section 6.3).

Third, the efficiency dilution findings for the UK and US may mean that energy efficiency policies may not work as desired, if account for dilution effects are not properly taken. A compounding issue is that efficiency dilution may also contain components (at an aggregate scale) of energy rebound: i.e. savings in higher efficiency sectors may rebound into increased use in lower efficiency sectors. For example, rapid growth in usage of low efficiency end uses (e.g. air conditioning, low temperature heating, mobile phones and tablets) suggests consumers may be willing to respend a proportion of energy efficiency savings from other areas (e.g. lower fuel use from more fuel efficient cars) in these very low efficiency sectors. It is certainly not clear that energy-policy models pick up such nuances at present, as their focus is final energy end uses, not at a useful work level.

6.2.2.2 Aggregate useful work and primary exergy results

A summary of the aggregate results from Chapter 3 of comparable 1971-2010 results between the US, UK and China is given in Table 6-3. GDP data (at constant $2005US) is sourced from World Bank (2013).

Table 6-3: Change in variable 1971-2010 (base year 1971 = 1.00)

Country	Primary Exergy	Exergy efficiency	Useful work	GDP
UK	1.01	1.42	1.43	2.5
US	1.32	1.16	1.53	3.0
China	3.96	2.46	9.76	29.9

Since primary exergy and primary energy are very close in value[28], they may be used synonymously for our present discussions. For the UK and US results, the useful work based results potentially add new information compared to traditional energy analysis. The logic is as follows – let us start by observing that the indexed useful work gains were similar for both countries (1.4-1.5) compared to primary energy (1.0 for UK, 1.3 for US). GDP gains were also similar for the UK (2.5) and US (3.0). The traditional narrative (based on view of primary or final energy data) would be that the UK has been successful in decoupling primary energy from GDP gains, through e.g. technical innovation or replacement of energy intensive industries with service-based activities.

But Table 6-3 also suggests an alternative, useful work based explanation. The observation that the UK and US have exhibited similar useful work gains (40% to 50%) and GDP gains (150%-200%) is important, given the divergence of primary energy gains (0% for UK versus 30% for US). This suggests that it may be useful work – not primary energy – that an economy needs, whilst primary energy changes (ΔE) are dependent - through $\Delta U = \Delta\varepsilon * \Delta E$ - on changes in useful work (ΔU) and exergy efficiency ($\Delta\varepsilon$). In the case of China the gains are high

[28] For our cases of UK, US and China, since they have high proportion of fossil-fuel usage (coal, oil, gas) the primary energy to exergy coefficients are close to 1.0 (Szargut et al., 1988).

across the board: we see a thirty-fold gain in GDP, whilst a ten-fold gain in useful work is supplied by a 2.5-fold gain in exergy efficiency and 4-fold gain in primary energy.

To investigate whether useful work is more closely linked to GDP than primary energy, we would need to study the econometric cointegration relationships including Granger causality for both U-GDP and E-GDP. This would take a similar approach to that of U-GDP studies (Warr & Ayres, 2010) and E-GDP studies (Bruns et al., 2014).

However, whilst such analysis was outside the scope of the journal papers in Chapter 2 and 3, we can delve a little deeper based on the aggregate data that we do have. To do this, Table 6-3 is expanded to make a more detailed Table 6-4:

Table 6-4: Decadal changes in variables (base year 1971 = 1.00)

		1971-1980	1980-1990	1990-2000	2000-2010	1971-2010
UK	Useful work	1.03	1.13	1.24	1.00	1.42
	Exergy efficiency	1.02	1.13	1.14	1.07	1.41
	Primary exergy	1.00	1.00	1.08	0.93	1.01
	GDP	1.19	1.31	1.35	1.18	2.47
US	Useful work	1.21	1.10	1.17	0.98	1.53
	Exergy efficiency	1.09	1.06	1.00	1.00	1.16
	Primary exergy	1.10	1.04	1.16	0.99	1.32
	GDP	1.32	1.39	1.40	1.18	3.03
China	Useful work	1.71	1.56	1.62	2.31	9.96
	Exergy efficiency	1.27	1.19	1.29	1.28	2.50
	Primary exergy	1.35	1.31	1.25	1.80	3.98
	GDP	1.69	2.52	2.58	2.71	29.92

An initial review of Table 6-4 finds little evidence in support of our key assumption: that useful work (not primary energy) has closer linkages to economic growth. This is because for each country we see the highest decadal GDP gain coincides with the highest gain in useful work, and at the same time the highest gain in primary exergy. However this may be because of a different effect, given exergy efficiency gains in any decade appear limited (by technology) to around 30%. This means - by recalling $\Delta U=\Delta\varepsilon*\Delta E$ – that any additional gains in useful work are delivered through primary energy. Take China as an example: we can see how China's increase in exergy efficiency has been quite similar for each decade (20-30%), but that in the period of highest useful work and GDP growth (2000-2010) the additional gain in useful work was met by additional primary energy.

6.3 Research Objective B: Applying Useful Work Accounting to future energy scenarios

As described in paper 2 (Chapter 3), the UWA method developed for the UK-US study in paper 1 (Chapter 2) was applied to the case of China for 1971-2010. The summary of key results, insights and implications discussed in this Section 6.3 are intended to be deeper and broader than those offered within the journal paper constraints of Chapter 3, as future energy scenarios was only a third of the paper (1971-2010 UWA analysis and decomposition being the other two parts).

The first notable point lies in the modelling approach itself: the development of the UWA-based approach to estimate future primary energy use for China, for 2010-2030, under high and low exergy efficiency growth scenarios. The steps were shown in Figure 1-29 and are reproduced for convenience in Figure 6-3:

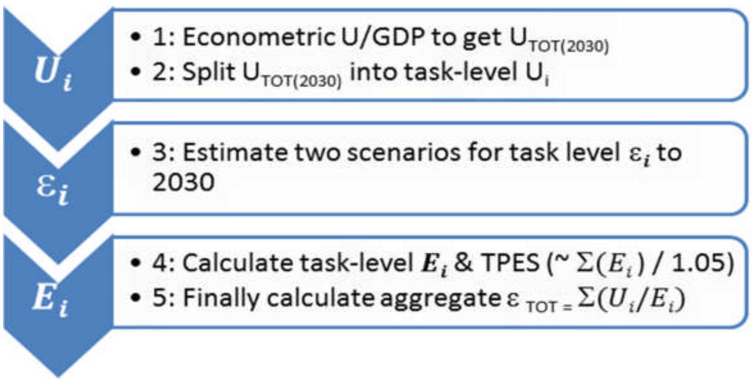

Figure 6-3: China Primary energy forecast – method summary

Whilst Ayres and Warr (2005; 2006) used their Resource EXergy Service (REXS) models to study future exergy efficiency, it was applied in the context of its effect on economic growth. This is therefore the first time a UWA approach has been applied to the study of future primary energy demand, and in broad terms, the technique produced successful outputs, i.e. credible estimates of aggregate exergy efficiency and primary energy to 2030. It should be noted that the method is constructed on the basic underlying PhD assumption: that useful work is more closely linked – versus primary energy - to economic activity. Whilst the assumption was openly acknowledged in the paper (Chapter 3), the closer linkage of U-GDP versus E-GDP for China (see Table 6-3) was also suggested as evidence for its possible validity. Aside from empirical evidence, Percebois (1979) suggests conceptually that useful work based intensity (U/GDP) is more economically meaningful than primary energy intensity (E/GDP).

Secondly, an interesting – and unexpected – result was that China's aggregate efficiencies reach an asymptotic limit of 13-14% by 2030. Figure 3-8 – reproduced as Figure 6-4 - shows how two quite different efficiency scenarios made little impact to this finding. Instead it is the structural shifts to service-based economy that has the greatest effect on constraining the overall efficiency gain: as China moves to include a larger fraction of energy demand from non-industrial (e.g. service, transport and household) sectors. These sectors are much less exergy efficient than industrial energy use, and so depress – via efficiency dilution – gains in overall efficiency. The asymptotic limit reached by China is in the same 13-15% banding found for the UK-US efficiency profiles.

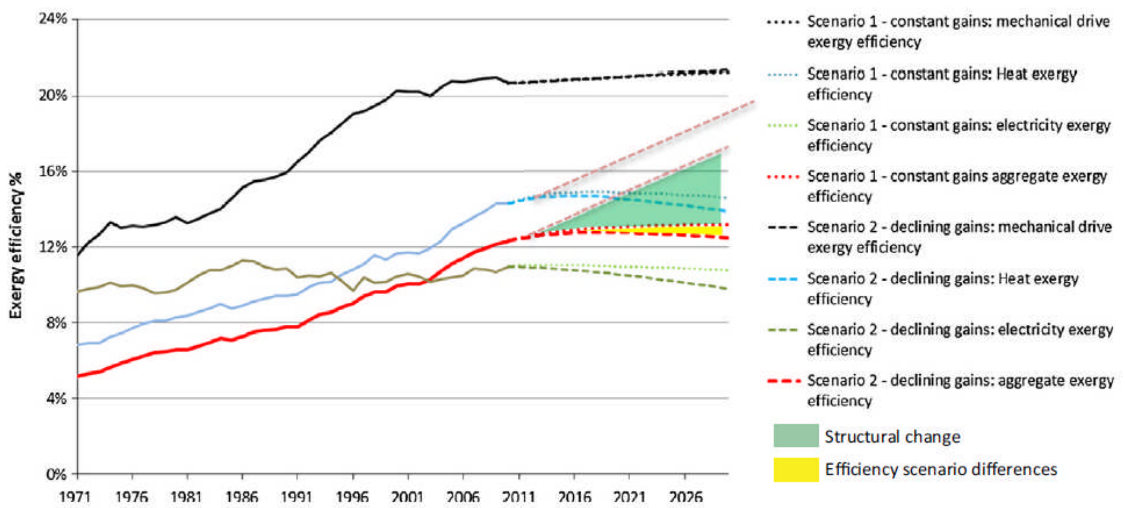

Figure 6-4: China – exergy efficiency scenario results

The third notable result is that the primary energy projections given in Figure 3-9 for China's primary energy demand in 2030 were 6,000-6,300 Mtoe/year, significantly higher than the 4,500-5,200Mtoe range of shown reference studies which adopt the same 2010 base year. The higher UWA-based estimate is due to the choice of useful work based energy intensity rather than primary energy intensity: a comparative E-GDP based estimate in Figure 3-9 gives 5,200Mtoe in 2030, in line with the reference studies.

So the question arises: what is it that is bound up in the UWA-based method that causes the higher primary energy projections? To examine this, Table 6-5 summarises changes in useful work, exergy efficiency and primary exergy in 20 year periods, and shows how the effect of efficiency stagnation ($\Delta\varepsilon$ ~1.0) in 2010-2030 is to 'pull' primary energy to otherwise higher levels (ΔE=2.1-2.2).

Table 6-5: Comparison of historic and future scenario UWA results

Time period	Efficiency scenario	Change in useful work, $\Delta U = \Delta E \times \Delta\varepsilon$	Change in exergy efficiency, $\Delta\varepsilon$	Change in primary exergy, ΔE
1971-1990	-	2.67	1.51	1.77
1990-2010	-	3.74	1.66	2.25
2010-2030	Low	2.21	1.00	2.21
2010-2030	High	2.21	1.04	2.12

Mainstream models may miss this efficiency dilution effect, by assuming gains to exergy efficiency continue – which are implicit within the models as they use final or primary energy datasets, not useful work or exergy efficiency. Also, they may underestimate increases in demand for lower efficiency services that we have seen occur in the UK-US studies, as economies mature and consumer incomes rise. For example, the dilution trend means mainstream models might underestimate the growth in low temperature heating and air-conditioning, which also may impact on our understanding of rebound, i.e. to lower efficiency sectors.

The conventional energy narrative on energy transitions is that since industry is energy intensive, a transition to a service-based economy will result in relative energy/economy (E-GDP) decoupling. The IEA follow this narrative by stating "along with energy efficiency, structural shifts in China's economy favouring expansion of services, mean less [primary] energy is required to generate economic growth" (IEA, 2015, p.8), and as evidence they forecast an even lower primary energy estimate for China in 2030, of 4,000Mtoe. However, the UWA based results and insights for China offer an alternative narrative: if industry is more exergy efficient than services, and if economic growth relies on useful work not primary energy, then the useful work gains in residential and service sectors will yield a higher demand (than suggested by mainstream models) for primary energy. In addition, consumption-based energy accounting may acerbate this ‘re-coupling’ effect by including primary energy used in other countries used for offshored manufacturing.

Following on, is the insight that exergy efficiency (on its own) may not be an appropriate policy goal. Pursuit of higher efficiency may mean higher primary energy use - which also harm climate mitigation efforts, since it would translate into policies seeking to increase the use of energy intensive (yet high efficiency) processes (e.g. steel making) and reduce lower efficiency processes (e.g. low-temperature heating). In addition, prioritising energy intensive industries at the expense of energy services which enhance quality of life (e.g. thermal comfort) would not seem appropriate. Carnahan et al. (1975, p.28) foresaw this issue, stating “the maximization of ε [exergy efficiency] becomes a matter for policy consideration. It is a technical goal to be placed alongside economic, environmental, and conservation goals”.

Overall, the UWA-based method has led to different estimates and insights about future trends of China’s primary energy use versus mainstream energy analysis. If confirmed, higher primary energy demand would mean reaching carbon reduction targets will be much harder, and energy efficiency and renewables efforts will have to increase beyond current and planned policies.

6.4 Research Objective C: assessing energy rebound using useful work

Two papers (Chapter 4 and Chapter 5) provide the evidence base for this Objective, which is centred on the idea of using the UWA results from UK-US (Chapter 2) and China (Chapter 3) studies to estimate long term total energy rebound.

6.4.1 Literature review

Starting with the literature review in Chapter 5, three (at least initially) surprising findings emerge from the summary (in Section 5.2) of the current research frontier relating to the estimation of total rebound. The first is that, despite recent progress in terms of understanding (and in some cases estimation) of rebound, the Jevons paradox after 150 years essentially remains unsolved: we don't know (conclusively) whether energy efficiency causes more or less energy to be used.

Second, few estimates of total economy-wide rebound exist. Current empirical studies focus on part of total rebound - the more accessible consumer-sided direct and indirect rebound, due to input data and theoretical frameworks being more available. The lack of total rebound studies is due to complexity on several fronts: the lack of a common energy efficiency definition (most are physical or monetary proxies for thermodynamic efficiency); interaction between energy efficiency and economic growth (i.e. it requires estimation of counterfactual energy use), and emergent properties that only become apparent at scale.

Third, despite energy efficiency being a large component of emissions reduction trajectories, energy rebound appears largely ignored in policy, whereas we might expect policy makers to include aspects of rebound on a precautionary principle.

6.4.2 Empirical estimation of CES functions

Moving back to Chapter 4, the most interesting point is that a gap existed at all in the literature, i.e. the divergence between the empirical use and guidance for energy-augmented CES functions - allowing space to write a journal paper. After researching the most appropriate estimation technique (see Section 5.2), a CES production function based method was selected. The original intention was to write a single paper on energy rebound (i.e. Chapter 5), and include CES functions within the Methods section.

However, in researching CES functions for the rebound paper (Chapter 5) and also working with colleagues[29] on a separate CES paper (Santos et al., 2016),

[29] In parallel, I was working in a collaborative research group (myself, Joao Santos, Matt Heun) formed from the Exergy Economics network (see section 6.6), which was testing the inclusion of useful work in CES based APFs, and its effect on the Solow residual.

numerous aspects were found which affected the econometrically estimated parameters. These issues were somewhat disparate, with no consolidated place in the literature. This is important, as energy-augmented CES functions are being increasingly used in research and modelling, serving as inputs to policy (van der Werf, 2008).

Therefore CES modelling choices have real-world impacts. Given this, and with the issues too numerous to cover within the rebound paper (Chapter 5), I decided to write a paper on this topic: highlighting the key aspects of CES functions and their empirical specification and solution.

6.4.3 Estimation of rebound

All of this validates the research gap that the UWA based method (using exergy efficiency) aims to contribute, suggesting that alternative UWA-based energy analysis technique may be helpful. The basis of the approach developed in Chapter 5 is to specify and then estimate the unknown CES function parameters, which are then inserted into rebound equations for the APF and AES-PES methods. Two issues are important to discuss. First is the CES function specification itself. We used the more flexible structure of equation 5-10 (reproduced as equation 6-1 below) than Saunders' (2008) equation 5-4, allowing values for both ρ and ρ_1 to be determined, without the previous unity constraint on the inner nest (KL) elasticity. This is important, since it permits a wider CES solution space, and in turn estimates of rebound.

$$Y = \theta\, A[\delta_1[(\delta\, K^{-\rho_1} + (1-\delta)L^{-\rho_1}]^{\rho/\rho_1} + (1-\delta_1)(\tau F)^{-\rho}]^{-\frac{1}{\rho}}; A \equiv e^{\lambda t} \qquad \textbf{(6-1)}$$

The second issue to highlight is that by using UWA aggregate values (U, τ) for the first time in an empirical CES study, different values of the six unknown CES parameters (δ, δ_1, ρ, ρ_1, θ, λ) are estimated than would otherwise have been the case. Zhang and Lin (2013) provide such an example where efficiency parameter (τ) was unknown, and thus is estimated as part of the econometric solution for the function. In such cases, the value of τ is that which achieves a best fit to the overall function, and will most likely bear no relation to the actual energy efficiency. Also by using empirical UWA values (U, τ), this reduces the number of unknown parameters, which improves convergence and fitting of the function.

Next, moving to the estimated values of total energy rebound, Figure 5-10 (reproduced below as Figure 6-5) summarises the base-fit estimates of total energy rebound using the APF and AES-PES methods for the UK, US and China:

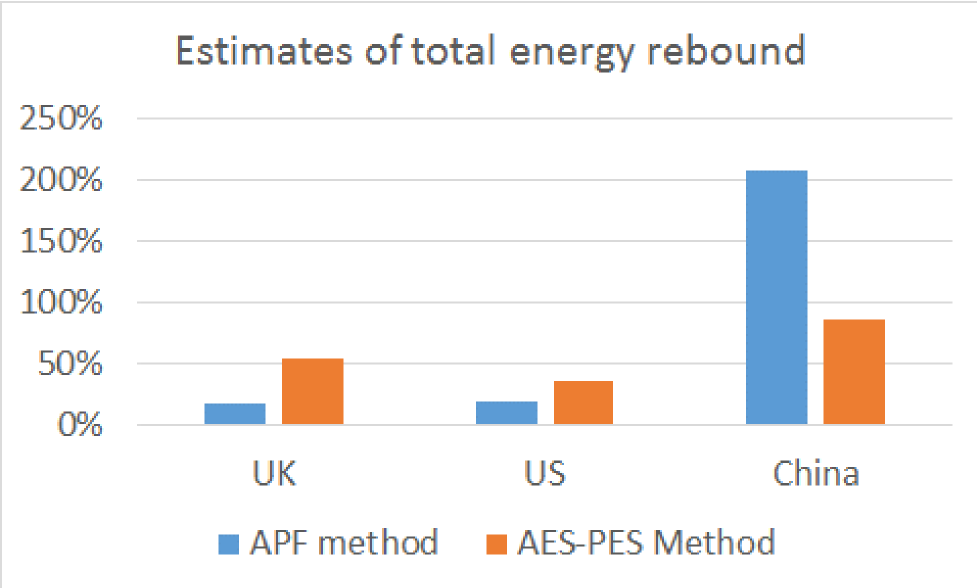

Figure 6-5: Summary of base-fit rebound results

Several points are worthy of discussion. First, the APF and AES-PES methods developed for the UWA datasets appear to have been successful, in that 1. the CES function was solved and unknown parameters estimated; 2. the estimated values (discussed next) appeared credible and broadly similar between the two methods; 3. the study was the first multiple-method, multiple-country analysis of total energy rebound. This provides a broader base for comparative insights.

Second, we gain important insights from the values of the estimated rebound. The results suggest that China's rebound is high (close to, or above backfire), whilst the UK and US had smaller, partial rebound. A possible explanation for the rebound values are based on the industrialisation stage of that country. As China is still industrialising, so the energy use and efficiency measures have greater weight on the producer side, where (as noted in Chapter 5) we might expect larger rebound, versus the more service based economies of the UK and US, as shown in Figure 6-6:

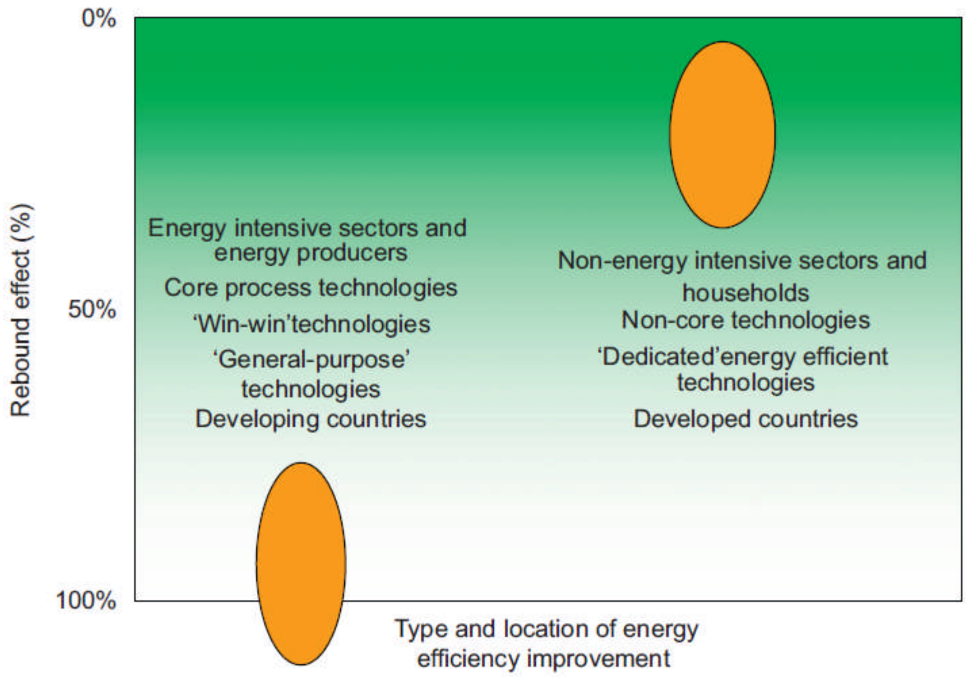

Figure 6-6: Conditions under which rebound may be large or small (Sorrell, 2009)

This has implications for energy transitions and climate policy, particularly in developing and industrialising countries, i.e. if efficiency policies increase – not decrease - energy use. Additional insights are gained through resampling, and the provision of 2.5% and 97.5% resampled base-fit estimates. For example, from the APF method we can say with less confidence (versus the UK) that the US exhibits partial rebound, since US upper bound 97.5% rebound value was reported as infinite. Confidence interval data is given very rarely for rebound studies - Zhang & Lin (2013) provide one example - but which provides important additional information.

Whilst the focus of the paper was the estimation of total energy rebound, insights can also be gained from the estimated CES parameters. First, the analysis highlighted the importance of σ, the elasticity of substitution (between capital-labour composite and energy) as a vital parameter, and the one with the largest influence on the value of rebound estimates. It also added explanation to the rebound values: China had much higher value of σ, meaning the substitution from energy savings to higher labour-capital use (which in turn requires energy input) is much easier. In such cases we would expect higher rebound.

Second, the CES parameters also allow a study into the basic assumption of the PhD study: is useful work more closely linked to economic growth than primary energy? Though outside the scope and allowable space of the rebound paper in Chapter 5, an analysis was run to study this question. In short, we run the kl, kl(e) and kl(u) CES functions for the UK, US and China, and report in Table 6-6 the Solow residual (lambda, λ) and sum of squared errors (SSE). The assertion being tested is that if useful work can explain more of economic growth (than primary energy), then the Solow residual will be smaller since the explanatory variables (k, l, u) contribute more to economic growth from within the CES function.

Table 6-6: Base-fit parameters for kl, kl(e) and kl(u) models

Country	Parameter	CES model		
		kl	kl(e)	kl(u)
UK	Lambda	0.0020	0.0116	0.0071
	SSE	0.0291	0.0126	0.0136
US	Lambda	0.0089	0.0088	0.0093
	SSE	0.0043	0.0029	0.0019
China	Lambda	0.0460	0.0447	0.0559
	SSE	0.0319	0.0257	0.0235

The results in Table 6-6 show how including energy may not improve the ‘fit’, since the Solow residual (lambda) is not significantly reduced for the kl(e) and kl(u) models compared to the kl base model. This raises the question as to ‘what is a better fit?’, since adding energy reduces the SSE, but not the Solow residual. This is something discussed by Santos et al (2016), who argue the traditional view (i.e. reducing the Solow residual = a better fit) may be wrong, and that SSE is perhaps a candidate more suitable for the ‘best fit’ parameter. In our case, moving from kl(e) to kl(u) models has no clear effect – since if lambda rises then SSE falls, so in that sense our results suggest no clear winner. Alternative, cointegration based methods may be helpful for future research, as highlighted in Section 6.6.2.

6.5 Research Objective D: Synthesis - assessing the extent that useful work can provide insights to national-level energy use, rebound and economic growth

The synthesis (in this Section 6.5) provides a broader, cross-aspect format for discussion of the merits of the UWA-based alternative economy-wide energy analysis technique, helping to lay the evidence base for the conclusions reached in Section 6.6. First, the key insights from the three singular Research Objectives (A to C) are outlined, together with their implications (Sections 6.5.1). Second, the limitations of the approach are considered (Section 6.5.2). Third, a set of key questions that stem from the thesis are set out and discussed. (Section 6.5.3).

6.5.1 Key insights and implications

6.5.1.1 Analytical insights

Four key insights emerge from the analyses. The first is that efficiency dilution, combined with structural change, may cause a natural limit to national-scale exergy efficiency of around 13-15%. Decomposition of historical aggregate results found that efficiency dilution has occurred both in the UK and US, whilst future energy projections infer upcoming dilution for China. The implication of efficiency dilution is that aggregate gains assumed by energy efficiency policies may not translate fully into energy savings. A redesign of policies may be required, to limit or account for dilution.

The second insight is that the UWA-based method suggests that primary energy demand for China in 2030 is ~20% higher than mainstream energy economic methods. This would be – if confirmed[30] - a significant finding given China is the world's largest energy consumer, and would require a response through energy supply and emissions policies. It would also have implications for how we model future energy demand, since mainstream energy models focus on the energy supply side (primary and final energy), whereas exergy-based models may have greater predictive power by modelling the demand side, i.e. closest to energy services (useful work).

The third insight is that total primary energy rebound may be around unity (i.e. backfire) in industrialising countries such as China, where producer-sided energy rebound may act as a dynamic of economic growth (and increased energy use). If energy efficiency causes increases (rather than decreases) to energy use, then the implications for energy-related emissions reduction policies are significant. Emissions policies in the context of backfire (R_e >1.0) would need a different response, through for example a tax to capture economic savings, or compensatory increases to renewables. The conflict with economic growth priorities would be a key policy battleground. Meanwhile, more mature, industrialised countries such as the UK and US, which exhibit lower (partial) rebound, would also need to consider the fact that they have a larger impact when considering rebound on a consumption basis: since China makes products that we buy. This is a similar landscape to the discussions over responsibility for energy-related CO_2 emissions.

Fourth, we return to the underlying assumption of the thesis: that it is useful work that pushes (or perhaps pulls - since establishing causality direction is tricky) the economy, not primary energy. The UK-US UWA results offered the best suggestive links for this hypothesis: since the UK-US had similar useful work growth (+50%) versus very different primary energy gains (US = +30%, UK = +1%). Whilst UK primary energy decoupling is one possibility, so too is the prospect that useful work drives the economy. The insight offered here, then, is that efforts to study this assumption would be of great benefit, given the suggested findings of efficiency dilution, underestimated future energy, and high

[30] A large caveat is required: since the method developed is predicated on the assumption that it is useful work and not primary energy, that an economy needs. And this assumption is not yet proven,

rebound in industrialising countries. For example, multi-country econometric cointegration studies of U-GDP versus E-GDP would be helpful.

6.5.1.2 Broader insights

Taking a wider view, several insights emerge. The first relates to the lack of a common energy efficiency metric, and how it acts as a constraint to energy analysis and policy. The literature reviews for the various papers highlighted the key issue of a disparate, non-thermodynamic definition of energy efficiency. In mainstream energy analysis, by relying on proxy indicators for thermodynamic efficiency, studies into historical and future energy use (including rebound) are therefore constrained as to what they can find. The breadth of efficiency metrics (leading to a lack of coherent rebound studies) may be one reason why policy makers fail to include energy rebound in policy.

Second, this ‘gap between modelling and policy’ may also exist in mainstream energy economic (e.g. CGE) model-to-policy routes. Whilst CES aggregate production functions have grown in popular usage, the issues involved in their econometric solution seem to be left behind, translating to weaker results. Such lack of robustness - illustrated by the need for the third paper (Chapter 4) - was surprising. Next, as Sorrell (2014) highlights, the key CGE parameter – the elasticity of substitution - may simply be wrong. At best, there seems a clear need to re-examine current energy economics model-to-policy routes: as current expertise working in ‘modelling’ and ‘policy’ silos does not seem ideal. At worst, mainstream modelling may lock-in results within certain bounds, leading to serious errors and impacts on energy and emissions policies.

The third insight offered is not new, but is important: our analyses suggest that the issues of energy use, energy efficiency and economic growth are complex and interwoven, and that such complexity needs to be included in mainstream analysis. For example, the high rebound (backfire) result for China was due to high efficiency gains increasing energy use above the counterfactual baseline, supporting the core ‘engine of growth’ argument of Ayres and Warr (2010) and Kümmel (2013). Also, as Sorrell notes, “the dispute over Jevons paradox may therefore be linked to a broader question of the contribution of energy to economic growth” (2009, p.1467).

6.5.2 Limitations to the UWA-based approach

Building towards an overall assessment of the method (Section 6.6.), it is relevant now to consider the limitations of the UWA-based approaches, together with any strategies that I used to test (or mitigate) weaknesses.

Inconsistencies in the UWA method between studies remains the major issue which needs to be addressed. Without a more robust, consistent platform, the credibility of the technique is undermined. For example, the change in electricity allocation and end use efficiencies I introduced in the UK-US paper (Chapter 2) had major effects, as shown in Figure 6-1. In short, the efficiency dilution results (found via LMDI decomposition in Chapter 3) would not have otherwise been found. Not only are different insights are drawn, but the UWA results form input data to other (e.g. rebound) studies, translating in turn to potentially very different findings in those studies. So consistency matters, and work towards a common, accepted methodological framework is acknowledged as a high priority (Sousa et al., 2016).

Considering the UWA methodology I adopted, the IEA energy balance data and mapping was the most robust component. By comparing to nationally available datasets in both UK-US paper (Chapter 2) and China paper (Chapter 3), I found that differences compared to national datasets were small (<5%) and systematic - which therefore had less impact for my trends-based analyses. The largest variation in UWA results come from the next step: estimation of task-level exergy efficiency data for the IEA mapped categories, since availability of efficiency data (or data to calculate efficiencies) was scarce. Separate to the IEA energy-mapping-efficiency process, are the muscle work calculations. For industrialising China, these had significant impacts for overall efficiency, and would have potentially even larger impacts for developing country analyses.

My adopted mitigation strategies were based on rules of practical model development, rather than specific exergy-only measures. First, I built the model framework - then once it was running properly and debugged – spent the most time on the sectors with the highest primary energy use (e.g. electricity end use for UK-US, industrial energy use for China). Second, I spent considerable time reviewing sources of data used in previous exergy analyses before seeking new data of my own, such as transport powertrain data (Thomas, 2014). Third, I compared results where possible to other analyses – such as the first US analysis model, reinstating the Ayres and Warr assumed efficiencies, and found close agreement to their published aggregate time-series exergy efficiency for the US (Ayres et al., 2003).

Finally, a key limitation lies in the novelty of my UWA-based methods, such as modified UWA methods, LMDI decomposition and CES-based energy rebound analysis. It means that the results – though interesting – will not be adopted by policy makers without further studies and the transition of the technique into mainstream energy economics. To start this process, more studies can be encouraged in this area – for example the network of researchers (see Section 6.6.2) looking into this technique as a means to explore energy use and economics.

6.5.3 Key questions stemming from the thesis

From these insights and limitations, three key questions emerge which are important to consider prior to the overall assessment in Section 6.6

6.5.3.1 #1: Why is exergy efficiency not adopted as a national metric?

The first question, simply put, is why – given the lack of common efficiency definition – is exergy efficiency not adopted as an economy-wide energy efficiency metric? In the real-world, efficiency metrics are based on price elasticity or composite indices. This creates an inertial, self-perpetuating cycle, where a diverse set of non-thermodynamic indicators are used for different purposes, and being measured by those indicators, there is little desire for change. For example, the EU-wide ODYSEE-MURE composite indicators (ODYSSEE-MURE, 2015) are now set up and well established. After the oil-crises of the 1970s, useful energy statistics were collated in Europe by Eurostat (1978, 1980, 1983, 1988), but after a time were discontinued. The UK Department of Energy & Climate Change (DECC, 2015) provide an insight in their annual Digest of UK Energy Statistics (DUKES) as to why national datasets are not collated:

*"final consumption may be expressed in the form of useful energy available after deduction of the losses incurred when final users convert energy supplied into space or process heat, motive power or light…Statistics on useful energy are not sufficiently reliable to be given in this Digest; there is a lack of data on utilisation efficiencies and on the purposes for which fuels are used." (*DECC, 2015, p.24)

Therefore, the appetite for exergy as an alternative metric within policy and energy accounting circles appears weak. Recent exergy advocacy in the EU (Science Europe, 2015) and US (American Physical Society, 2008) are rare counter-examples. Therefore, rather than a 'pull' from policy makers, the drive for its use as a national metric may come from a 'push' from its (eventual) inclusion as a core part of energy economics modelling. This in turn requires the benefits of including an exergy-based approach to be clearly communicated to the energy economics community (see also Section 6.5.3.3).

6.5.3.2 #2: Is energy economics looking at the wrong end of the energy conversion chain?

The key assumption underlying the thesis is that it is useful work, not primary energy, which the economy needs. This is seen through the lens of suggesting that useful work is closer to what consumers (and producers) ultimately seek: energy services. Therefore we might find U-GDP to be more stable than E-GDP. But it is potentially not as straightforward for several reasons. First, this view might lead us to think that greater exergy efficiency would be a key policy goal. But this would lead to greater steel production, at the expense of consumer-sided uses such as air-conditioning or low temperature heat. Thus, tension between energy intensive (but exergy efficient) industry versus lower energy using (yet exergy inefficient) residential sectors would occur.

A second consideration is that primary energy use is more relevant for emissions policies, whereas useful work may be more relevant for links to economic growth. Thus both ends of the energy-conversion chain are important to study. Tensions may also exist that are worthy to study: for example delivering increases to energy services (through efficiency gains) may drive economic growth, increasing counterfactual energy use, in direct opposition to emissions policies.

A third, related point relates to development pathways: the contrast between useful work and primary (or final) energy studies may be starker for developing and industrialising countries. For example, the stronger energy rebound (backfire) in China may have major implications for our understanding of energy efficiency and energy rebound as drivers of energy use and economic growth. In contrast (leaving consumption-based energy use and rebound to one side), mature economies with stagnant overall efficiency (ε ~ 13-15%) will mean closer matching between useful work and primary energy demands (from $\Delta U = \Delta E^{*}\Delta\varepsilon$).

6.5.3.3 #3: Why is exergy analysis the poor cousin of mainstream energy analysis?

Despite its purported advantages (Section 1.2.3) and supporters (Science Europe, 2015; American Physical Society, 2008; Rosen et al., 2008), UWA and economy-wide exergy analysis appears to remain a poor relation of mainstream energy analysis. In simple terms, exergy and useful work analyses have had limited impact on macroeconomic models, or policy itself.

Ayres and Warr are prolific examples that the exergy economics community have published in high impact Journals such as *Energy* (Ayres et al., 2003; Ayres et al., 2007; Warr & Ayres, 2010; Ayres, 2001) and *Ecological Economics* (Warr et al., 2008; Ayres, 1998; Warr & Ayres, 2012). This means that whilst mainstream energy analysts are potentially reached, it is not being taken on by this community, since mainstream models continue to ignore exergy and useful work. There may be several reasons for this, which are important to discuss as they affect future research (Section 6.6.2).

First is that it appears (to the initial reader) to be a complex topic, which means it is both hard to reach and engage audiences, which serves to leave economy-wide exergy analysis out in the cold[31]. Even the language is confusing: different authors use ‘useful work’ (Carnahan et al., 1975; Warr & Ayres, 2012; Serrenho et al., 2014), ‘useful energy’ (Percebois, 1979; Ayres & Voudouris, 2014) and ‘useful exergy’ (Ayres et al., 2011; Voudouris et al., 2015; Laitner, 2014) when they mean exactly the same term. Second relates to the topics of the published

[31] Though of course, by the definition of exergy, that depends on the outside reference temperature.

studies themselves, which are heavily weighted – largely by the weight of contributions from Bob Ayres (Kümmel et al., 2010; Voudouris et al., 2015; Ayres et al., 2013; Ayres & van den Bergh, 2005) - to the study of economics, rather than energy itself. This appears the opposite way around to what is required: i.e. building solid foundations on energy insights, then applying this to the study of economics.

Third even for the economic-sided studies, the focus is on the use of complex and novel techniques such as the use of the LINEX function (Warr & Ayres, 2012) or new parametric approaches (Ayres & Voudouris, 2014). The simple fact is that novel data (useful work) in a novel method (e.g. LINEX) is difficult to access for mainstream energy-economists. Fourth, is that an adversarial, superior narrative runs through many exergy-based studies such as Voudouris et al: "this failure to capture the impact of primary resources (as useful energy) on economic growth leads to inappropriate formulation of economic growth theories" (2015, p.812). By prominently advocating superiority over other mainstream techniques, this alienates the audience which it is trying to reach. A more subtle strategy, whereby exergy analysis should be seen as complementary to - rather than competing with - energy analysis, might be a better approach (Hammond, 2004).

6.6 Overall assessment

The aim of this thesis was to assess what insights could be gained into economy-wide energy use and rebound, by using UWA as an alternative energy analysis technique. My motivation was based on the research gap set out earlier in Figure 1-24: that 1. mainstream energy analysis has not provided a sufficient evidence base for emissions and energy policy, and 2. UWA and exergy analysis is an under-utilised approach that could add valuable insights.

In this section I provide overall conclusions from the research and set out areas for future research.

6.6.1 Key conclusions

This thesis has examined following research question: "*How can useful work and exergy analysis inform understanding of energy use, rebound and economic* *growth?*" Several key conclusions are made. First, and foremost, the results found were potentially important: efficiency dilution in the UK and US, an asymptotic upper limit of 15% to national-level exergy efficiency, underestimating Chinas energy use in 2030 by 20%, and high rebound (potentially backfire) for industrialising China. If confirmed, they suggest a significant – or at least alternative - contribution can be made by UWA and exergy analysis compared to mainstream energy economics. Methodologically, these insights are possible as useful work is as close as we can thermodynamically measure energy before it is exchanged for energy services. This thermodynamic approach allows the study of aggregate energy (exergy) efficiency over time, but also unlocks the study of energy rebound's role (together with energy efficiency) in economic growth. This overcomes a significant constraint of other non-energy aggregate efficiency metrics used in traditional energy economics methods.

Second, despite its potential to provide new perspectives to the key energy questions given in Figure 1-5, there appears little appetite for exergy efficiency to be taken on as a new national-level efficiency metric, or more widely for exergy to be included in policy. This is due to a lack of a 'pull' – i.e. inertia of incumbent measurement systems and policy processes, and also a lack of a 'push' from mainstream energy economics models – as exergy is missing.

Thirdly, following on, the best route to widen the study of exergy analysis is thereby to start to embed exergy analysis techniques into mainstream models. This would create the space for a 'push' towards policy. Currently exergy-analysis is done in stand-alone models well outside of the mainstream academic and government models that are used to inform policy. This approach is producing interesting results (as seen in this thesis), but is not having traction in engaging the mainstream energy economics community. Breaking down barriers and including exergy variables into mainstream models will require action in several areas. Addressing analytical weaknesses (to make the exergy-analysis models more robust) is obvious, but arguably communication lies even closer to the heart of how to engage the mainstream audience, starting with the need for humility in its proposition as a complementary technique versus traditional analysis. The previous failings of the LINEX based approach serve as a salient reminder.

Overall, useful work and exergy analysis shows great promise as an alternative, economy-wide energy analysis technique. Given the need to develop more tools in the energy policy box to rapidly reduce carbon emissions, this is welcome.

6.6.2 Future research direction

From the research and insights offered in this thesis, three key areas are recommended for further work: energy use, economics and communication. These are described in the following sections.

6.6.2.1 Energy analysis

There are various aspects of energy analysis which should be considered: the first is the work towards a more robust methodology. This is already underway as a research strand: taking on some of the components outlined in Paper 1 (e.g. industrial energy, non-energy use, muscle work efficiency), and has produced a submitted paper (Sousa et al., 2016). Another paper is planned, as a quantitative paper to test the significance of the aspects under consideration.

Second, within energy analysis itself, focus on core issues such as Energy Return On energy Invested (EROI), historical energy modelling or energy forecasting. The inclusion of consumption-based assessments of useful work and exergy efficiency could be an important area - following the lead of emissions modelling – such that potential offshoring of high exergy efficiency processes to China can be included, which will lower China's but raise the UK-US efficiency. The assessment of a global UWA assessment could be included in that workstream, to understand global exergy efficiency and useful work changes over time. The extension of UWA to reach and include energy services would be of key merit, since useful work is a current proxy for energy services.

My current contributions beyond my core PhD thesis is as co-author to the methods and EROI papers (Sousa et al., 2016; Correa et al., 2015). Also relevant is that I am now employed as a UK Energy Research Council (UKERC) post-doctoral researcher, where part of the role is to integrate energy analysis via exergy efficiency into a UK macro-econometric model. This will test – possibly for the first time - how exergy analysis might be integrated into mainstream energy economic modelling, including future energy demand forecasting.

6.6.2.2 Economic analysis

The key economic question remains: “does useful work provide a closer link to economic growth than primary energy?” Using cointegration approach to study this in more detail is part of ongoing exergy economics network workstreams. If wider evidence of this is found, it will reveal that the exergy analysis approach - in relation to the study of economics - is merited, and that the study of energy at the other end of the conversion chain should become more widely adopted.

It will also be important to study the energy use – exergy efficiency – economic output (U-ε-GDP) linkages in more detail. Taking China, the analysis in paper 2 (Chapter 3) and paper 4 (Chapter 5) does not reveal how much of the 30-fold gain in economic growth is due to efficiency gains. The rebound paper (Chapter 4) also suggests possible backfire in China, in which case energy use would be higher than without efficiency gains – a striking result. The production function approach in Paper 3 (Chapter 4) and Paper 4 (Chapter 5) attributed economic growth in a CES function from three factors of factor of production: capital, labour and useful work. But considering how efficiency may be itself a driver of economic output may also be worthy of study as a separate component, i.e. $Y = f(K,L,\varepsilon,U)$. This gets to the heart of Ayres and Warr’s assertion that efficiency is the driver of economic growth. Therefore separating components (energy use, rebound, efficiency) versus the counterfactual remain key issues to resolve.

My current contributions beyond my core PhD thesis is as co-author to the CES paper (Santos et al., 2016).

6.6.2.3 Communication and advocacy

Finally, beyond the quantitative workstreams of energy and economics analysis, lies a softer, qualitative need for improvements to communication, to overcome some of the barriers (see Section 6.5.3.3) to facilitate exergy analysis’s more mainstream adoption. Historically, exergy economics research using the UWA technique has been disparate. Therefore, developing a broader, coherent network, which collaboratively targets research funding is an important aspiration. It will require that it also humbly places the research question ahead of the method, since exergy analysis is merely a different energy analysis tool.

My current contributions in this area start as an active member of the exergy economics network. Also I have contributed to the Science Europe's Exergy Opinion paper (Science Europe, 2015), and also a longer Exergy brochure due for publication in June 2016. At a personal level, I have made over a dozen presentations at various conferences since my PhD started on my exergy-based research. I have made efforts to present and engage at conferences which are aimed at mainstream energy-economists (e.g. International Energy Workshop, and the British Institute of Energy Economics) as well as to ecological economists (e.g. ESEE).

6.6.3 Final reflections: Exergy's role in the global climate challenge

2015 was the hottest year on record, and marked the point when the average global temperature rose for the first time to 1.0°C above pre-industrial levels[32]: half way to the 2°C limit considered the threshold beyond which 'dangerous' climate change may occur. Staying within this 2°C threshold by rapid reduction of GHG emissions is therefore our global climate challenge. In large part this is an energy challenge, since energy-related carbon emissions are responsible for around 80% of global GHG emissions.

To reduce energy-related CO_2 emissions, energy demand reduction through energy efficiency is a key policy area. Currently, mainstream energy economics – the study of the supply and use of energy, combined with economics – provides the main evidence base for such policies. However, relying too heavily on energy economics may be a misplaced faith: since it provides only limited – or at least one-sided - evidence on key questions such as trends in national-level energy efficiency, the size of energy rebound, and the role of energy in economic growth. These questions matter since they effect the design of energy policies.

A key barrier within mainstream energy economics is the lack of a coherent, consistent definition of energy efficiency. Currently a diverse set of indicators -

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32 http://www.nasa.gov/press-release/nasa-noaa-analyses-reveal-record-shattering-global-warm-temperatures-in-2015

using physical, monetary or hybrid approaches - are used, as proxies for thermodynamic energy efficiency. The use of UWA and exergy analysis offers a potential underused route to measure thermodynamic energy efficiency at a national-level. By using exergy analysis alongside economics, exergy economics – as found in this thesis - offers potentially important insights to the study of energy use and economic growth.

Given required timescales of the global climate challenge, it seem sensible to develop all the tools in the climate ‘policy box’. Communication and engagement may play a pivotal role: enabling exergy economics to complement (rather than compete with) traditional energy economics, helping to lay a broader evidence base for energy and economic policy.

6.7 References

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Appendix A Supporting information to Chapter 2: Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010

A.1 IEA mapping to useful work categories

The mapping is given below for the US analysis in Table A1. The mapping is very similar for the UK analysis. It follows the approach taken by Serrenho et al, with some small local variations for in-country data (Serrenho et al., 2016).

Table A1: US IEA mapping to useful work categories

IEA Sector		Energy carrier		Useful work category
Energy Sector own use	Coal mines	Coal& Coal Products		Med Temp Heat2 - 200'C
		Natural Gas		Med Temp Heat2 - 200'C
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Electricity		Electricity - Energy sector own use
	Oil and gas extraction	Oil & Oil Products	Crude oil	Med Temp Heat2 - 200'C
		Oil & Oil Products	Natural gas liquids	Med Temp Heat2 - 200'C
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Natural Gas		Med Temp Heat2 - 200'C
		Electricity		Electricity - Energy sector own use
	Blast furnaces	Coal& Coal Products		High Temp Heat
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Motor gasoline	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Other Kerosene	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
	Gas works	Coal& Coal Products		High Temp Heat
		Natural Gas		Med Temp Heat2 - 200'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Motor gasoline	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Other Kerosene	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Electricity		Electricity - Energy sector own use
	Coke ovens	Coal& Coal Products		High Temp Heat
		Natural Gas		High Temp Heat
		Oil & Oil Products	Fuel Oil	High Temp Heat
		Electricity		Electricity - Energy sector own use
	Patent fuel plants	Coal& Coal Products		Med Temp Heat2 - 200'C
	Oil refineries	Coal& Coal Products		Med Temp Heat2 - 200'C
		Natural Gas		Med Temp Heat2 - 200'C
		Oil & Oil Products	Refinery gas	Med Temp Heat2 - 200'C
		Oil & Oil Products	Ethane	Med Temp Heat2 - 200'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Med Temp Heat2 - 200'C
		Oil & Oil Products	Motor gasoline	Med Temp Heat2 - 200'C
		Oil & Oil Products	Gasoline type jet fuel	Med Temp Heat2 - 200'C
		Oil & Oil Products	Kerosene type jet fuel	Med Temp Heat2 - 200'C
		Oil & Oil Products	Other Kerosene	Med Temp Heat2 - 200'C
		Oil & Oil Products	Gas/diesel oil	Med Temp Heat2 - 200'C
		Oil & Oil Products	Fuel oil	Med Temp Heat2 - 200'C
		Oil & Oil Products	Naphtha	Med Temp Heat2 - 200'C
		Oil & Oil Products	White spirit & SBP	Med Temp Heat2 - 200'C
		Oil & Oil Products	Lubricants	Med Temp Heat2 - 200'C
		Oil & Oil Products	Bitumen	Med Temp Heat2 - 200'C
		Oil & Oil Products	Paraffin waxes	Med Temp Heat2 - 200'C
		Oil & Oil Products	Petroleum coke	Med Temp Heat2 - 200'C
		Electricity		Electricity - Energy sector own use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
	Own use in electricity, CHP & Heat plants	Electricity		Electricity - Energy sector own use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
	Pumped storage plants	Electricity		Electricity - Energy sector own use
	Nuclear industry	Electricity		Electricity - Energy sector own use
	Non-specified (energy)	Natural Gas		Med Temp Heat2 - 200'C
		Oil & Oil Products	Gas/diesel oil	Med Temp Heat2 - 200'C
		Oil & Oil Products	Fuel oil	Med Temp Heat2 - 200'C
		Electricity		Electricity - Energy sector own use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
Total Final Consumption				
1. Industry	Iron and steel	Coal& Coal Products	Coal, Coke oven coke, coke oven gas, blast furnace gas	High Temp Heat
		Combustible Renewables	Industrial waste	High Temp Heat - 600'C
		Natural Gas		High Temp Heat
		Oil & Oil Products	Natural gas liquids	High Temp Heat
		Oil & Oil Products	Liquefied petroleum gases (LPG)	High Temp Heat
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	High Temp Heat
		Electricity		Electricity - Industry use
		Heat		High Temp Heat - 600'C
	Chemical and petrochemical	Coal& Coal Products		50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Industrial waste	50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Municipal wastes	50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Primary solid biofuels	50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Biogases	50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Other liquid biofuels	50% Med Temp Heat2 / 50% High Temp Heat
		Natural Gas		50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Refinery gas	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Liquefied petroleum gases (LPG)	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	50% Med Temp Heat2 / 50% High Temp Heat
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume 50% MTH / 50% HTH
	Non-ferrous metals	Coal& Coal Products		50% Med Temp Heat2 / 50% High Temp Heat
		Natural Gas		50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Natural gas liquids	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Liquefied petroleum gases (LPG)	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	50% Med Temp Heat2 / 50% High Temp Heat
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume 50% MTH / 50% HTH
	Non-metallic minerals	Coal& Coal Products		50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Industrial waste	50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Primary solid biofuels	50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Other liquid biofuels	50% Med Temp Heat2 / 50% High Temp Heat
		Natural Gas		50% Med Temp Heat2 / 50% High Temp Heat

IEA Sector		Energy carrier		Useful work category
1. Industry (Cont'd)	Non-metallic minerals (contd)	Oil & Oil Products	Natural gas liquids	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Liquefied petroleum gases (LPG)	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	50% Med Temp Heat2 / 50% High Temp Heat
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume 50% MTH / 50% HTH
	Transport equipment	Coal& Coal Products		50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Biogases	50% Med Temp Heat2 / 50% High Temp Heat
		Natural Gas		50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Natural gas liquids	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Liquefied petroleum gases (LPG)	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Motor gasoline	Mechanical Drive - Gasoline fuel (Petrol cars)
		Oil & Oil Products	Aviation gasoline	Mechanical Drive - Aviation fuel, jet fuel
		Oil & Oil Products	Gasoline type jet fuel	Mechanical Drive - Aviation fuel, jet fuel
		Oil & Oil Products	Kerosene type jet fuel	Mechanical Drive - Aviation fuel, jet fuel
		Oil & Oil Products	Other Kerosene	Mechanical Drive - Gas/diesel oil (assume diesel cars)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	50% Med Temp Heat2 / 50% High Temp Heat
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume 50% MTH / 50% HTH
	Machinery	Coal& Coal Products		50% Med Temp Heat2 / 50% High Temp Heat
		Natural Gas		50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Natural gas liquids	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Liquefied petroleum gases (LPG)	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	50% Med Temp Heat2 / 50% High Temp Heat
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume 50% MTH / 50% HTH
	Mining and quarrying	Coal& Coal Products	Hard coal (if no detail)	50% Med Temp Heat2 / 50% High Temp Heat
		Coal& Coal Products	Other bituminous coal	50% Med Temp Heat2 / 50% High Temp Heat
		Natural Gas		50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	50% Med Temp Heat2 / 50% High Temp Heat
		Electricity		Electricity - Industry use
	Food and tobacco	Coal& Coal Products		Med Temp Heat1 - 100'C
		Combustible Renewables	Industrial waste	Med Temp Heat1 - 100'C
		Combustible Renewables	Primary solid biofuels	Med Temp Heat1 - 100'C
		Combustible Renewables	Biogases	Med Temp Heat1 - 100'C
		Natural Gas		Med Temp Heat1 - 100'C
		Oil & Oil Products	Natural gas liquids	Med Temp Heat1 - 100'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Med Temp Heat1 - 100'C
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	Med Temp Heat1 - 100'C
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
	Paper, pulp and print	Coal& Coal Products		Med Temp Heat1 - 100'C
		Combustible Renewables	Industrial waste	Med Temp Heat1 - 100'C
		Combustible Renewables	Municipal wastes	Med Temp Heat1 - 100'C
		Combustible Renewables	Primary solid biofuels	Med Temp Heat1 - 100'C
		Combustible Renewables	Biogases	Med Temp Heat1 - 100'C
		Combustible Renewables	Other liquid biofuels	Med Temp Heat1 - 100'C
		Natural Gas		Med Temp Heat1 - 100'C
		Oil & Oil Products	Natural gas liquids	Med Temp Heat1 - 100'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Med Temp Heat1 - 100'C
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	Med Temp Heat1 - 100'C
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
	Wood and wood products	Coal& Coal Products		Med Temp Heat1 - 100'C
		Combustible Renewables	Industrial waste	Med Temp Heat1 - 100'C
		Combustible Renewables	Primary solid biofuels	Med Temp Heat1 - 100'C
		Combustible Renewables	Other liquid biofuels	Med Temp Heat1 - 100'C
		Natural Gas		Med Temp Heat1 - 100'C
		Oil & Oil Products	Natural gas liquids	Med Temp Heat1 - 100'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Med Temp Heat1 - 100'C
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	Med Temp Heat1 - 100'C
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
	Construction	Coal& Coal Products		Med Temp Heat1 - 100'C
		Natural Gas		Med Temp Heat1 - 100'C
		Oil & Oil Products	Motor gasoline	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	Med Temp Heat1 - 100'C
		Electricity		Electricity - Industry use
	Textile and leather	Coal& Coal Products		Med Temp Heat1 - 100'C
		Combustible Renewables	Primary solid biofuels	Med Temp Heat1 - 100'C
		Natural Gas		Med Temp Heat1 - 100'C
		Oil & Oil Products	Natural gas liquids	Med Temp Heat1 - 100'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Med Temp Heat1 - 100'C
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	Med Temp Heat1 - 100'C
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
	Non-specified (industry)	Coal& Coal Products		50% Med Temp Heat2 / 50% High Temp Heat
		Combustible Renewables	Industrial waste	Med Temp Heat1 - 100'C
		Combustible Renewables	municipal waste	Med Temp Heat1 - 100'C
		Combustible Renewables	Primary solid biofuels	Med Temp Heat1 - 100'C
		Combustible Renewables	Biogases	Med Temp Heat1 - 100'C
		Combustible Renewables	Non-specified primary biofuels and waste	Med Temp Heat1 - 100'C
		Natural Gas		50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Natural gas liquids	Med Temp Heat1 - 100'C
		Oil & Oil Products	Refinery gas	Med Temp Heat1 - 100'C
		Oil & Oil Products	Ethane	Med Temp Heat1 - 100'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Mechanical Drive - Industry static motors (diesel engines)

IEA Sector		Energy carrier		Useful work category
1. Industry (Cont'd)	Non-specified (industry) (Cont'd	Oil & Oil Products	Motor gasoline	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Other Kerosene	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Fuel oil	50% Med Temp Heat2 / 50% High Temp Heat
		Oil & Oil Products	Naphtha	50% Med Temp Heat2 / 50% High Temp Heat
		Heat - renewables	Geothermal	Renewable Heat (Geothermal / solar hot water) - assume med temp heat1 100'C
		Electricity		Electricity - Industry use
		Heat		Heat (unspecified) - assume med temp heat1 - 100'C
2. Transport	Domestic aviation	Oil & Oil Products	Aviation gasoline	Mechanical Drive - Aviation fuel, jet fuel
		Oil & Oil Products	Gasoline type jet fuel	Mechanical Drive - Aviation fuel, jet fuel
		Oil & Oil Products	Kerosene type jet fuel	Mechanical Drive - Aviation fuel, jet fuel
	Road	Combustible Renewables	Biogasoline	Mechanical Drive - bio-diesel / bio-gasoline (road transport)
		Combustible Renewables	Biodiesels	Mechanical Drive - bio-diesel / bio-gasoline (road transport)
		Natural Gas	Natural Gas	Mechanical Drive - Gas/diesel oil (assume diesel cars)
		Oil & Oil Products	Natural gas liquids	Mechanical Drive - Gas/diesel oil (assume diesel cars)
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Mechanical Drive - Gas/diesel oil (assume diesel cars)
		Oil & Oil Products	Motor gasoline	Mechanical Drive - Gasoline fuel (Petrol cars)
		Oil & Oil Products	Other Kerosene	Mechanical Drive - Gas/diesel oil (assume diesel cars)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Gas/diesel oil (assume diesel cars)
		Oil & Oil Products	Fuel oil	Mechanical Drive - Gas/diesel oil (assume diesel cars)
	Rail	Coal& Coal Products		Mechanical Drive - Coal (steam powered trains)
		Combustible Renewables	Biodiesels	Mechanical Drive - bio-diesel (diesel trains)
		Oil & Oil Products	Other Kerosene	Mechanical Drive - Gas/diesel fuel (diesel trains)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Gas/diesel fuel (diesel trains)
		Oil & Oil Products	Fuel oil	Mechanical Drive - Gas/diesel fuel (diesel trains)
		Electricity		Electricity - Transport - Mechanical drive (rail)
	Pipeline transport	Natural Gas		Mechanical Drive - Gas fired engines (for pipeline transport)
	Domestic navigation	Oil & Oil Products	Motor gasoline	Mechanical Drive - Diesel/gas oil fuel (Boat engines)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Diesel/gas oil fuel (Boat engines)
		Oil & Oil Products	Fuel oil	Mechanical Drive - Diesel/gas oil fuel (Boat engines)
	Non-specified (transport)	Combustible Renewables	Biodiesels	Mechanical Drive - bio-diesel / bio-gasoline (road transport)
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Gas/diesel oil (assume diesel cars)
3. Other	Residential	Coal& Coal Products		Low Temp Heat 20'C
		Coal& Coal Products	Gas works gas	Town gas lighting
		Combustible Renewables	Primary solid biofuels	Low Temp Heat 20'C
		Natural Gas		Low Temp Heat 20'C
		Oil & Oil Products	Natural gas liquids	Low Temp Heat 20'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Low Temp Heat 20'C
		Oil & Oil Products	Other Kerosene	Low Temp Heat 20'C
		Oil & Oil Products	Gas/diesel oil	Low Temp Heat 20'C
		Oil & Oil Products	Fuel oil	Low Temp Heat 20'C
		Heat - renewables	Geothermal	Renewable Heat (Geothermal / solar hot water) - assume low temp heat 20'C
		Heat - renewables	Solar thermal	Renewable Heat (Geothermal / solar hot water) - assume low temp heat 20'C
		Electricity		Electricity - residential use
	Commercial and public services	Coal& Coal Products		Low Temp Heat 20'C
		Combustible Renewables	Industrial waste	Low Temp Heat 20'C
		Combustible Renewables	municipal waste	Low Temp Heat 20'C
		Combustible Renewables	Primary solid biofuels	Low Temp Heat 20'C
		Combustible Renewables	Biogases	Low Temp Heat 20'C
		Combustible Renewables	Other liquid biofuels	Low Temp Heat 20'C
		Natural Gas		Low Temp Heat 20'C
		Oil & Oil Products	Natural gas liquids	Low Temp Heat 20'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Low Temp Heat 20'C
		Oil & Oil Products	Motor gasoline	Mechanical Drive - Industry static motors (diesel engines)
		Oil & Oil Products	Other Kerosene	Low Temp Heat 20'C
		Oil & Oil Products	Gas/diesel oil	Low Temp Heat 20'C
		Oil & Oil Products	Fuel oil	Low Temp Heat 20'C
		Heat - renewables	Geothermal	Renewable Heat (Geothermal / solar hot water) - assume low temp heat 20'C
		Electricity		Electricity - commerical / public sector use
		Heat		Heat (unspecified) - assume low temp heat 20'C
	Agriculture/forestry	Coal& Coal Products		Med Temp Heat1 - 100'C
		Combustible Renewables	Primary solid biofuels	Med Temp Heat1 - 100'C
		Oil & Oil Products	Natural gas liquids	Med Temp Heat1 - 100'C
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Med Temp Heat1 - 100'C
		Oil & Oil Products	Motor gasoline	Mechanical Drive - Gas/diesel fuel (tractors)
		Oil & Oil Products	Other Kerosene	Med Temp Heat1 - 100'C
		Oil & Oil Products	Gas/diesel oil	Mechanical Drive - Gas/diesel fuel (tractors)
		Oil & Oil Products	Fuel oil	Med Temp Heat1 - 100'C
		Electricity		Electricity - other (eg agriculture) use
	Fishing			
	Non-specified (other)	Coal& Coal Products		Med Temp Heat1 - 100'C
		Combustible Renewables	Industrial waste	Med Temp Heat1 - 100'C
		Combustible Renewables	municipal waste	Med Temp Heat1 - 100'C
		Combustible Renewables	Primary solid biofuels	Med Temp Heat1 - 100'C
		Combustible Renewables	Biogases	Med Temp Heat1 - 100'C
		Combustible Renewables	Non-specified primary biofuels and waste	Med Temp Heat1 - 100'C
		Oil & Oil Products	Other Kerosene	Med Temp Heat1 - 100'C
		Heat - renewables	Geothermal	Heat (unspecified) - assume low temp heat 20'C
		Electricity		Electricity - other (eg agriculture) use
4. Non energy use	non energy use	Natural Gas	Natural Gas	Non energy use - gas
		Oil & Oil Products	Natural gas liquids	Non energy use - oil
		Oil & Oil Products	Refinery gas	Non energy use - oil
		Oil & Oil Products	Ethane	Non energy use - oil
		Oil & Oil Products	Liquefied petroleum gases (LPG)	Non energy use - oil
		Oil & Oil Products	Naphtha	Non energy use - oil
		Oil & Oil Products	White spirit & SBP	Non energy use - oil
		Oil & Oil Products	Lubricants	Non energy use - oil
		Oil & Oil Products	Bitumen	Non energy use - oil
		Oil & Oil Products	Paraffin waxes	Non energy use - oil
		Oil & Oil Products	Petroleum coke	Non energy use - oil
		Oil & Oil Products	Non-specified oil products	Non energy use - oil

A.2 US and UK analysis – Detailed input data

The input data is presented in the following sections:

- A2.1: Exergy coefficients
- A2.2: Input IEA energy data
- A2.3: Exergy to useful work conversion equations
- A2.4: Useful work calculations - Heat
- A2.5: Useful work calculations - Mechanical Drive
- A2.6: Useful work calculations - Electricity
- A2.7: Useful work calculations - Non-energy
- A2.8: Useful work calculations - Muscle work

A.2.1 Exergy coefficients

The following exergy inflow coefficients were used to transform the IEA input energy (TPES) values to exergy (chemical energy) equivalent values, as shown below in Table A2. This is the starting point for our analysis, in that it provides (in sum) the denominator (total exergy input) for aggregate exergy efficiency, and also the start point for following the exergy conversion losses through to end useful work (in sum, the numerator).

Table A2: summary of adopted exergy coefficients

Energy source	**Exergy inflow coefficient**	**Notes & References**
Coal & coal products	1.088	Taken from Ayres & Warr (2010), Table 3.1, expanded from Szargut et al. (1988)
Natural Gas	1.04	
Oil & oil products	1.07	
Combustible renewables (e.g. biomass)	1.15	
Nuclear	1.00	Warr et al (Table 2, 2010) – this is the assumed coefficient to convert uranium into nuclear fuel.

Energy source	Exergy inflow coefficient	Notes & References
		IEA data assumes 0.33 conversion from electricity to starting TPES energy value. Power station conversion loss factor (~0.33) occurs after this point, so overall nuclear fuel to electricity factor ~0.33
Hydro	0.85	Warr et al (Table 2, 2010) – this is the assumed coefficient to convert inflow of energy sources to into electricity, delivered to point of use IEA data assumes 1.00 conversion from renewable electricity to starting TPES energy value. Hydro - Pumped storage taken as same factor as natural flow hydro, as energy to pump water re-appears in energy used by own sector
Geothermal	0.35	
Solar photovoltaics	0.07	
Solar thermal	0.10	
Tide, wave and ocean	0.07	
Wind	0.15	
Other sources	0.10	

The values adopted are the same or very close to those from other exergy assessments (e.g. (Chen & Chen, 2009; Gasparatos et al., 2009)).

A.2.2 Input IEA energy data

The next stage was to take IEA Total Primary Energy Supply (TPES) data from their extended energy balance data (International Energy Agency (IEA), 2013), and convert this to exergy equivalent values. Close agreement as shown in Figure A1 was found to the Ayres & Warr exergy datasets (Warr, 2010), as shown below, and on this basis the IEA data was deemed suitable to use.

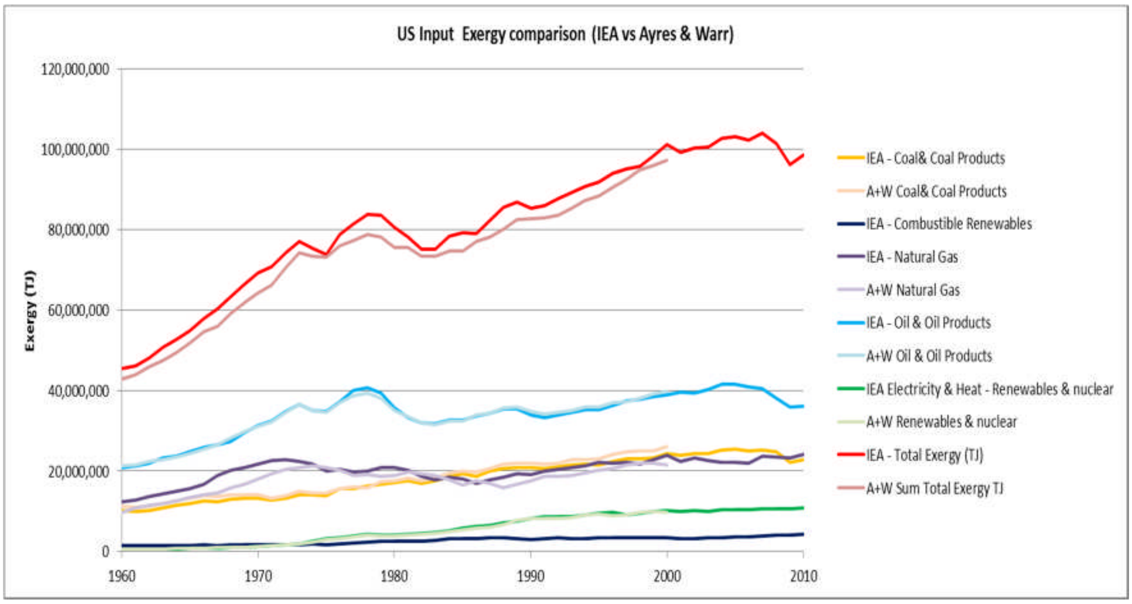


Figure A1: US input exergy – IEA (2013) derived values vs Warr (2010) comparison

A.2.3 Exergy to useful work conversion equations

The exergy efficiency for each type of energy use is given below in Table A3, with examples of key energy end uses:

Table A3 – exergy efficiency for difference sources / end uses (Adapted from Carnahan et al (1975a) and Serrenho et al., (2016))

End Use \ Source		Work W_{in}	Fuel Heat of Combustion $\lvert\Delta H\rvert$	Exergy B Heat Q_1 from hot reservoir at T_1
		$W_{max} = W_{in}$	$W_{max} = B$	$W_{max} = Q_1\left(1-\frac{T_0}{T_1}\right)$
Work W_{out}	$W_{min} = W_{out}$	$\epsilon = \eta = \frac{W_{out}}{W_{in}}$ (e.g. Section A2.5/A2.6 – Electric mechanical drive,)	$\epsilon = \frac{W_{out}}{W_{in}} \approx \eta$ (e.g. Section A2.5 – internal combustion car)	$\epsilon = \frac{W_{out}}{Q_1\left(1-\frac{T_0}{T_1}\right)} = \frac{\eta}{1-\frac{T_0}{T_1}}$
Heat Q_2 added from warm reservoir at T_2	$W_{min} = Q_2\left(1-\frac{T_0}{T_2}\right)$	$\epsilon = \frac{Q_2}{W_{in}}\left(1-\frac{T_0}{T_2}\right) = \eta\left(1-\frac{T_0}{T_2}\right)$ (e.g. Section A2.6 - Electric heating)	$\epsilon = \frac{Q_2}{B}\left(1-\frac{T_0}{T_2}\right) = \eta\left(1-\frac{T_0}{T_2}\right)$ (e.g. Section A2.4 - Direct heating)	$\epsilon = \frac{Q_2\left(1-\frac{T_0}{T_2}\right)}{Q_1\left(1-\frac{T_0}{T_1}\right)} = \eta\frac{1-\frac{T_0}{T_2}}{1-\frac{T_0}{T_1}}$
Heat Q_2 extracted from cool reservoir at T_3	$W_{min} = Q_3\left(\frac{T_0}{T_3}-1\right)$	$\epsilon = \frac{Q_3}{W_{in}}\left(\frac{T_0}{T_3}-1\right) = \eta\left(\frac{T_0}{T_3}-1\right)$ (e.g. Section A2.6 - Electric air-conditioning)	$\epsilon = \frac{Q_3}{B}\left(\frac{T_0}{T_3}-1\right) \approx \eta\left(\frac{T_0}{T_3}-1\right)$	$\epsilon = \frac{Q_3\left(\frac{T_0}{T_3}-1\right)}{Q_1\left(1-\frac{T_0}{T_1}\right)} = \eta\frac{\frac{T_0}{T_3}-1}{1-\frac{T_0}{T_1}}$

A.2.4 Heat- useful work calculations

For heat, the governing exergy efficiency equation from Table A3 is:

$$\epsilon = \frac{Q_2}{B}\left(1-\frac{T_0}{T_2}\right) = \eta\left(1-\frac{T_0}{T_2}\right)$$

This translates as - first determine the device or process energy efficiency, then multiply by the Carnot temperature ratio ($1-T_0/T_2$).

A.2.4.1 Temperature data

The summary of the various data sources are provided in Table A4:

Table A4: summary of heat classes and adopted Carnot temperatures

Heat Sub-category	Temp T_0		Temp T_2	
	Values	Data Source	Values	Data Source Summary
High Temperature Heat (HTH) – 600°C	Average yearly air temperature (Kelvin)	UK Hadley temp data (Met Office, 2013) US Gov data (National Oceanic and Atmospheric Administration (NOAA), 2013)	600°C = 873K	(Warr et al., 2010)
Med Temperature Heat 2 (MTH2) – 200°C			200°C = 473K	
Med Temperature Heat 1 (MTH1) – 100°C			100°C = 373K	
Low Temperature Heat (LTH) – 15-20°C	Average winter air temperature (Kelvin)		15-20°C = 288-293K (UK)	UK – Table 3.06 (Department of Energy & Climate Change (DECC), 2013) US - (Milne & Boardman, 2000; Roberts & Lay, 2013; ASHRAE, 2010; Carnahan et al., 1975a)

Warr et al (Warr et al., 2010) take three classes of heat: HTH (600°C); MTH (200°C); LTH (100°C). Our approach is the same except to split the latter category into two sub-groups: hot water / cooking as MTH1 (100°C), and space heating as LTH (15-20°C).

National datasets for outside air temperatures 1960-2010 were obtained (Met Office, 2013; National Oceanic and Atmospheric Administration (NOAA), 2013). For LTH (assumed to be mainly space heating used in winter), the outside air temperature is taken as the national average of December to February, whilst for

MTH1 (assumed to be cooking and other year-round activities), the outside temperature was taken as the average yearly temperature. For LTH the indoor temperature was 15-20°C, based on UK data for 1970-2010 (Department of Energy & Climate Change (DECC), 2013). Longitudinal datasets for US indoor temperatures were lacking. Instead, partial data and anecdotal evidence was found for US indoor temperatures including:

- Carnahan et al. (1975a) assumed internal room temperature was 70°F (21.6°C);
- Milne and Boardman (2000, p.414) who stated “the average household temperatures in the US … are generally significantly higher [than the UK]”;
- Beamer et al. (2011, p.2) reported “residents typically set thermostats between 70 °F (21 °C) and 71.6 °F (22 °C), and remained comfortable while the indoor air temperature remained between 62.6 °F (17 °C) and 77 °F (25 °C)”.
- The American Physical Society (2008), took 70°F = 21.6°C (p.72) same as Carnahan et al. (1975a).
- Warr et al (2010) assume a constant indoor (winter) temperature of 20°C for the entire period 1900-2000.
- Roberts & Lay (2013): 60 houses were surveyed. average living room temperature in heating season was 65°F = 18.3°C (Figure 22).
- ASHRAE (2010) guidance for office temperatures recommends heating systems are set between 68-74° F (20.0-23.3°C).

The US commercial / domestic LTH split is around 35% from our IEA based mapping calculations, compared to the UK which is around 10%. Therefore taking domestic room temperatures for the UK is appropriate, but for the US a weighted approach is suitable, so using a domestic average of 20°C and commercial average of 21.65°C gives us a weighted average of 20.6°C. This is almost the same value as the 20°C assumed by (Warr et al., 2010) but lower than Carnahan et al (1975a).

Collectively this suggests that US indoor temperatures due to LTH are at least as high as in the UK, and so an internal temperature of 18°C (1960) rising to 20.6°F (2010) was taken for the analysis, as shown below in Figure A2:

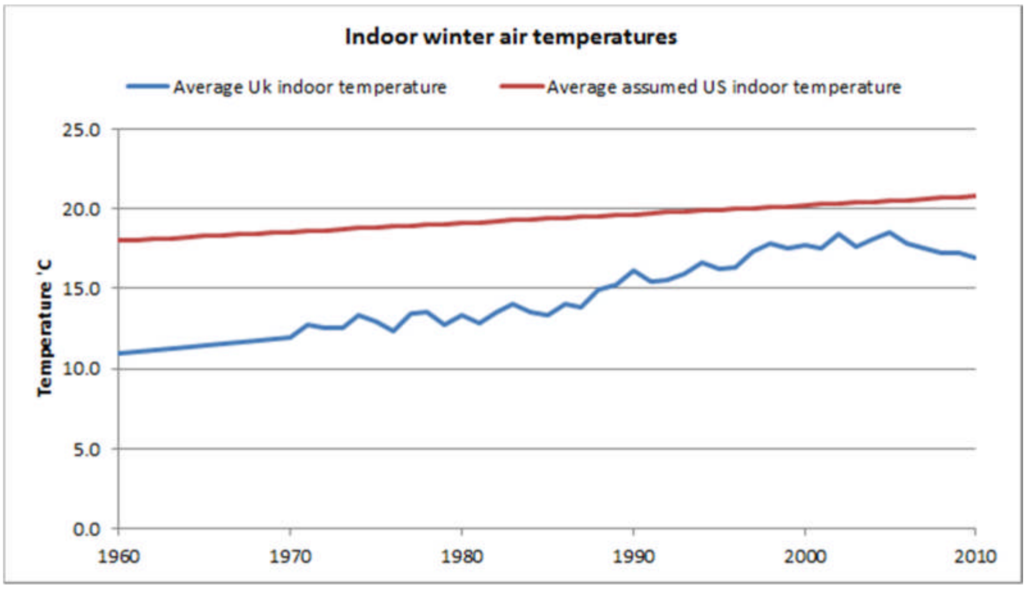


Figure A2: Assumed indoor room temperatures in Winter (heating) season

A.2.4.2 HTH (600'C) and MTH2 (200'C) – exergy efficiency calculations

First, HTH exergy efficiency values are calculated. The energy efficiency is calculated, as the ratio of the minimum energy / actual energy. For steel, the figures of Fruehan (Fruehan et al., 2000) were taken for recycled Electric Arc Furnace (EAF) steel 1.3GJ/tes and virgin steel - Basic Oxygen Furnace (BOF)/Open Hearth Furnace (OHF) - 8.6GJ/tes. These are the same values as taken by Ayres and Warr (2010). Steel production data split by electric arc and basic oxygen components was obtained for UK from the ISSB (International Steel Statistics Bureau (ISSB), 2013) and for the US 1960-1990 from Ayres et al, Table A5, (Ayres et al., 2005b), and 1990-2010 from the US Geological Survey, (2011). The energy consumption data was obtained for the UK for 1960-1973 from the *UK Iron and Steel Annual Statistics* (UK Iron and Steel Institute, 1973) and for 1973-2010 from EEF - UK Steel, p.5, (EEF - UK Steel, 2011); whilst the US data was obtained for 1960-1994 from Worrell (2001) and 1994-2010 from various sources (Stubbles, 2000; Energetics Inc., 2004; Hasanbeigi et al., 2011; US Energy Information Administration (USEIA), 2013). The resultant plots leading to overall energy efficiencies are shown below in Figure A3:

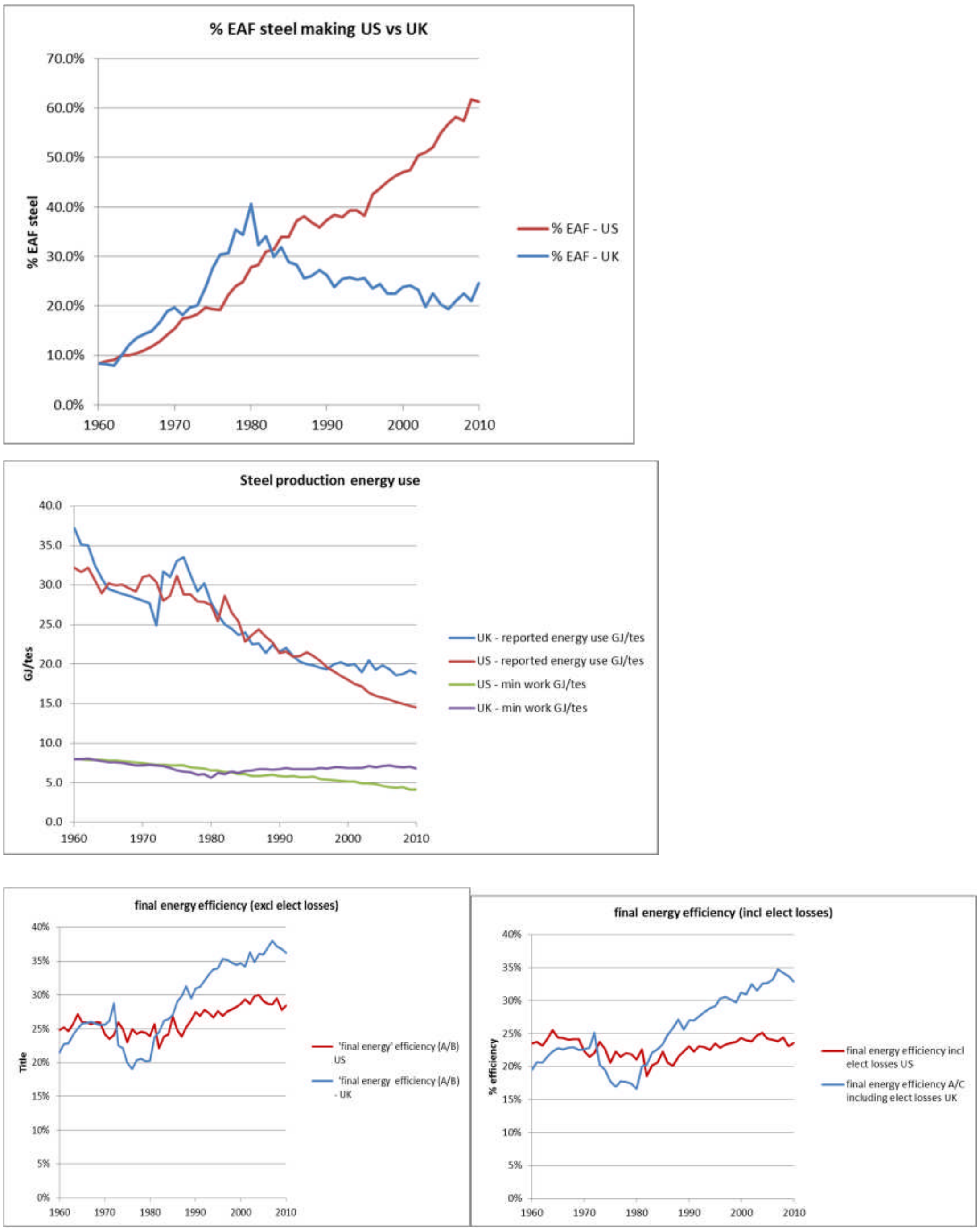
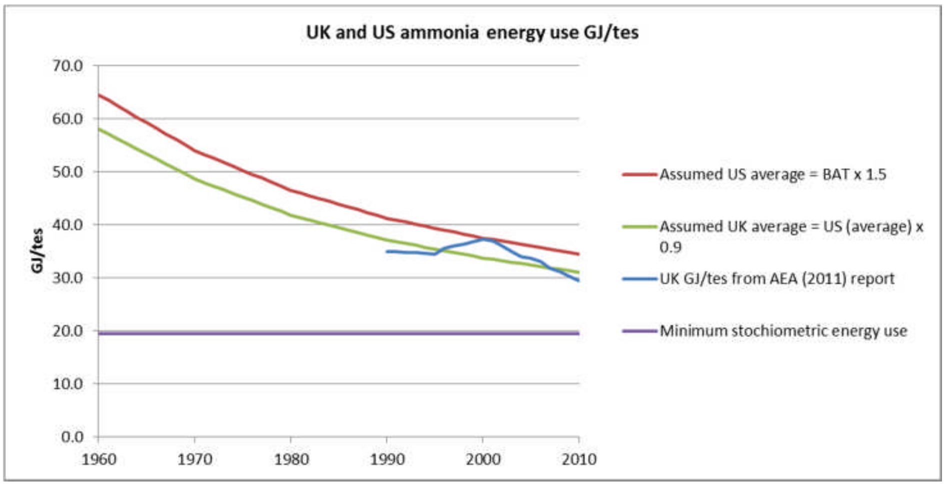


Figure A3: steel production, energy use and efficiency data

For ammonia, the minimum energy requirement value of 19.4GJ/tes was taken from Rafiqul et al (2005), which is very close to Smil's value of 20.0GJ/tes, Figure 1.24, (Smil, 2003). Time-series (GJ/tes) energy consumption data was obtained for the US from Ayres, (Figure 16, (Ayres et al., 2003)) who gave Best Available Technology (BAT) values for 1900-2000. Based on other data sources which give US average-versus-BAT values for discrete years and UK/EU versus US efficiency (Worrell et al., 1994; Worrell et al., 2000; Phylipsen et al., 2002), values of 1.5 × BAT were adopted for average US ammonia industry efficiency, and UK ammonia efficiency was taken to be 0.9 × US average data, as values for UK ammonia energy efficiency were only partially available (e.g. Table 4.10, (AEA Technology plc., 2011)). The results are plotted below in Figure A4:



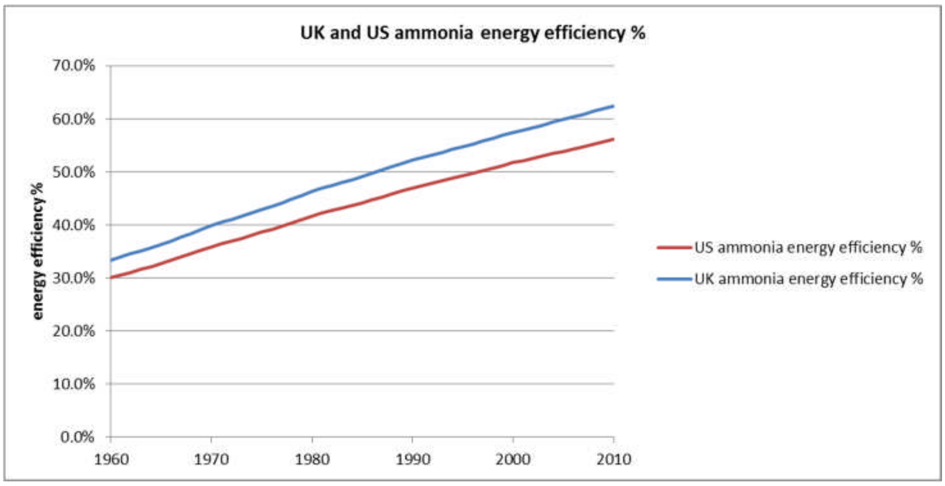


Figure A4: Ammonia - US and UK energy use and efficiencies

Next the individual exergy efficiencies are calculated, and then a weighted average is taken, based on the HTH contribution of the steel versus petrochemical sector. Ammonia is taken as the average exergy efficiency of the petrochemical sector.

Medium temperature heat (MTH2) applications are typically light manufacturing e.g. paper, food. In the absence of specific data sources of GJ/tes data, the approach taken was to take the same energy efficiency as HTH, and therefore the MTH2 exergy efficiency values were simply a pro-rata Carnot temperature ratio (i.e. 873K versus 473K).

A.2.4.3 MTH1 (100’C) and LTH (20’C) exergy efficiency calculations

Low Temperature Heat (LTH) and Medium Temperature Heat 100°C (MTH1) were derived by a similar process. First the device level (first law) energy efficiencies adopted by Serrenho et al. (2016) were reviewed. They were taken from Fouquet (2008), and rise linearly from 50% in 1960 to 90% in 2000. Reviewing other datapoints: average residential boiler efficiency in the US in 1985 was 74% and in 2006 was 85% (Section 5.3.4, (US Department of Energy, 2011)) versus 82% in 2010 for the UK (Table 3.34, (Department of Energy & Climate Change (DECC), 2013)); average commercial boiler efficiency in US in 2003 was 77% (Section 5.3.2, (US Department of Energy, 2011)), a similar but more asymptotic profile was adopted for the UK and US analysis, as shown below in Figure A5:

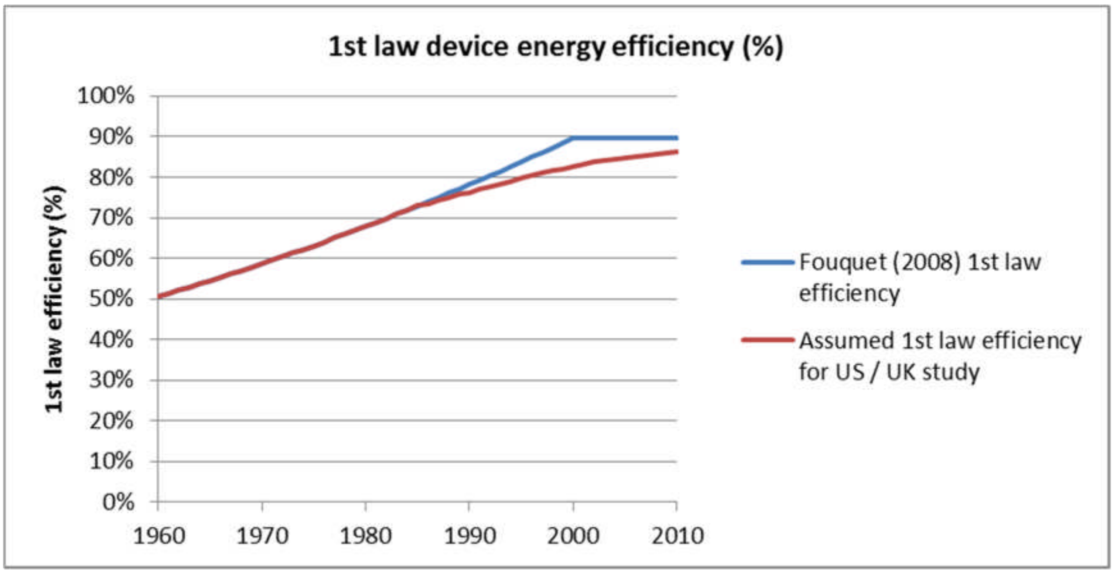


Figure A5: 1st law LTH/MTH1 device efficiencies 1960-2010

Next the Carnot temperature ratios are added, using temperatures as previously set out earlier in Section A2.4

Lastly, town gas (derived from coal) used mainly for lighting is calculated as a separate case. It was prevalent in the 1960s (though still only occupying <0.5% of total energy use at that time), and disappeared completely by 1990. On this basis (in lieu of better datasets) the values for exergy efficiency were taken directly from Ayres and Warr REXS datasets (Warr, 2010).

A.2.5 Mechanical Drive - useful work calculations

For mechanical drive, the governing exergy efficiency equations from Table A4 are below:

- Electric mechanical drive, e.g. rail (electric)

$$\epsilon = \eta = \frac{W_{out}}{W_{in}}$$

- Internal combustion, e.g. car, aircraft, rail (diesel engine) boat

$$\epsilon = \frac{W_{out}}{W_{in}} \approx \eta$$

The following classes in Table A5 of mechanical drive were derived during the mapping process (See also Section A1)

Table A5: Summary of mechanical drive categories

Fuel sources	Mapping Code	Engine type
Oil & Oil Products	OMD1	Mechanical Drive - Gas/diesel oil (assume diesel vehicles
Oil & Oil Products	OMD2	Mechanical Drive - Domestic Aviation fuel, jet fuel
Oil & Oil Products	OMD3	Mechanical Drive - Gasoline fuel (Petrol cars)
Oil & Oil Products	OMD4	Mechanical Drive - Diesel/gas oil fuel (Boat engines)
Oil & Oil Products	OMD5	Mechanical Drive - Industry static motors (diesel engines)

Fuel sources	Mapping Code	Engine type
Oil & Oil Products	OMD6	Mechanical Drive - Gas/diesel fuel (diesel trains)
Oil & Oil Products	OMD7	Mechanical Drive - Gas/diesel fuel (tractors)
Combustible Renewables	CRMD1	Mechanical Drive - bio-diesel / bio-gasoline (road transport)
Combustible Renewables	CRMD2	Mechanical Drive - bio-diesel (diesel trains)
Natural Gas	GMD1	Mechanical Drive - Gas/diesel oil
Natural Gas	GMD2	Mechanical Drive - Gas fired engines (for pipeline transport)
Coal & Coal Pro ducts	CMD1	Mechanical Drive - Coal (steam powered trains)
Coal& Coal Products	CMD2	Mechanical Drive - Coal (steam powered boats)
Electricity	EMD1	Electricity mechanical drive - trains

A.2.5.1 Road vehicles (OMD1, OMD3)

For road transport, we started with published data Table 4.11-4.18 (US Department of Transportation, 2013); Table TRA010 (Department for Transport (Dft), 2013); Table 2.6 (Department of Energy & Climate Change (DECC), 2013), for the US and UK of vehicle kms by type of vehicle and fuel consumption data covering 1960-2010. The national datasets are checked versus IEA datasets, to ensure datasets are sufficiently similar for mpg calculation approach to be valid as shown in Figure A6 and Figure A7:

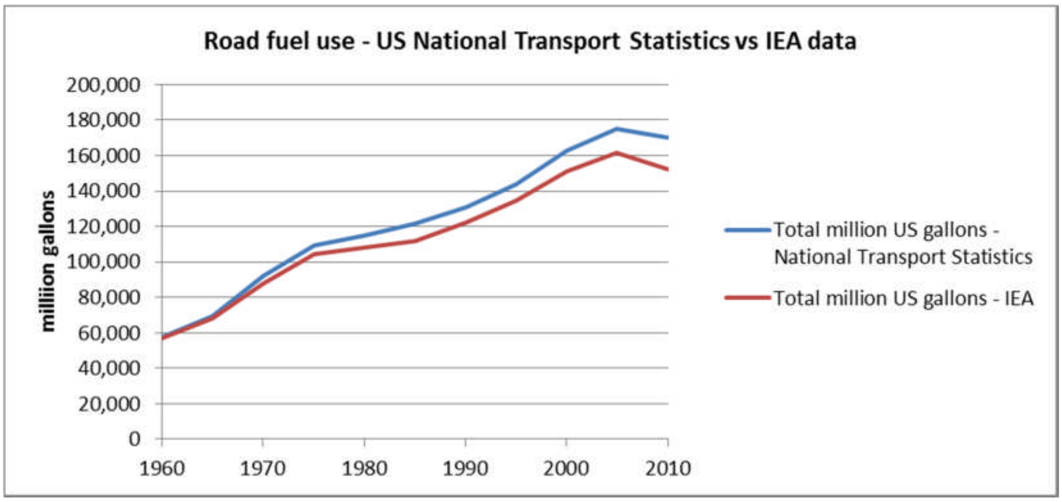


Figure A6: US local road fuel use data vs IEA data.

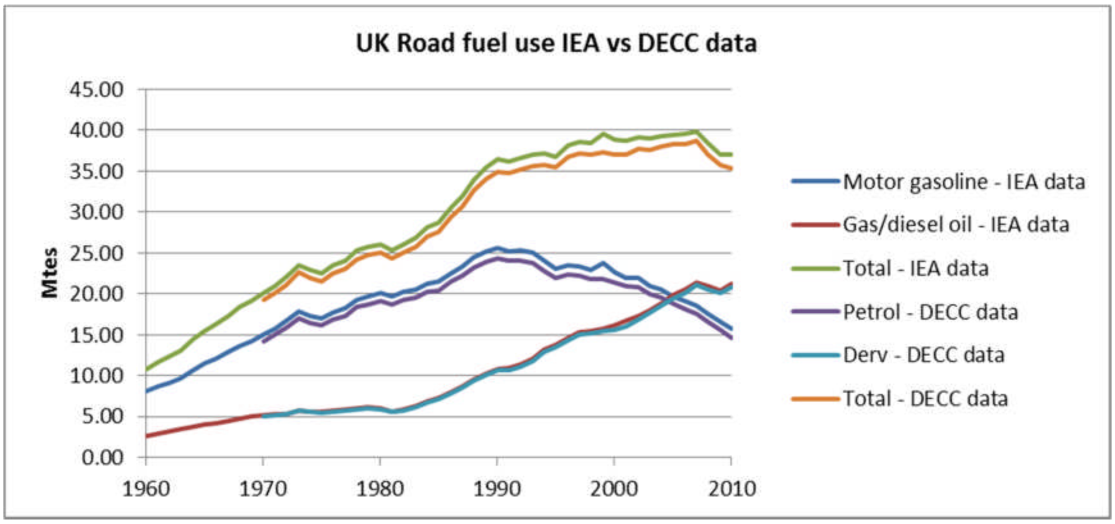


Figure A7: UK local (DECC) road fuel use data vs IEA data.

Using this data we then calculate the fuel economy in mpg, by task level (sub-class) and fuel input. Finally this is then aggregated back to petrol and diesel, to calculate overall miles per US gallon (mpUSg) values for 1960-2010 for both US and UK petrol and diesel road transport, as shown in Figure A8:

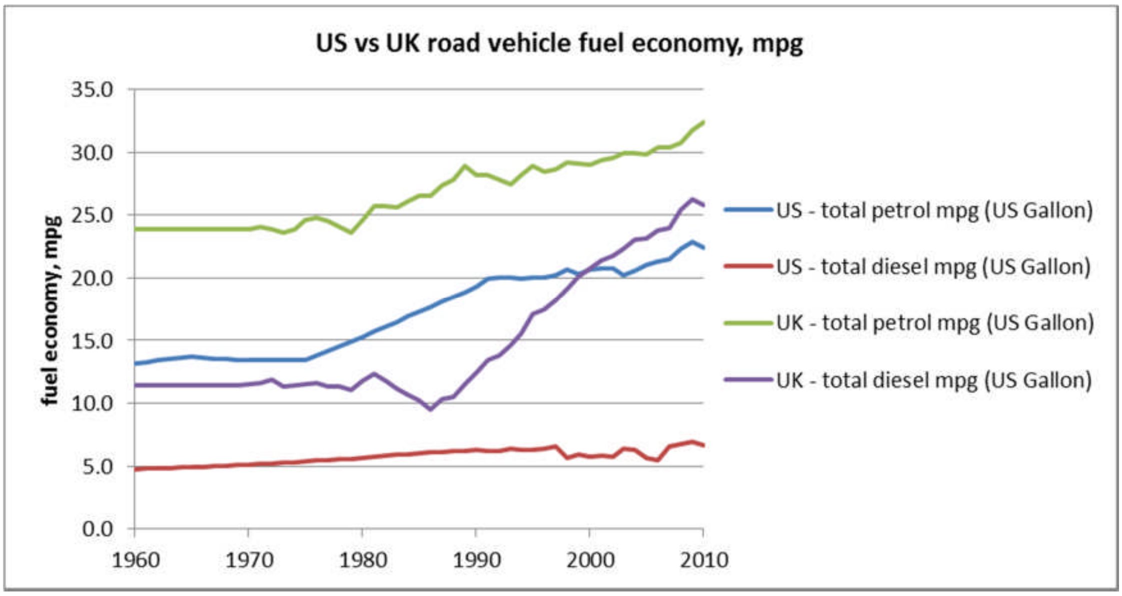


Figure A8: US vs UK road vehicle fuel economy

The second stage was to derive a best-fit declining exponential function y = 35(1-e-0.025x) to relate fuel economy to exergy efficiency, for road based petrol cars in the US since this is where we have the most data. We used the following datasets:

- An origin (0mpUSg, 0% exergy efficiency)
- An assumed point of 8% exergy efficiency in 1970, from Carnahan et al. (Carnahan et al., 1975b).
- US efficiency and fuel economy test data from Oak Ridge National Laboratory data for 68 tested vehicles (Thomas, 2014).
- A terminal asymptotic exergy efficiency of 35%, which for diesel vehicles, based on assumed maximal engine efficiencies from Warr et al, p.107-109 (Warr et al., 2010).

Diesel engines are taken as 25% more efficient (p.324, (Chen et al., 2006)); (p.1916, (Warr et al., 2010)) so a US starting point for diesel cars of 10% in 1970 is assumed.

Code	Description	Exergy efficiency, ε (x = mpUSg)
OMD1	Mechanical Drive - Gas/diesel oil (assume diesel vehicles	$\varepsilon = 43.75(1-e^{-0.025x})$
OMD3	Mechanical Drive - Gasoline fuel (Petrol cars)	$\varepsilon = 35(1-e^{-0.025x})$

The plots of the final equations are shown below in Figure A9:

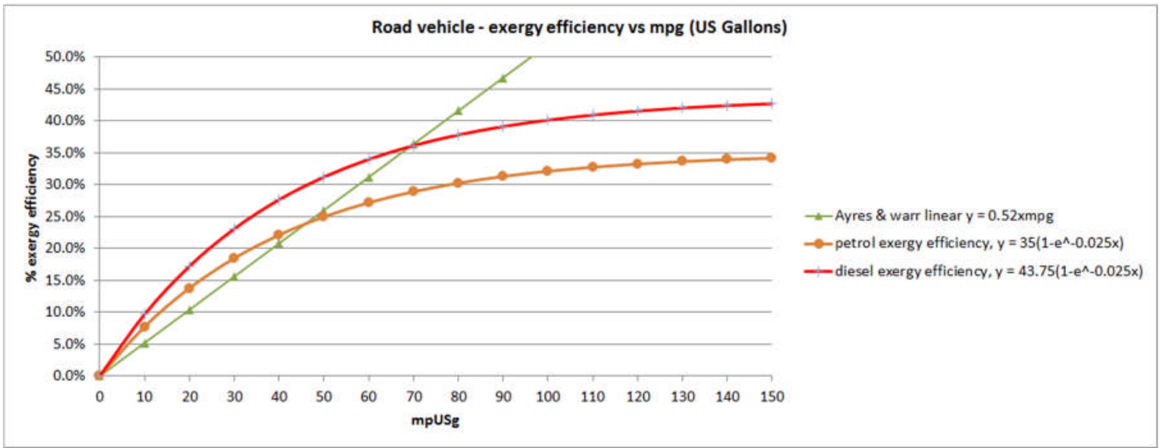


Figure A9: Road vehicle exergy efficiency vs fuel economy derived curves

The actual mpg data for each year can then be input to arrive at annual exergy efficiency values for petrol and diesel road vehicles, as shown below in Figure A10:

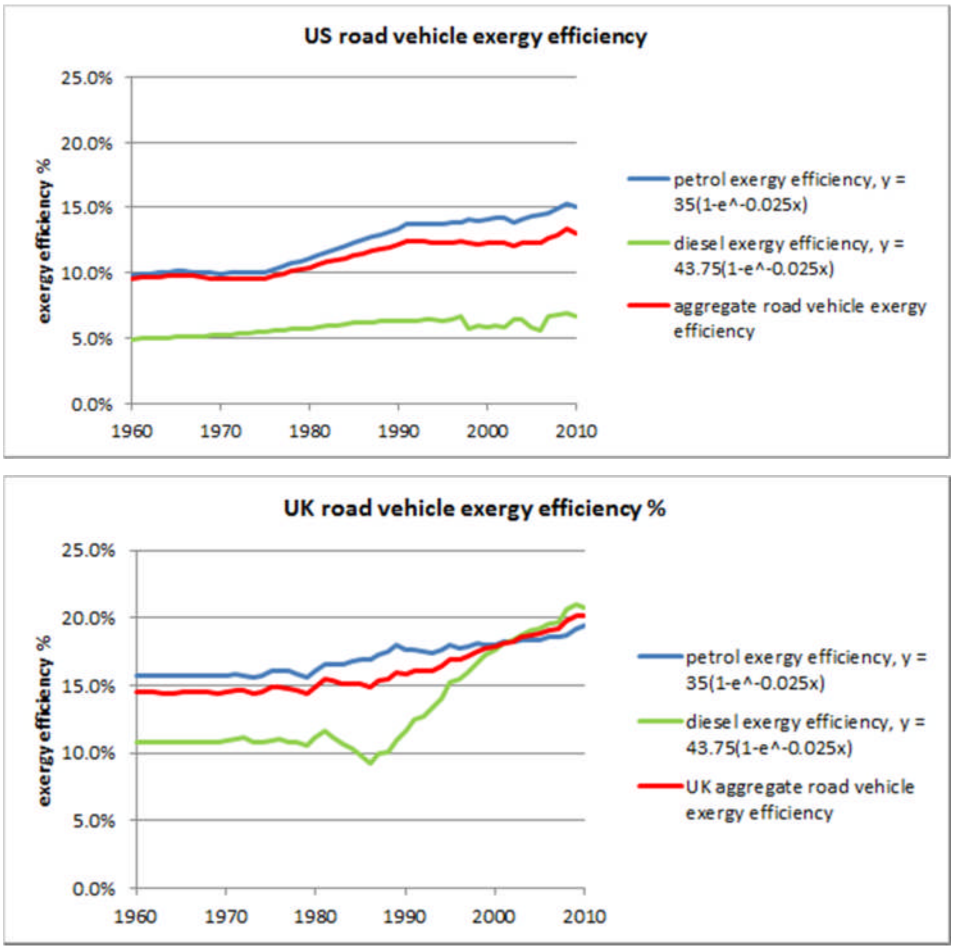


Figure A10: US and UK road vehicle exergy efficiencies

A.2.5.2 Rail (OMD6, CMD1, EMD1)

For rail transport, we have three main types of vehicle: Diesel (OMD6); Steam (CMD1); Electric (EMD1) trains. The process for diesel and electric trains is the same as for road vehicles. First, we start with published data on train kms by fuel source, (Tables TSGB0401, RAI0103, LRT0106, LRT9902a, LRT9902b, (Department for Transport (Dft), 2011) , Tables 4.5, 4.6, 4.16, 4.17, (US Department of Transportation, 2013)). In terms of fuel sources:

- US trains assumed to be all diesel
- UK freight trains taken to be diesel
- UK passenger trains taken as diesel and electric by split of kms

The US datasets contain data on rail car as well as loco data, so we take the car kms data by fuel source directly. For the UK data, we need to make some assumptions since national level data by car is not available. So we assume:

- 40 cars per UK freight train (US value is 70, so this assumes shorter trains due to greater density of built up area in UK)
- 4 cars = cars per UK diesel passenger train from Network Rail (Network Rail, 2013) data.
- 6.5 cars = cars per electric passenger UK train (Network Rail, 2013).

Next we collate data on fuel usage in ktoe Table 2.1 (Department of Energy & Climate Change (DECC), 2013), then converted to equivalent US diesel gallons (286.2 US Gallons of diesel = 1toe). Using this data we then calculate the fuel economy in mpg per rail car for diesel and electric trains as shown in Figure A11.

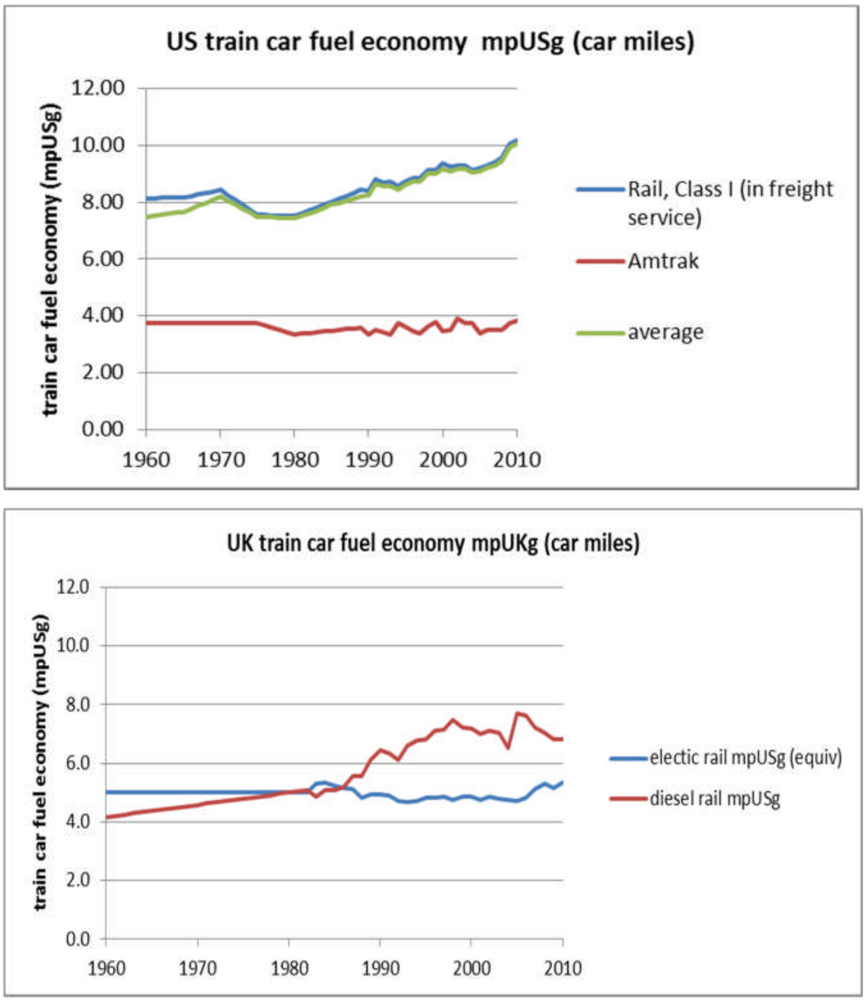


Figure A11: US and UK train car fuel economy

The next stage is to derive exergy efficiency – fuel economy (ε-mpUSg) equations for both diesel and electric trains. We have a assumed start point of 21% exergy efficiency for US diesel trains in 1970, based on 30% engine efficiency (Summers, 1971) and assumed 30% loss factors (Ayres et al., 2003). The calculated fuel economy in 1970 is 8mpg (US), so this is now our assumed start point. A terminal exergy efficiency of 50%, based on a maximal engine efficiency by Johansson (2010). The resultant equation is plotted below in Figure A12 with the 1960-2010 US and UK values:

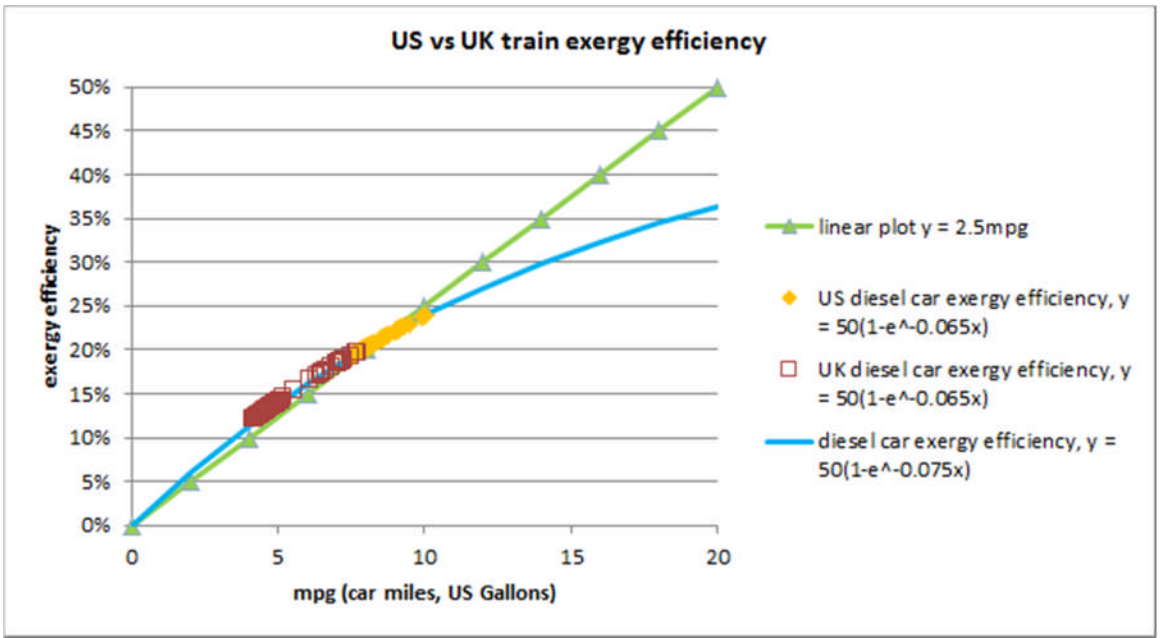


Figure A12: US and UK diesel train exergy efficiencies

For steam (coal powered) trains, in the absence of specific mpg data for steam trains, we assume that UK steam trains were 17% as efficient as diesel trains (~4% exergy efficiency), based on the transition of input fuel in ktoe that occurred during the transition from coal to diesel trains in the 1960-1970 decade. The same efficiency (~4%) was applied to US steam trains, in the absence of US mpg data.

For electric trains (relevant only for the UK) we use the same log-equation as for diesel trains, and merely convert the electrical energy used back to primary energy in Millions of Gallons. We can then calculate annual mpg data which then allows us to calculate equivalent annual exergy efficiency values using the declining exponential function.

Code	Description	Exergy efficiency, ε (x = mpUSg)
OMD6	Mechanical Drive - Gas/diesel fuel (diesel trains)	$\varepsilon = 50(1-e^{-0.065x})$
CMD1	Mechanical Drive - Coal (steam powered trains)	Take as 17% of diesel train (OMD6) efficiency for each year
EMD1	Electricity mechanical drive - trains	$\varepsilon = 50(1-e^{-0.065x})$ (electricity converted to USgallon equiv)

The actual mpg data for each year is then input to calculate annual exergy efficiency values for trains, as shown in Figure A13:

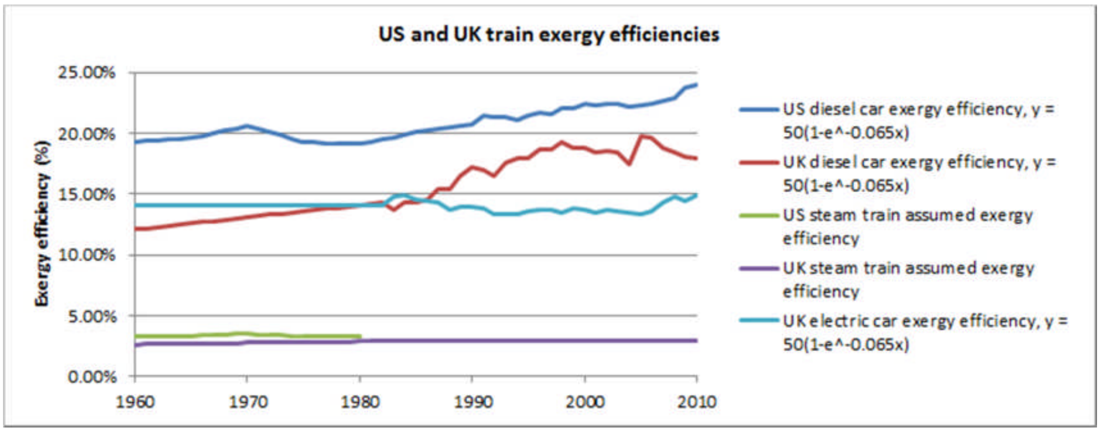


Figure A13: US and UK train car exergy efficiencies

A.2.5.3 Aircraft (OMD2)

For air transport, we have two main sub-classes: freight and passenger transport, which are both assumed both use the same aviation fuel source. Again, we start with published data on aircraft kms for the US (Table 1-35 - (US Department of Transportation, 2013)) and the UK ((Civil Aviation Authority, 2013), Table AVI0201 - (Department for Transport (Dft), 2011)). Next we collate fuel usage (Table 4-5 and Table 4-8, (US Department of Transportation, 2013); Table 2.1, (Department of Energy & Climate Change (DECC), 2013)) converted to equivalent US diesel gallons. Using this data we then calculate the fuel economy in mpUSg per plane for combined freight and passenger aircraft, as shown in Figure A14 below:

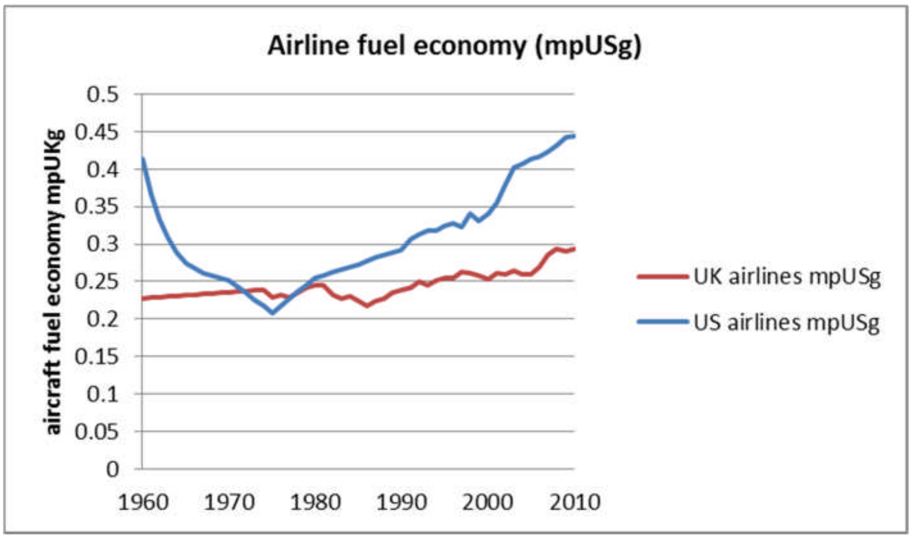


Figure A14: US and UK aircraft fuel economy

Then we derive the exergy efficiency equations for aircraft, and assume the same equation holds for US and UK aircraft. We take an assumed start point of 23% for US aircraft exergy efficiency in 1970 - the same as assumed by Warr et al (Warr et al., 2010). This is lower than the 28% given by Reistad Table 6, (Reistad, 1975), but in each case Reistad's values have been higher in other sectors (i.e. car, rail) than those taken for this analysis. The 1970 starting point fuel economy is 0.25mpUSgallon in both UK and US cases. A limiting exergy efficiency of 50% is assumed based on Massachusetts Institute of Technology data (MIT, 2013). The best fit declining exponential ε-mpg equation based on these points was then derived to be the following value:

Code	Description	Exergy efficiency, ε (x = mpUSg)
OMD2	Mechanical Drive - Domestic Aviation fuel, jet fuel	$\varepsilon = 50(1-e^{-2.25x})$

From the mpg data, the actual exergy efficiencies were calculated and are shown below in Figure A15 on the log-equation plot:

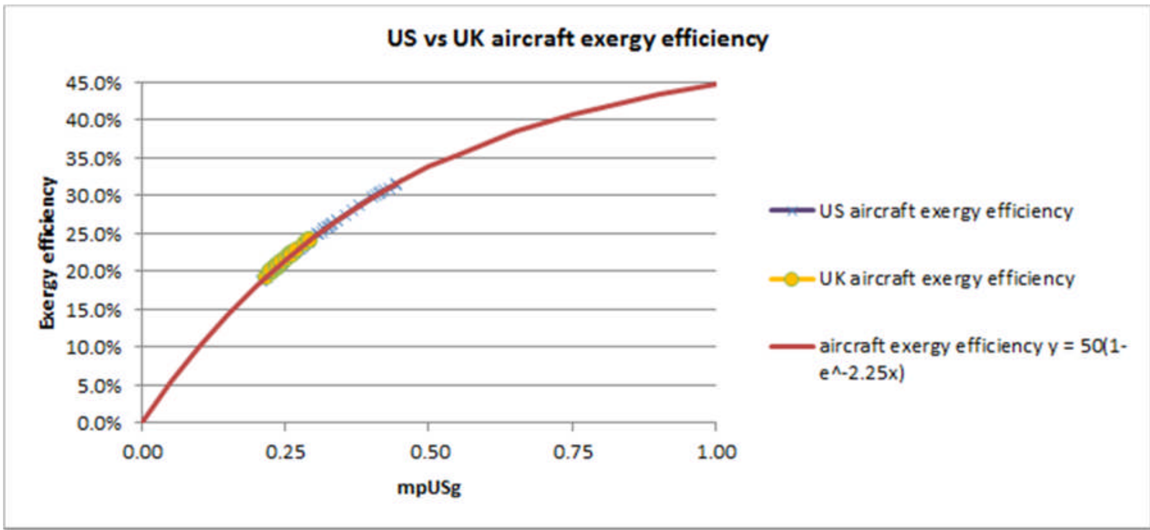


Figure A15: US and UK aircraft exergy efficiency vs log-equation

Finally, Figure A16 shows the aircraft exergy efficiency values below for the US and UK:

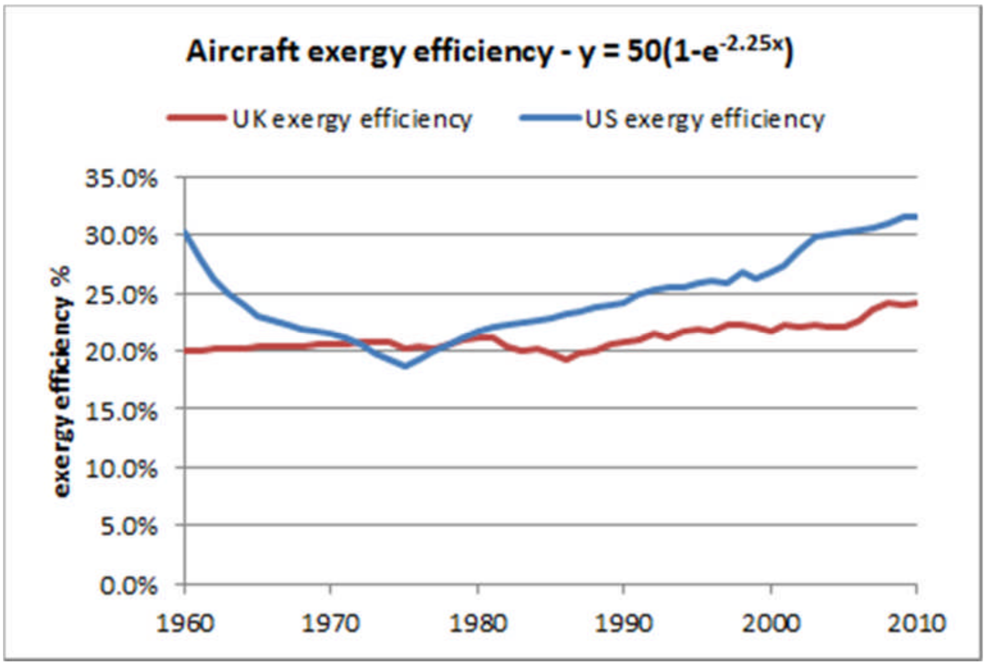


Figure A16: US and UK aircraft exergy efficiencies

A.2.5.4 Other Mechanical Drive sub-classes

Industry diesel motors (OMD5): For industry engines, in absence of other data, the data values follow Ayres & Warr assumption of an approximate Otto diesel efficiency minus 10-30% losses. So overall efficiency taken as 25% (1960) rising to 30% (2010).

Remaining vehicle classes (OMD4; OMD7; CRMD1; CRMD2; GMD1; GMD2; CMD2): Data (mpg) availability in these sub-classes is weaker, and in addition they consume only ~5% of the total mechanical drive input energy. Thus estimation of efficiencies was based on the other calculated values for road, rail and air, since this was felt to be a more accurate method than using the same log-mpg approach but using sub-standard datasets.

A.2.5.5 Final calculated efficiencies

Mechanical drive is split into the following categories in Table A6 below, based on the IEA mapping derived in Section A1.

Table A6: Summary of mechanical drive efficiencies

Fuel sources	**Mapping Code**	**Engine type**	**Exergy efficiency, ε (x = mpUSg)**
Oil & Oil Products	OMD1	Mechanical Drive - Gas/diesel oil (assume diesel vehicles	$\varepsilon = 43.75(1-e^{-0.025x})$
Oil & Oil Products	OMD2	Mechanical Drive - Domestic Aviation fuel, jet fuel	$\varepsilon = 50(1-e^{-2.25x})$
Oil & Oil Products	OMD3	Mechanical Drive - Gasoline fuel (Petrol cars)	$\varepsilon = 35(1-e^{-0.025x})$
Oil & Oil Products	OMD4	Mechanical Drive - Diesel/gas oil fuel (Boat engines)	take same as diesel trains in lieu of data
Oil & Oil Products	OMD5	Mechanical Drive - Industry static motors (diesel engines)	25% (1960) rising to 30% (2010)
Oil & Oil Products	OMD6	Mechanical Drive - Gas/diesel fuel (diesel trains)	$\varepsilon = 50(1-e^{-0.065x})$
Oil & Oil Products	OMD7	Mechanical Drive - Gas/diesel fuel (tractors)	similar to trucks so assume 50% of value for OMD1 diesel road vehicles
Combustible Renewables	CRMD1	Mechanical Drive - bio-diesel / bio-gasoline (road transport)	take average of OMD1 & OMD3

Fuel sources	**Mapping Code**	**Engine type**	**Exergy efficiency, ε (x = mpUSg)**
Combustible Renewables	CRMD2	Mechanical Drive - bio-diesel (diesel trains)	assume same as diesel train OMD6
Natural Gas	GMD1	Mechanical Drive - Gas/diesel oil	assume same as diesel car OMD1
Natural Gas	GMD2	Mechanical Drive - Gas fired engines (for pipeline transport)	assume same as industry static motor (OMD5)
Coal& Coal Products	CMD1	Mechanical Drive - Coal (steam powered trains)	Take as 17% of diesel train (OMD6) efficiency
Coal& Coal Products	CMD2	Mechanical Drive - Coal (steam powered boats)	Take same as steam trains CMD1
Electricity	EMD1	Electricity mechanical drive - trains	$\varepsilon = 50(1-e^{-0.065x})$ car miles (electricity converted to USgallon equiv)

A.2.6 Electricity

From Table A4, the following exergy efficiency equations shown in Table A7 are applicable for electrical end use:

Table A7: Electricity end use exergy efficiency equations

End Use \ Source		Work, W_{in} $W_{max} = W_{in}$
Work, W_{out}	$W_{min} = W_{out}$	$\epsilon = \eta = \frac{W_{out}}{W_{in}}$ (e.g. Electric mechanical drive,)
Heat Q_2 added from warm reservoir at T_2	$W_{min} = Q_2\left(1 - \frac{T_0}{T_2}\right)$	$\epsilon = \frac{Q_2}{W_{in}}\left(1 - \frac{T_0}{T_2}\right) = \eta\left(1 - \frac{T_0}{T_2}\right)$ (e.g. Electric heating)
Heat Q_2 extracted from cool reservoir at T_3	$W_{min} = Q_3\left(\frac{T_0}{T_3} - 1\right)$	$\epsilon = \frac{Q_3}{W_{in}}\left(\frac{T_0}{T_3} - 1\right) = \eta\left(\frac{T_0}{T_3} - 1\right)$ (e.g. Electric air-conditioning)

Thus the end use electricity exergy efficiency is built up in four parts as follows:

ε = exergy coefficients × grid efficiency × device energy efficiency × Carnot temperature ratio (if thermal work done).

A.2.6.1 Exergy coefficients

The exergy coefficients are the values that convert from primary energy back to the starting primary exergy values. They are taken from Table A2.

A.2.6.2 Grid efficiency

Next, the grid efficiency must be calculated. This is based on the IEA *main-producers* data, as shown in Figure A17:

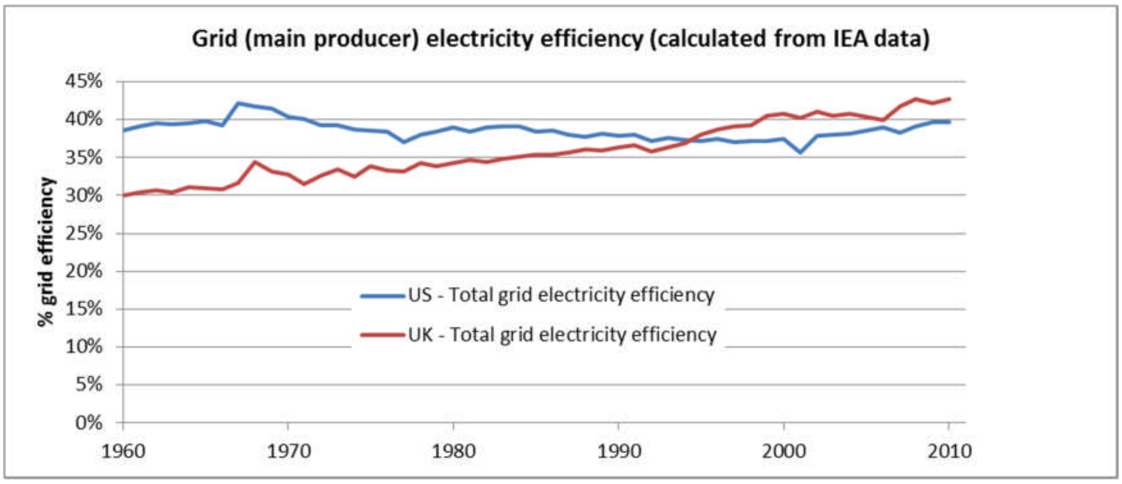


Figure A17: Grid electricity conversion efficiencies (primary energy to electricity)

A.2.6.3 IEA end use concordance mapping

Next, the IEA categories (Elect1 – Elect 6) are mapped to end use categories, using a concordance matrix approach to balance total electricity use. The IEA categories are given below in Table A8:

Table A8: IEA derived electricity categories

Elect1	Electricity - Energy sector own use
Elect2	Electricity - Industry use
EMD1	Electricity - Transport - Mechanical drive (rail)
Elect4	Electricity - residential use
Elect5	Electricity - commercial / public sector use
Elect6	Electricity - other (e.g. agriculture) use

The UK end use data was taken from (Fouquet, 2008; Department of Energy & Climate Change (DECC), 2013). The US end use data was taken from (Ayres et al., 2005b) and (US Department of Energy, 2011). The end use data is shown below in Figure A18 and Figure A19:

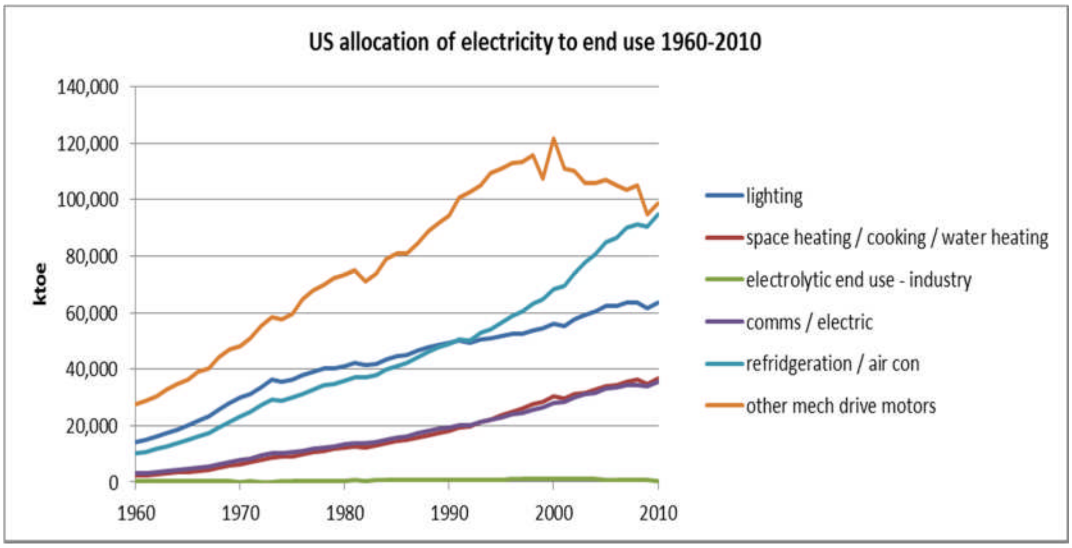


Figure A18: assumed US electricity end use consumption breakdown

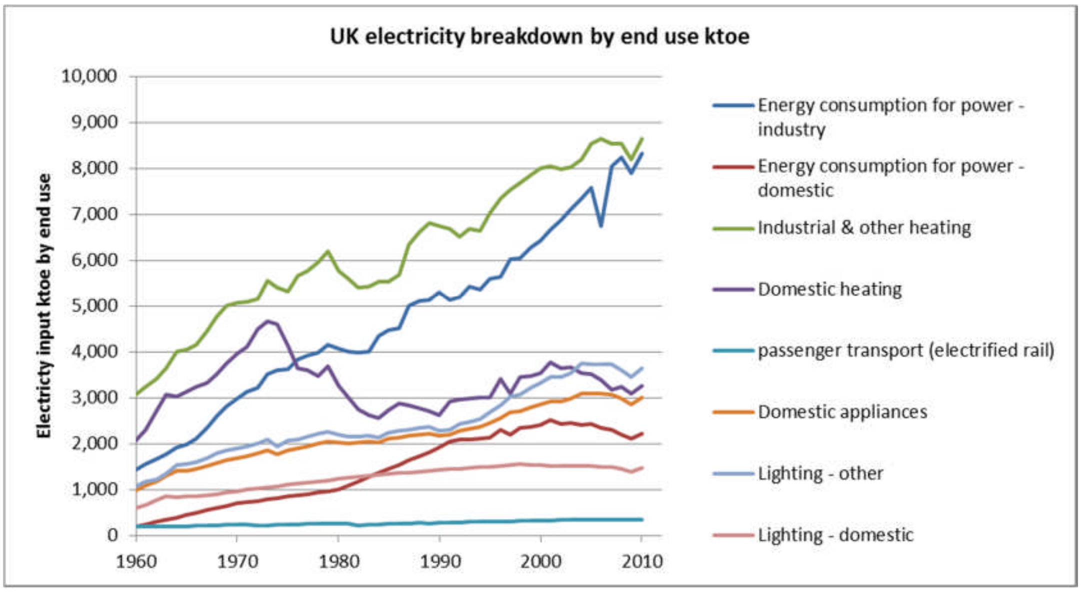


Figure A19: assumed UK electricity end use consumption breakdown

A.2.6.4 Device level energy efficiencies

Last, the device-level energy conversion efficiencies are calculated. They are assumed to be the same for both UK and US. They are based on those given for 1960-2010 by Ayres et al (2005a), which have subsequently been used by Serrenho et al (2016). This is replicated below in Table A9:

Table A9: Estimated electricity efficiencies by function USA 1900-2000 adopted by Ayres et al (2005a)

Estimates of the efficiency of electric power utilization by function USA 1900–2000

Year	Lighting (%)	Heating (%)		Electrolysis (%)	Electronic signal processing (%)	Electric motors (%)				
		High temperature	Low temperature			Refrigeration, cooling	Transport	Other (unallocated)		
								Residential	Commercial	Industrial and misc.
1900	1	80	3.0	13	0.001		60	70	75	75
1920	5	83	3.2	20	0.001					
1930						70	65	70		
1940	7	85	3.3	25	0.001					
1960	8.5	87	3.5	30	0.01	75	75	70	80	80
1980	11	89	4.0	35	0.1					85
2000	13	90	4.2	40	1	85	85	75	85	90

There are three exceptions from the values in Table A10 (highlighted in yellow) that are used in our analysis.

- Lighting

Device level efficiencies were taken from Fouquet and Pearson (2006) efficiency data, which give lower efficiencies as shown below in Figure A20:

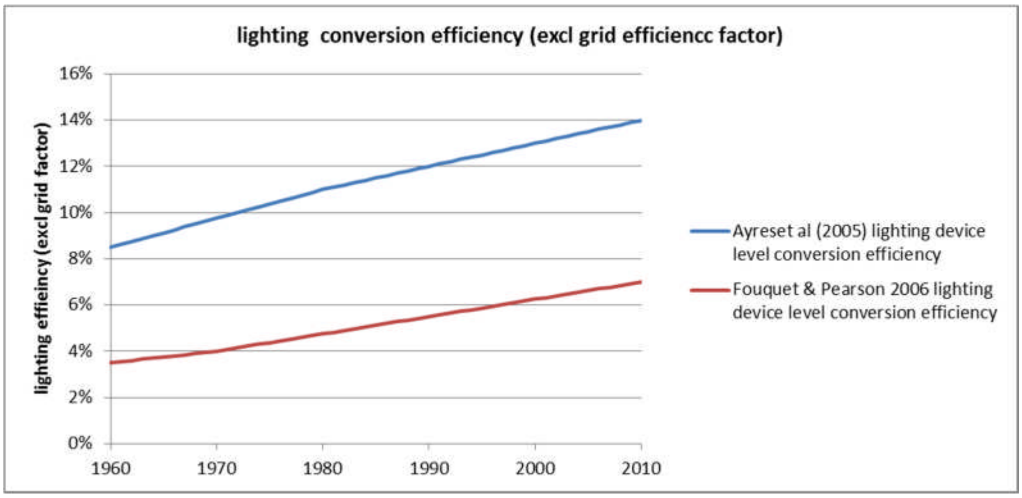


Figure A20: lighting conversion efficiencies: Fouquet and Pearson (Fouquet & Pearson, 2006) vs Ayres et al (Ayres et al., 2005a),

- Electrical appliances

More detailed calculations were derived, to add granularity to this growing sector. Energy consumption data was obtained from DECC (Department of Energy & Climate Change (DECC), 2013). Each sub-class of appliance then had post grid efficiency calculated as follows in Table A10:

Table A10: appliance exergy efficiencies

Appliance	**Device efficiency**	**Carnot ratio**	**Carnot temperatures**
Cold (eg refridgerator)	0.5 x motor (70-80%) – as (Ayres & Warr, 2010) + 0.5 x cold device (70-90%) – as (Ayres & Warr, 2010)	~7%	T_0 = 0'C; T_2 = room temp
Wet (eg dishwasher)	0.5 x motor (70-80%) – as (Ayres & Warr, 2010) + 0.5 x hot water (70-90%)	~21%	T_0 = room temp; T_2 = 100'C

Appliance	**Device efficiency**	**Carnot ratio**	**Carnot temperatures**
Consumer electronics (eg TV)	0.1% (1970); 1.0% (2010) as (Ayres & Warr, 2010)	N/A	N/A
Computing (eg IT)	0.1% (1970); 1.0% (2010) as (Ayres & Warr, 2010)	N/A	N/A
Cooking (eg electric hob)	90%	~21%	T_0 = room temp; T_2 = 100’C

Thus, barring minor differences in room temperatures, appliance end efficiency for each appliance/device are taken to be the same for UK and US as shown in Figure A21:

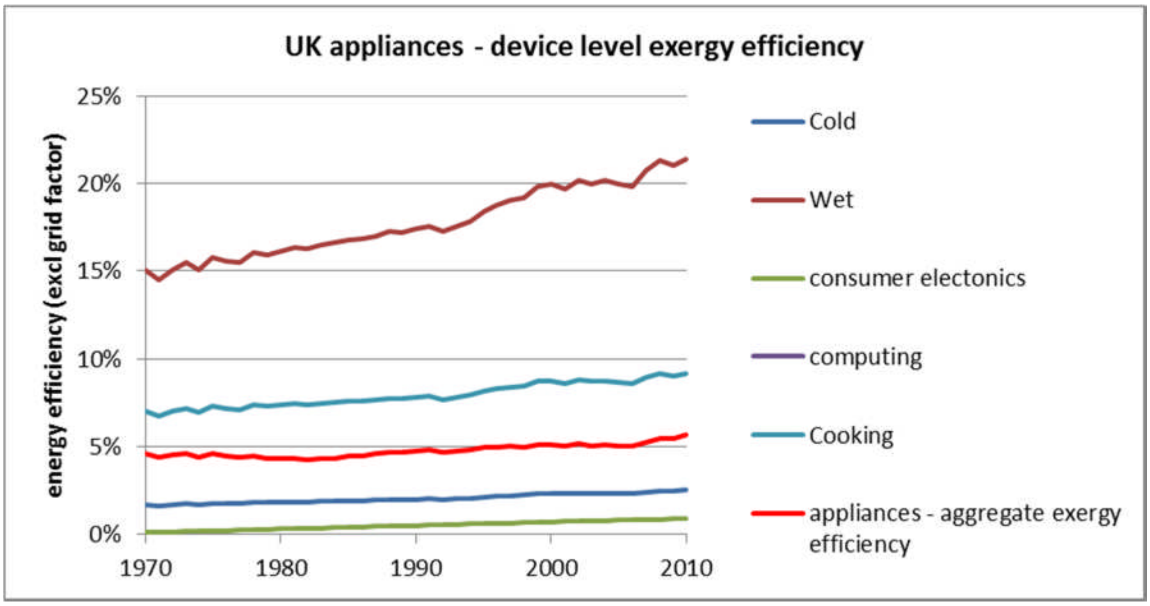


Figure A21: assumed appliance device level efficiencies

- Electrical heating / cooling

Table 5 from Ayres et al (2005a) provides first law (device) efficiencies for HTH and cooling, but second law (exergy) efficiencies for LTH. In other words the Carnot temperature ratio penalties are absent for the HTH and cooling cases, which we include now below.

A.2.6.5 Carnot temperature ratios

Finally, the Carnot temperatures ratios are calculated for electricity thermal end uses based on the heating temperatures shown earlier in Section A2.3, with air-conditioning a new/extra case for the US as noted below in Table A11:

Table A11: US and UK Carnot temperature ratios for electrical heating and cooling

Thermal end use	Hot temperature T_2	Cold temperature T_0
Air-conditioning	US and US July-Sept average outside air temperature	24.4°C (76°F) assumed summer indoor air-temperature, based on mid range of 73-79° F guidance provided by ASHRAE (ASHRAE, 2010) This concurs with Roberts & Lay, Figure 11, (Roberts & Lay, 2013), who give average house temperature in heating season to be 76-77°F = 24.4°C.
LTH	15-20°C (UK) and 20-23°C (US) – indoor / room temperatures 1960-2010	US and US Dec-Feb average outside air temperature
MTH1 – 100’C	100°C (373K)	US and US average yearly outside air temperature
HTH – 600’C	600°C (873K)	US and US average yearly outside air temperature

A.2.7 Non-energy

The effect of non-energy was investigated as follows. Firstly, non-energy was plotted as a % of total input energy (TPES), which resulted in the finding that it was around 5% of total input energy, as shown in Figure A22:

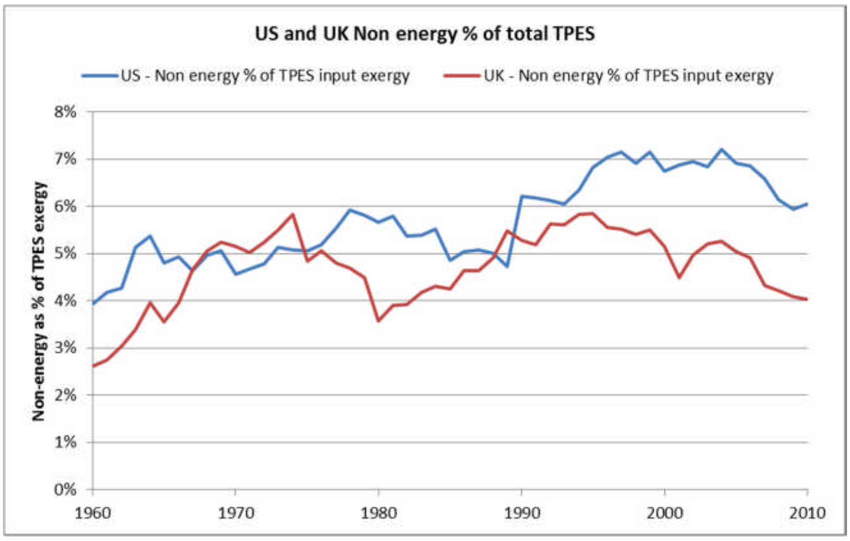


Figure A22: US and UK non-energy % of total energy supply (TPES) based on IEA data

Next, non-energy use breakdown was established as Figure A23 and Figure A24 show, to identify main categories, which were mainly gas (and then oil) derived non-energy uses.

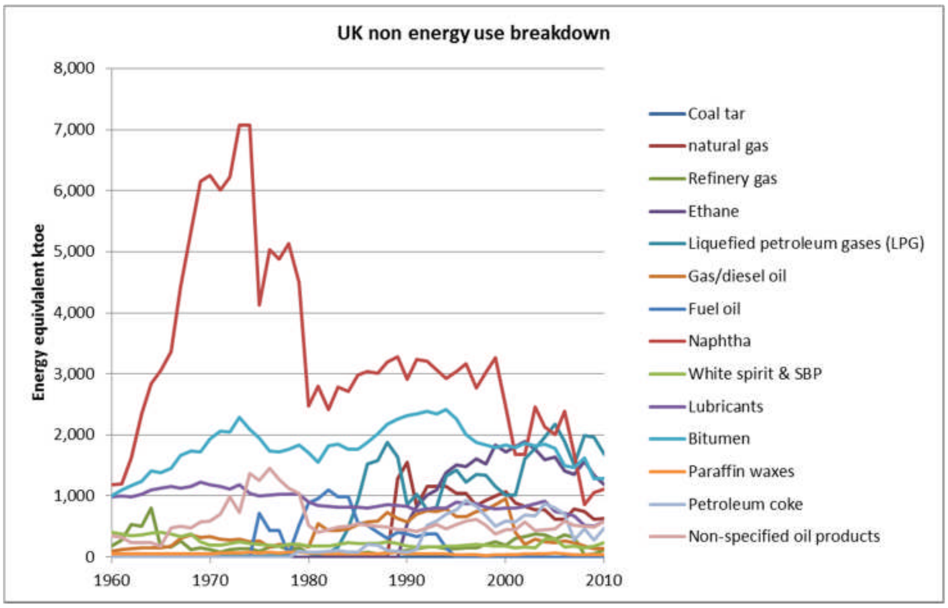


Figure A23: UK non-energy use breakdown

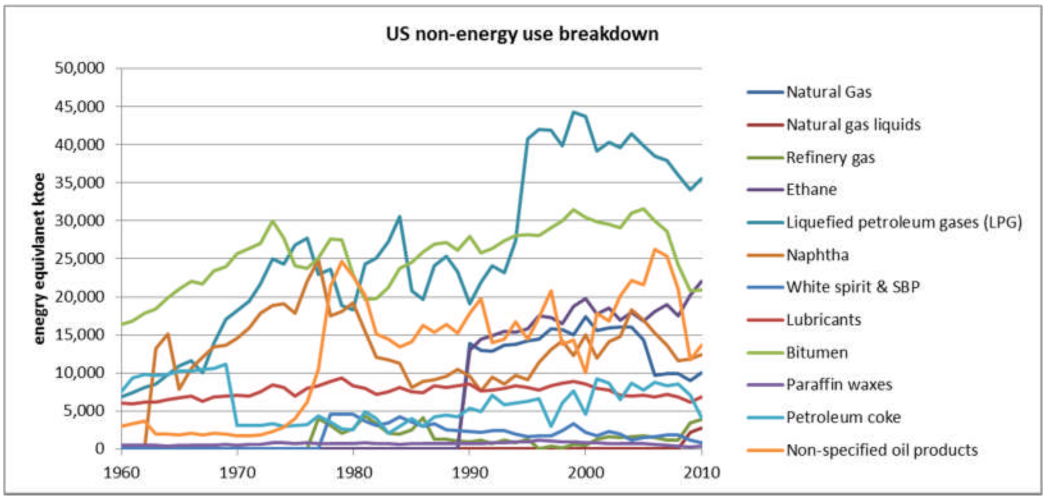


Figure A24: US non-energy use breakdown

A.2.8 Muscle work

There are various component parts of this required as follows:

- B1: Manual labour population – This is based on local country data for the UK (Turok & Edge, 1999) and US (Wyatt & Hecker, 2006)
- B2: Total UK & US population: taken from FAO Stat data 1961-2010 (Food and Agricultural Organisation of the United Nations (FAOSTAT), 2013)
- C: Total appropriated phytomass: using values from Wirsenius (Table 3.22, (Wirsenius, 2000)), Gross energy for North America = 90.32 GJ/capita; Gross energy for Western Europe = 41.84 GJ/capita
- D: total food intake per capita = total food supply/capita in kcal/day (Food and Agricultural Organisation of the United Nations (FAOSTAT), 2013) x wastage factor assumed as 0.90 (1960) increasing to 0.65 (2010) based on data from Wirsenius (2000) and Ayres & Warr (2010).
- F1: manual worker additional calorie intake: this is taken as 500 calories / day, i.e. additional 500kcal for each manual labour worker. Based on average total manual worker calories (2500-2900kcal) assumed by Warr et al (2008) minus average population calorie intake (2000-2400kcal) from

FAOstat data (Food and Agricultural Organisation of the United Nations (FAOSTAT), 2013)

- F2: manual worker additional energy intake/year: the additional 500kcal/day value is converted to a value of 0.78 GJ/year
- G1: food end use Gross energy (GE) to metabolisable energy (ME) ratio = 14.3/17.6 = 0.8125 for Western Europe and 15.1/18.6 = 0.812 for North America, from Wirsenius (Table 3.3, (Wirsenius, 2000))
- G2: 13% conversion efficiency to useful work output: (Smil, 1994)

The useful work and exergy inputs are then be calculated as follows:

- Useful work output (in TJ) = F2 x G1 x G2 x B2 x1000
- Exergy input (in TJ) = (B1/B2) x C x (F1/D) x B2 x 1000
- Exergy efficiency = useful work / exergy input

The results are calculated for each year 1960-2010, and are summarised below in Table A12 and Table A13 for 1960, 1970, 1980, 1990, 2000, 2010:

Table A12: UK manual labour calculations

UK calculations	1960	1970	1980	1990	2000	2010
(A) Total Exergy input TJ ((F1*B1)/(D*B2)) * (C*B2) * 1000)	**51,700**	**51,092**	**46,530**	**41,360**	**39,883**	**38,179**
(B1) Total UK manual labour Population (Millions)	7.5	7.0	6.0	5.0	4.5	4.0
(B2) Total UK Population (Millions) - FAOstat data 1961-2010	52.75	55.82	56.50	57.43	59.10	62.27
(C) Total phytomass Western Europe (GJ/cap / yr)	39.71	40.69	38.68	40.25	41.84	42.81
(D) total population calories in (kcal/cap/day) = supply x wastage	2,880	2,787	2,494	2,433	2,360	2,243
(F1) manual worker additonal calorie intake (kcal/cap/day)	500	500	500	500	500	500
(F2) manual worker additonal calorie intake GJ/cap/yr	0.78	0.78	0.78	0.78	0.78	0.78
(G1) metabolic / Gross energy ratio (ME/GE)	0.81	0.81	0.81	0.81	0.81	0.81
(G2) 13% conversion efficiency to useful work (Smil, 1994)	0.13	0.13	0.13	0.13	0.13	0.13
(H) Useful work output TJ (F2*G1*G2*B1) x 1000	**619**	**577**	**495**	**412**	**371**	**330**
o/a useful work / exergy efficiency = H/A (%)	**1.20%**	**1.13%**	**1.06%**	**1.00%**	**0.93%**	**0.86%**

Table A13: US manual labour calculations

US calculations	1960	1970	1980	1990	2000	2010
(A) Total Exergy input TJ ((F1*B1)/(D*B2)) * (C*B2) * 1000)	**398,474**	**499,450**	**549,898**	**615,176**	**683,276**	**663,282**
(B1) Total US manual labour Population (Millions)	30.2	35.8	37.1	38.9	40.3	36.3
(B2) Total US Population (Millions) - FAOstat data 1961-2010	187.00	209.46	229.83	253.34	282.50	310.38
(C) Total phytomass North America(GJ/cap / yr)	68.38	72.06	75.58	83.27	90.32	87.85
(D) total population calories in (kcal/cap/day) = supply x wastage	2,592	2,580	2,546	2,630	2,663	2,405
(F1) manual worker additonal calorie intake (kcal/cap/day)	500	500	500	500	500	500
(F2) manual worker additonal calorie intake GJ/cap/yr	0.78	0.78	0.78	0.78	0.78	0.78
(G1) metabolic / Gross energy ratio (ME/GE)	0.81	0.81	0.81	0.81	0.81	0.81
(G2) 13% conversion efficiency to useful work (Smil, 1994)	0.13	0.13	0.13	0.13	0.13	0.13
(H) Useful work output TJ (F2*G1*G2*B1) x 1000	**2,490**	**2,948**	**3,055**	**3,204**	**3,321**	**2,994**
o/a useful work / exergy efficiency = H/A (%)	**0.62%**	**0.59%**	**0.56%**	**0.52%**	**0.49%**	**0.45%**

A.3 US and UK results – Detailed Outputs

The extended results are presented in the following sections:

- A3.1 US & UK primary exergy results 1960-2010
- A3.2 US & UK exergy efficiency results 1960-2010
- A3.3 US & UK useful work results 1960-2010
- A3.4 Post analysis
- A3.5 Non energy

A.3.1 US & UK primary exergy results 1960-2010

A.3.1.1 US – exergy input results 1960-2010

These exclude non-energy inputs, and are shown in Figure A25 to Figure A29:

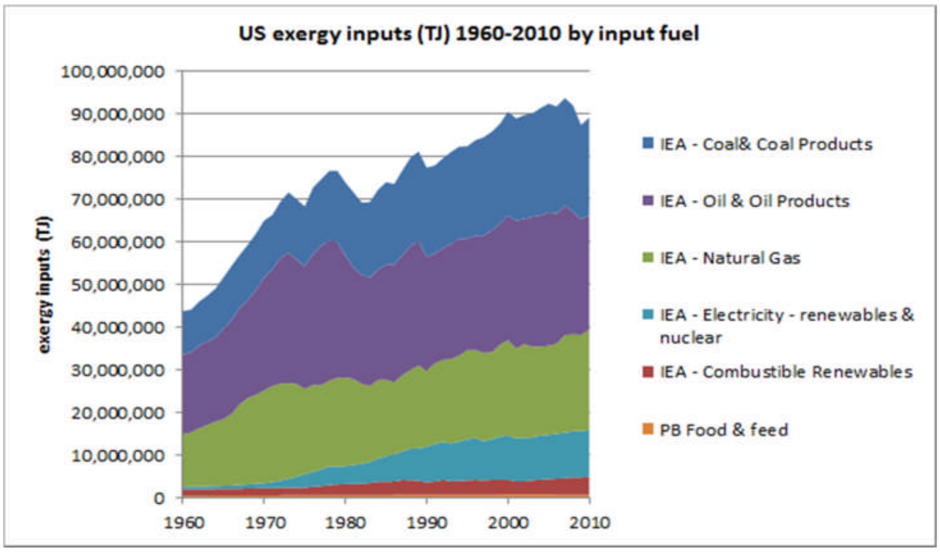


Figure A25: US primary exergy inputs by input fuel

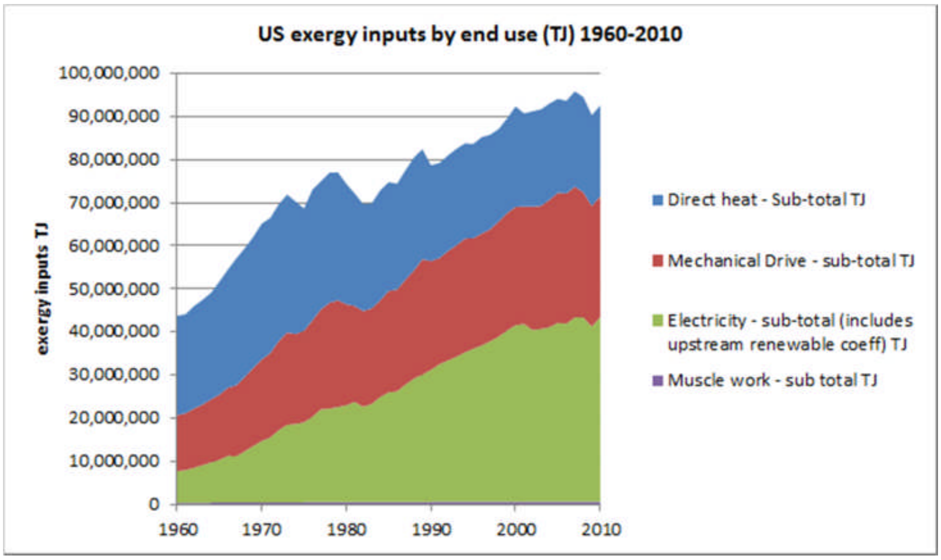


Figure A26: US primary exergy inputs by end use

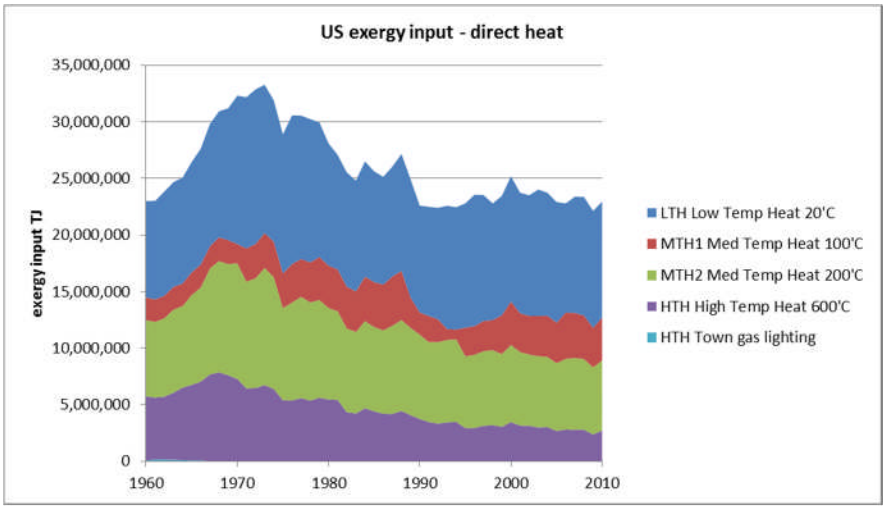


Figure A27: US primary exergy inputs for heat uses

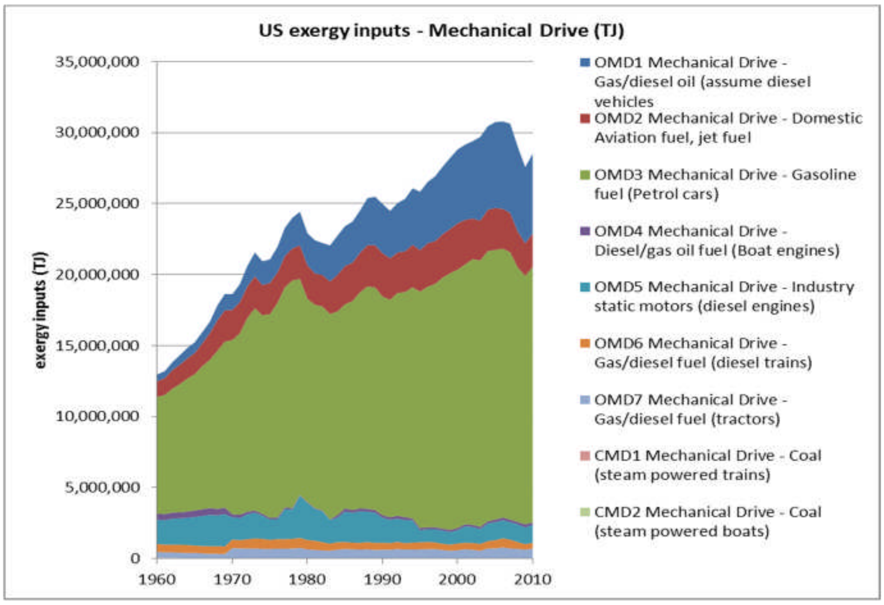


Figure A28: US primary exergy inputs for mechanical drive uses

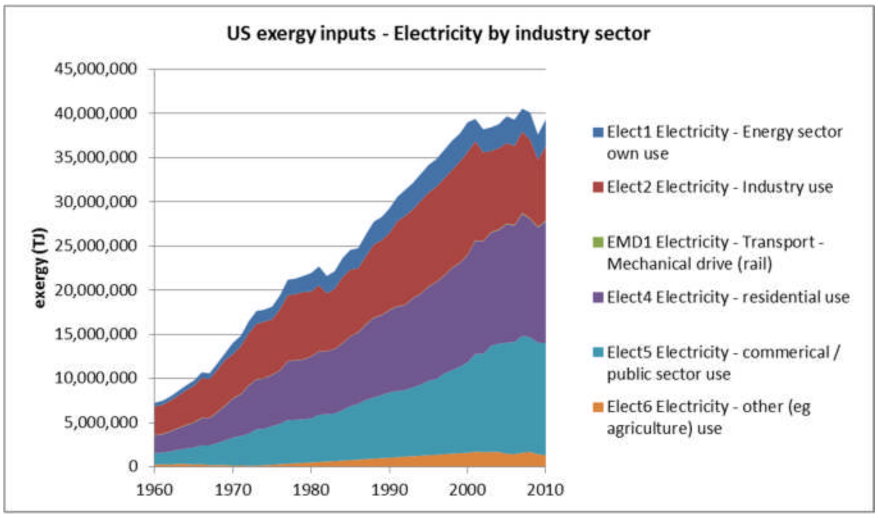


Figure A29: US primary exergy inputs for electricity uses

A.3.1.2 UK – exergy input results 1960-2010

These also exclude non-energy inputs and are shown in Figure A30 to Figure A35:

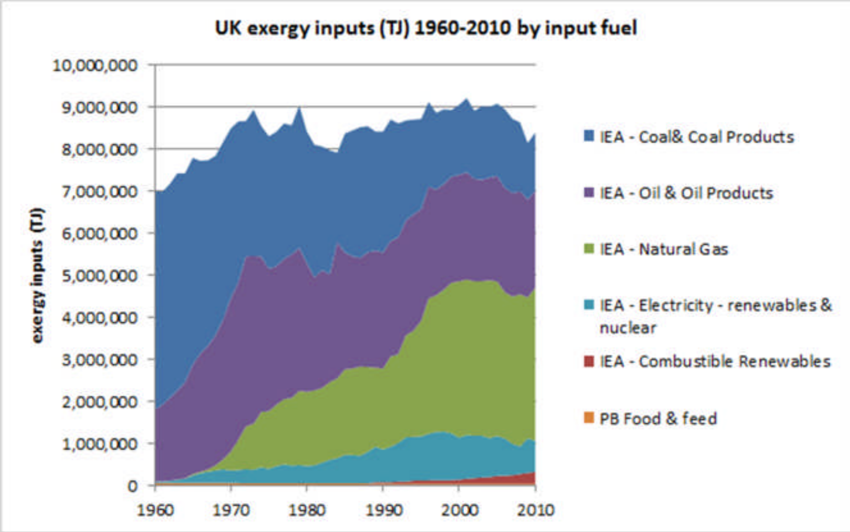


Figure A30: UK exergy inputs by fuel source

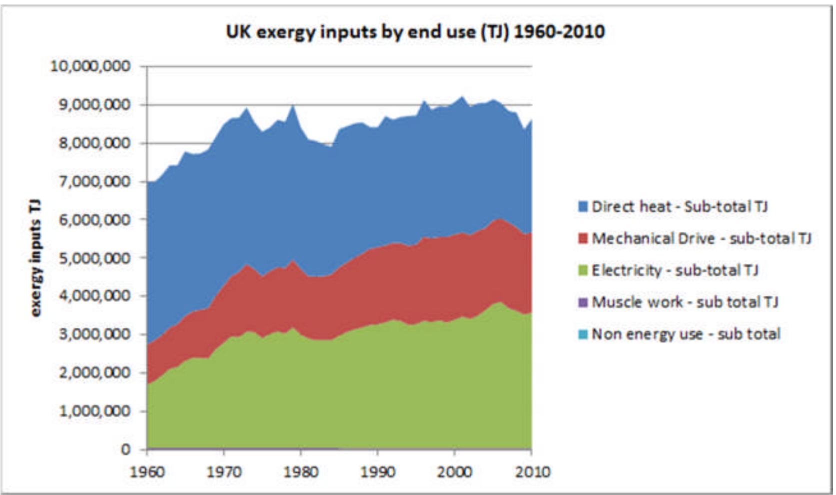


Figure A31: UK exergy inputs by end use

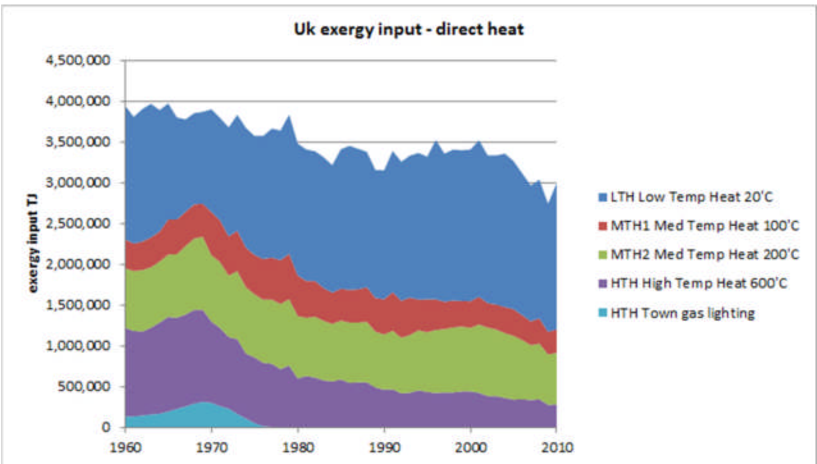


Figure A32: UK exergy inputs for heat use

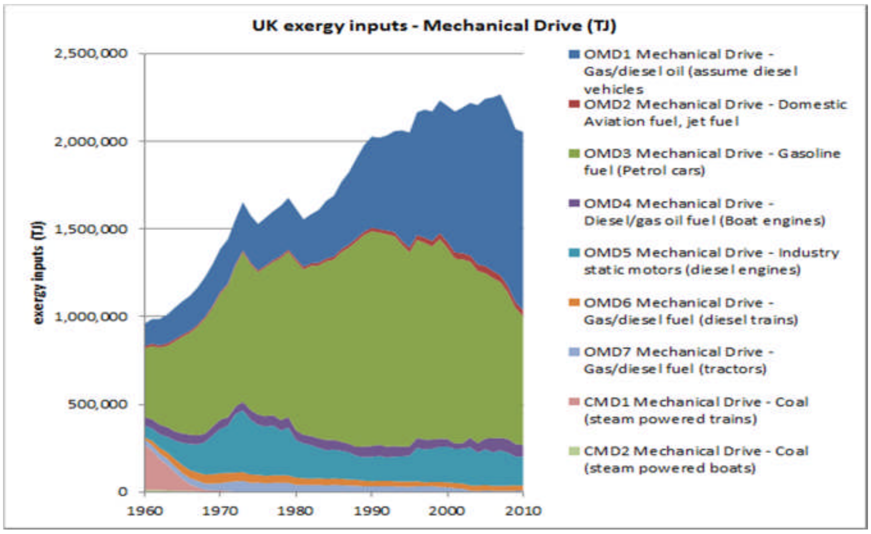


Figure A33: UK exergy inputs for mechanical drive use

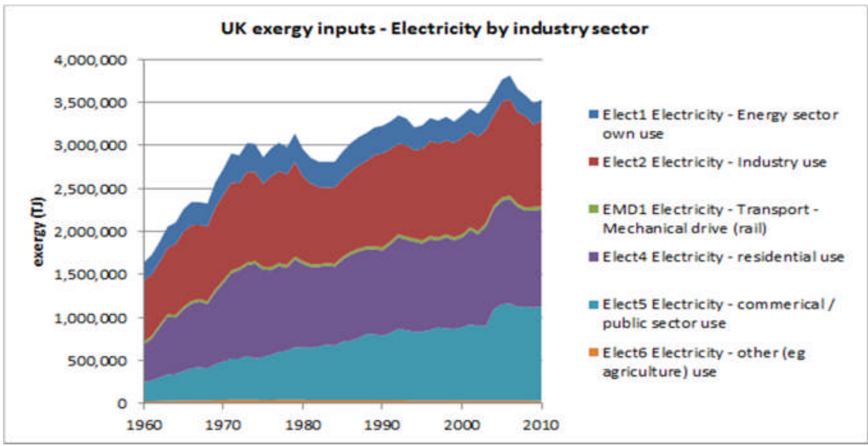


Figure A34: UK exergy inputs for electricity end use

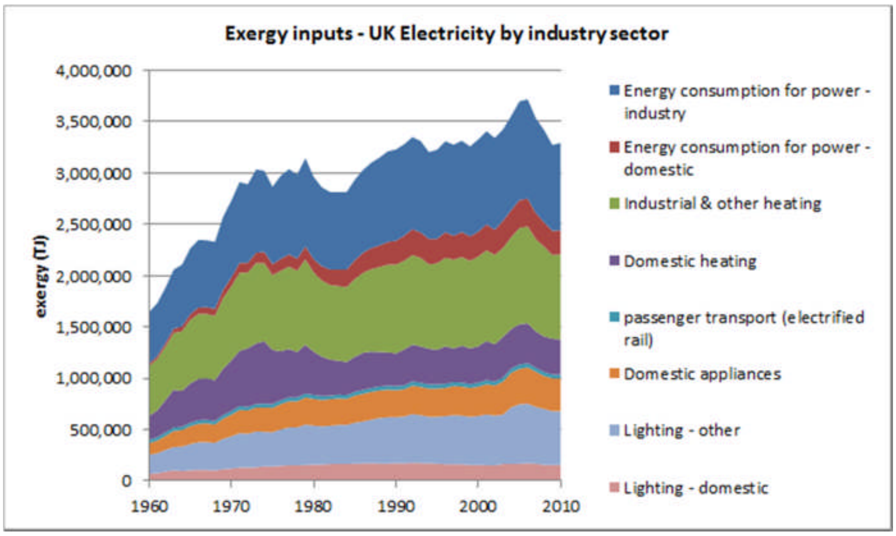


Figure A35: UK exergy inputs for electricity end use

A.3.2 US & UK exergy efficiencies 1960-2010

A.3.2.1 Mechanical drive efficiency values 1960-2010

These are shown in Figure A36 and Figure A37:

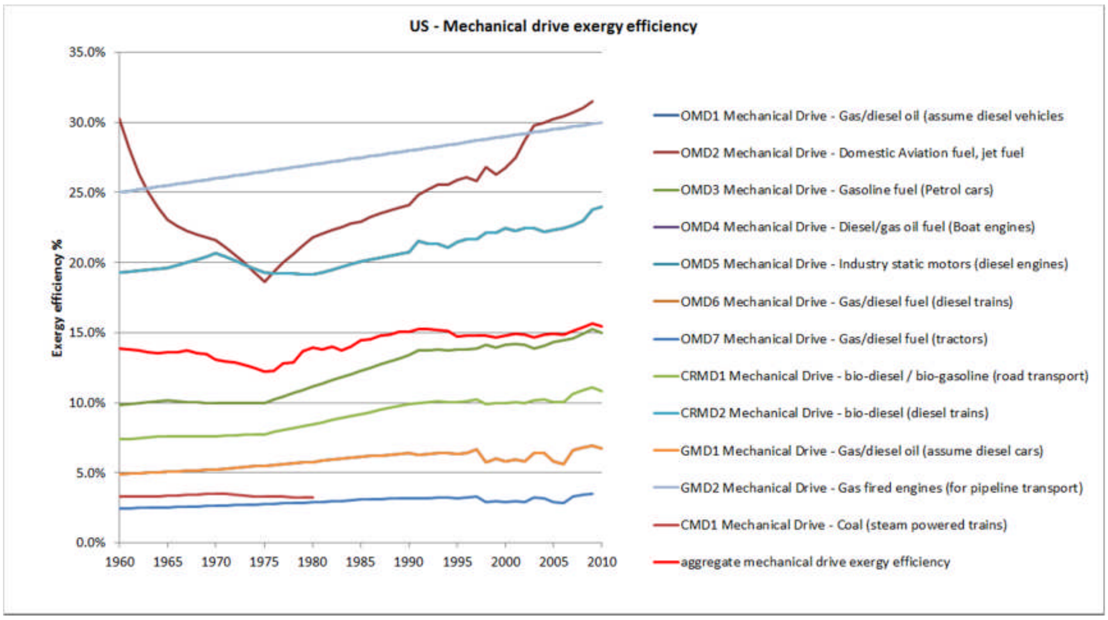


Figure A36: US mechanical drive task level exergy efficiencies

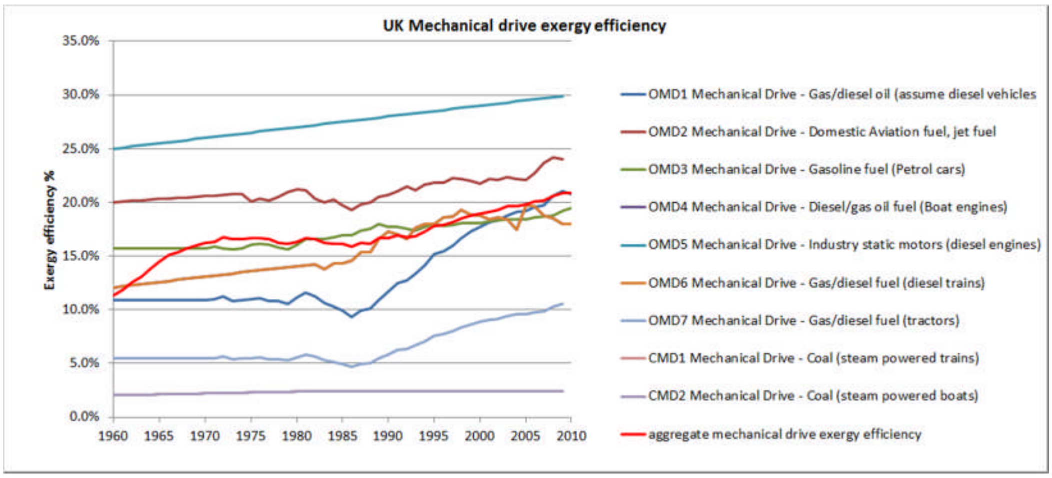


Figure A37: UK mechanical drive task-level exergy efficiencies

A.3.2.2 Heat efficiency values 1960-2010

The final derived task (sub-sector) level and aggregate heat efficiencies for UK and US are given below in Figure A38 and Figure A39. They show that efficiencies are similar, with US efficiencies slightly higher for LTH and MTH1 (greater Carnot temperature differences), and slightly lower for MTH2 and HTH (lower energy/device efficiencies). US exergy efficiency is slightly higher at an aggregate level due to a higher use of HTH, versus the UK which has increased its share of LTH.

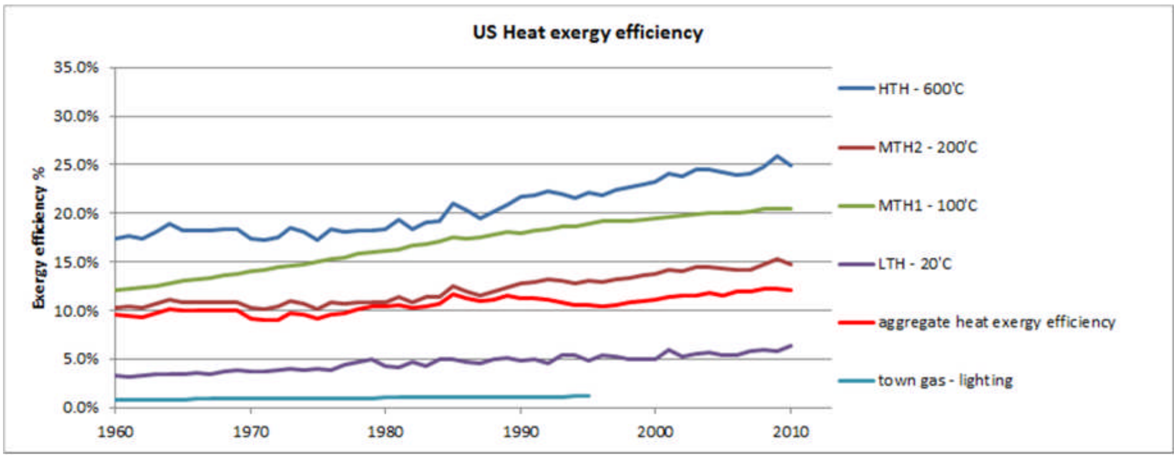


Figure A38: US heat exergy efficiencies at task (sub-class) level 1960-2010

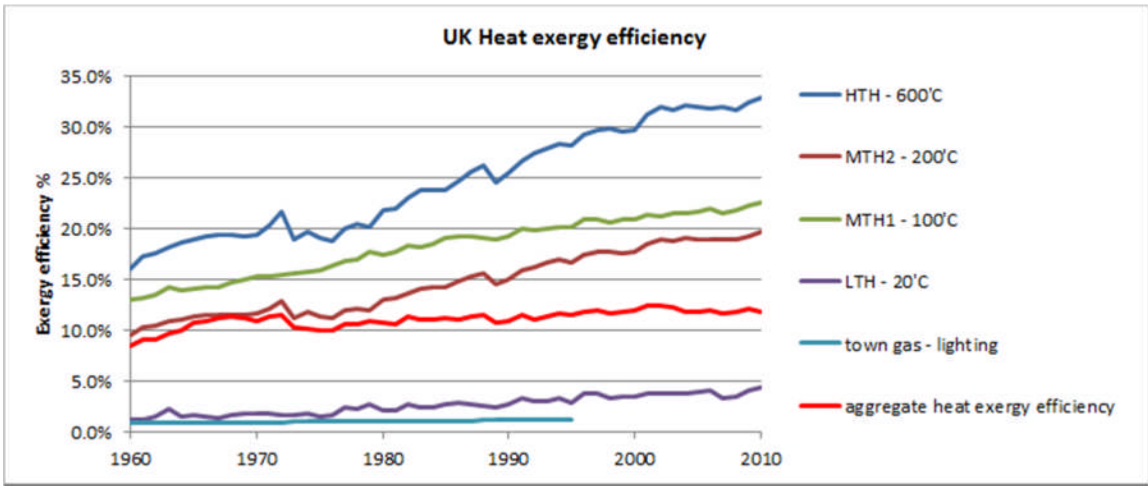


Figure A39: UK heat task-level exergy efficiencies

A.3.2.3 Electricity efficiency values 1960-2010

The final exergy efficiencies can then be calculated, and are shown in in Figure A40 to Figure A42. As we can see, the sub-sector efficiencies all increase except for residential, which decreases due to the efficiency dilution effect. This has a more significant effect on the US electricity efficiency, which declines from the 1960s as a result.

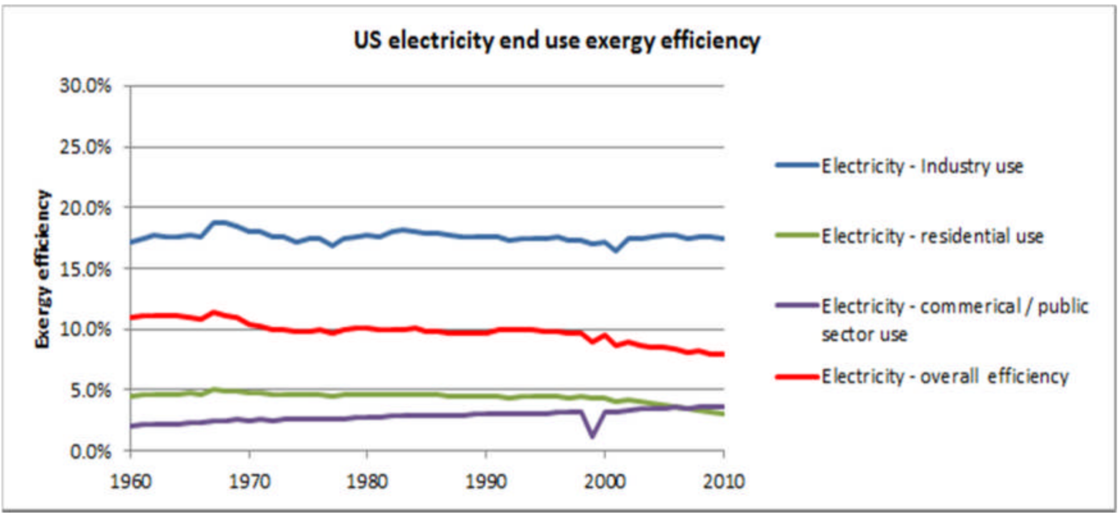


Figure A40: US electricity exergy efficiencies by main industrial category

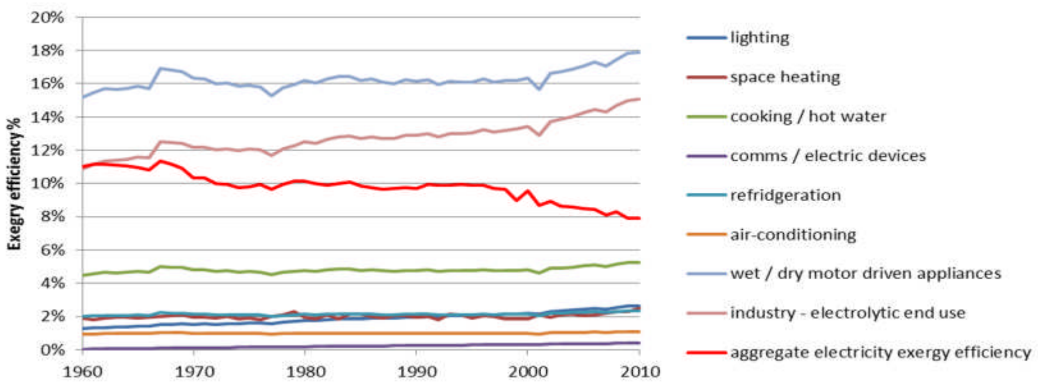


Figure A41: US electrical exergy efficiencies by task-level 1960-2010

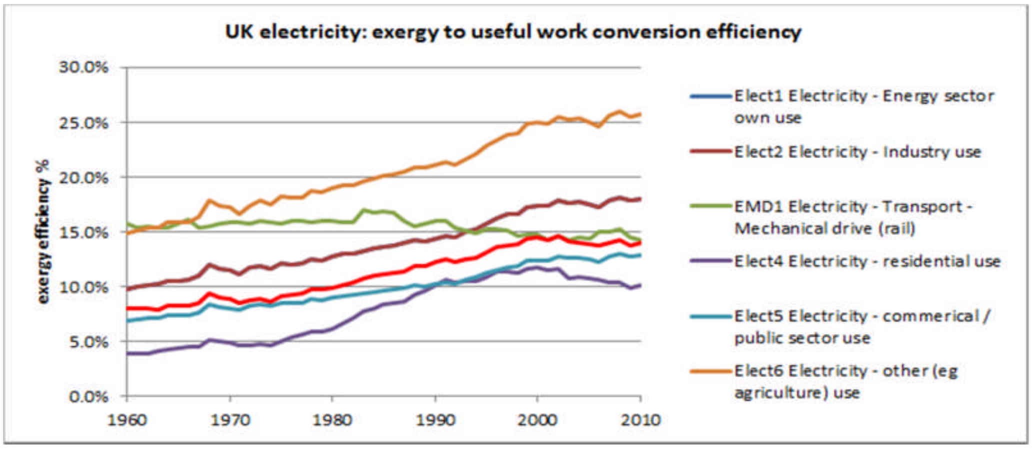


Figure A42: UK electricity exergy efficiencies by IEA end use category

A.3.3 US&UK useful work results 1960-2010

A.3.3.1 US – useful work results 1960-2010

These are shown in Figure A43 to Figure A47:

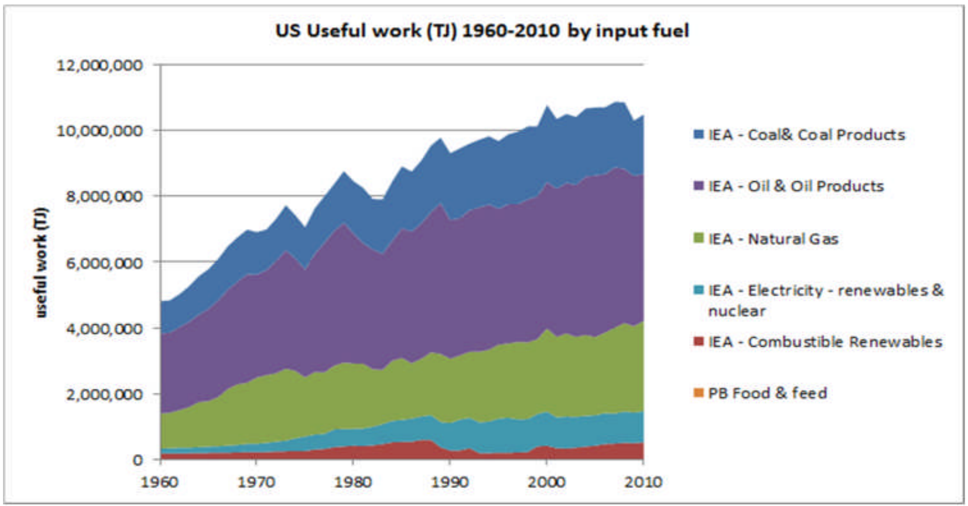


Figure A43: US Useful work by input fuel

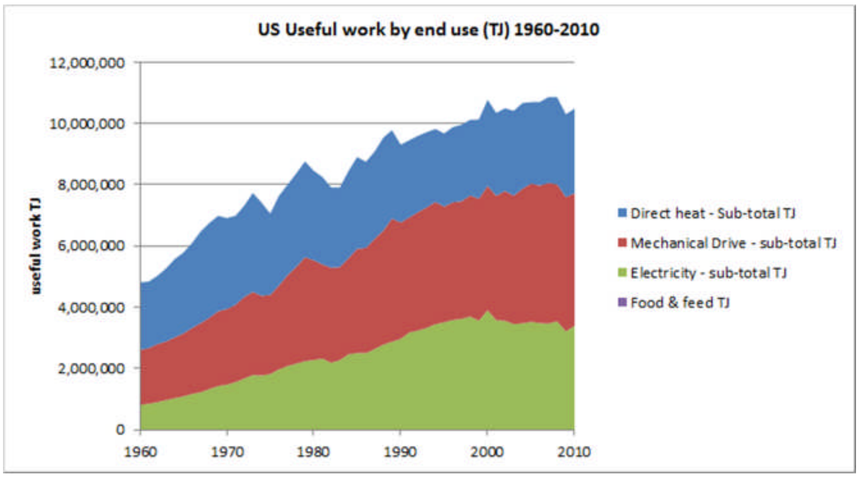


Figure A44: US useful work by end use

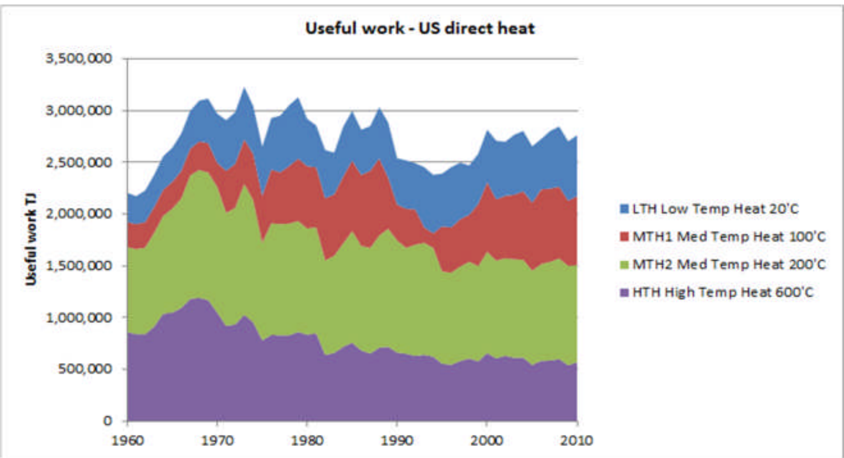


Figure A45: US useful work by heat end use task level

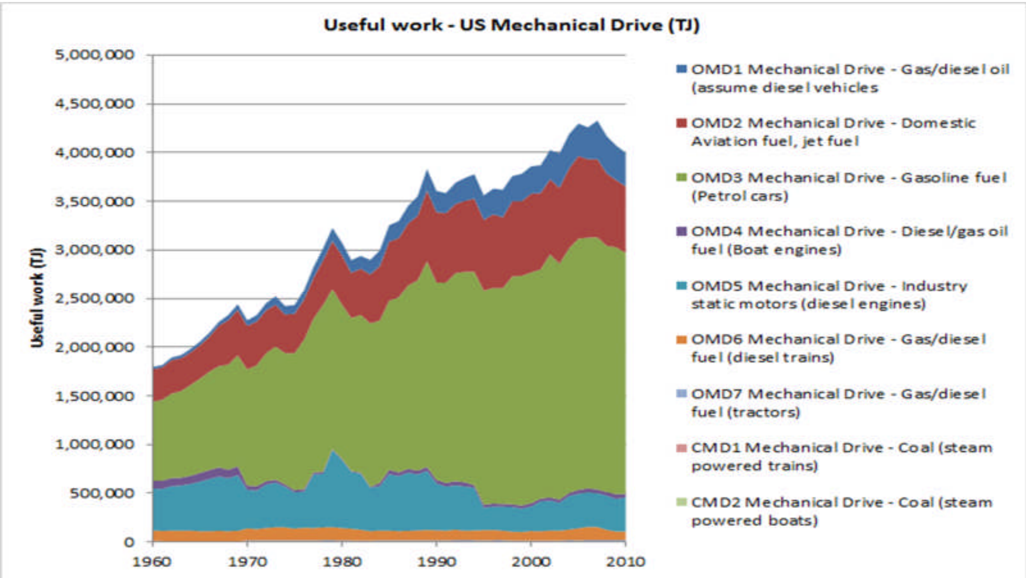


Figure A46: US useful work by mechanical drive end use task level

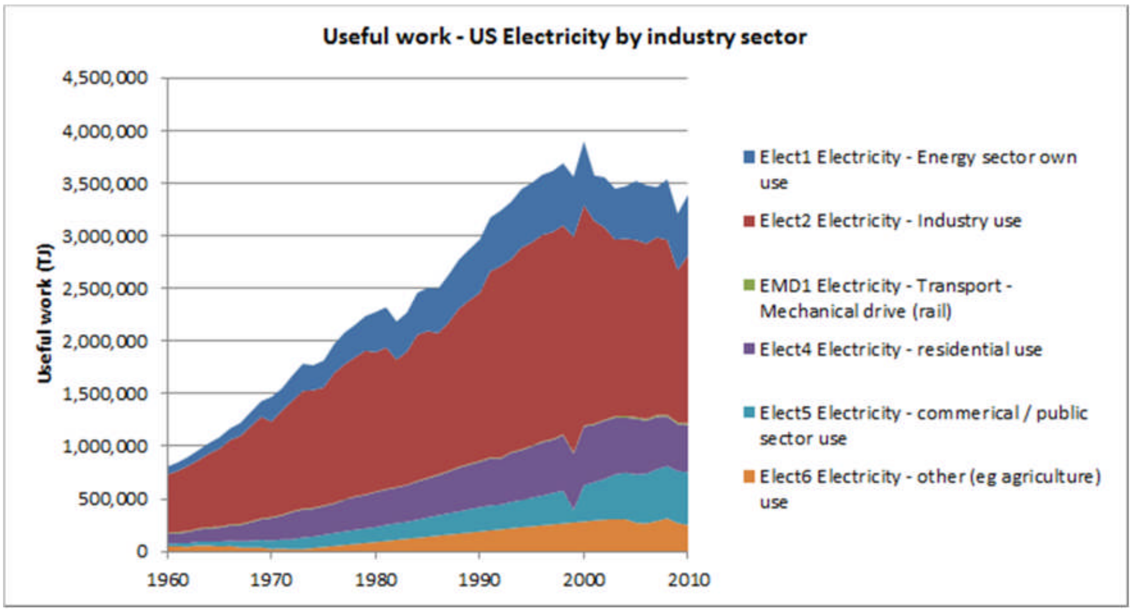


Figure A47: US useful work by IEA electricity end use category

A.3.3.2 UK – useful work results 1960-2010

These are shown in Figure A48 to Figure A53:

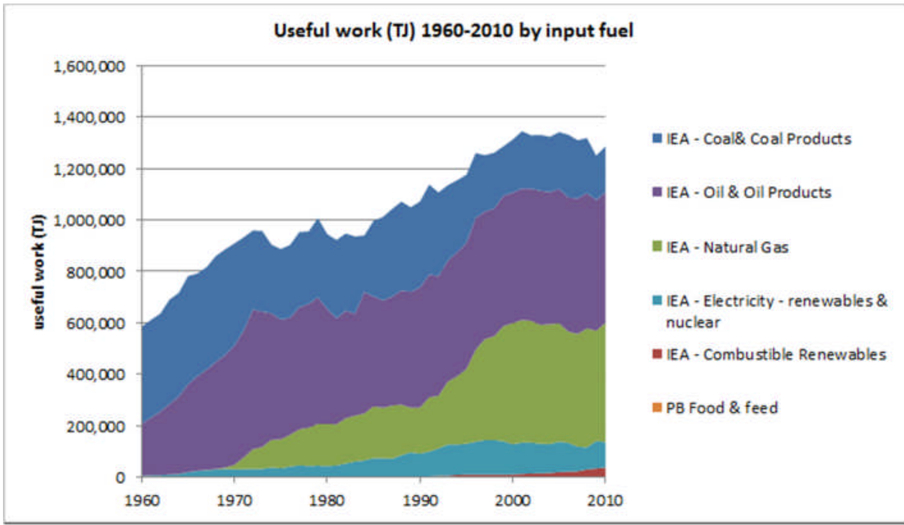


Figure A48: UK useful work by input fuel

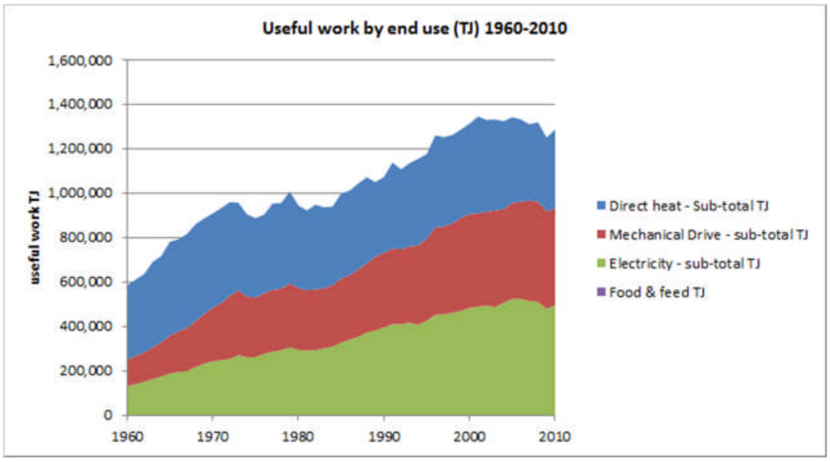


Figure A49: UK useful work by end use

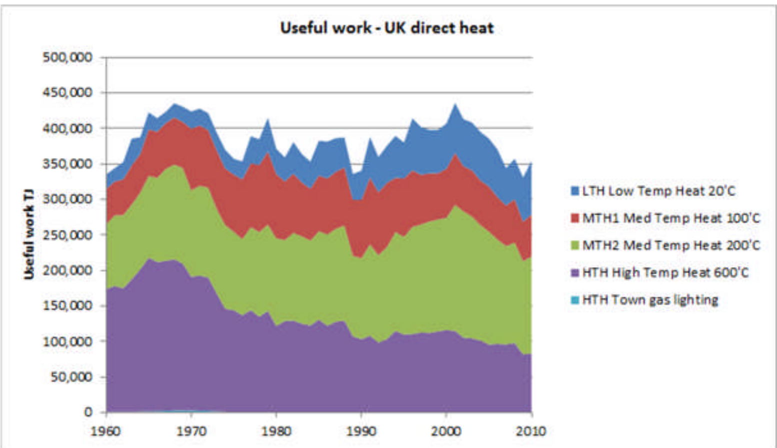


Figure A50: UK useful work by task-level heat use

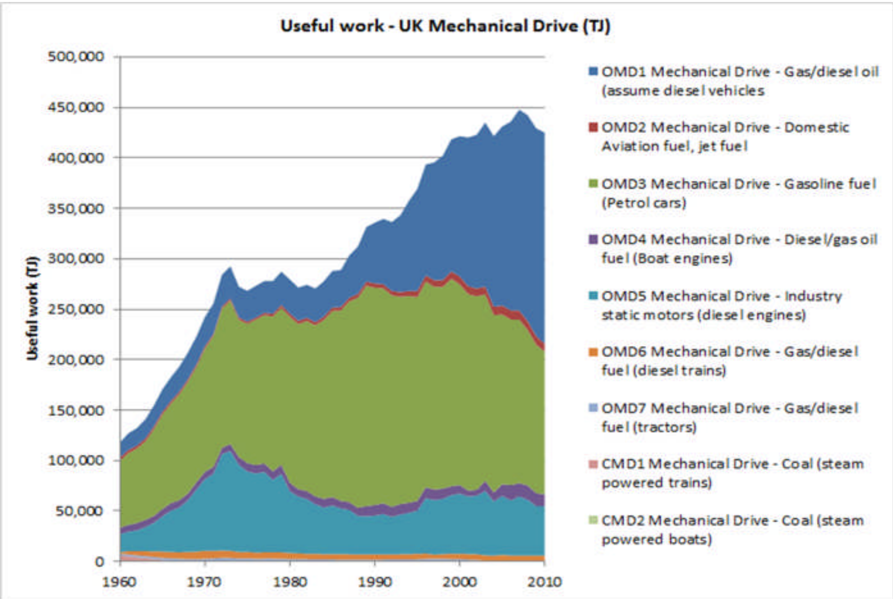


Figure A51: UK useful work by task-level mechanical drive use

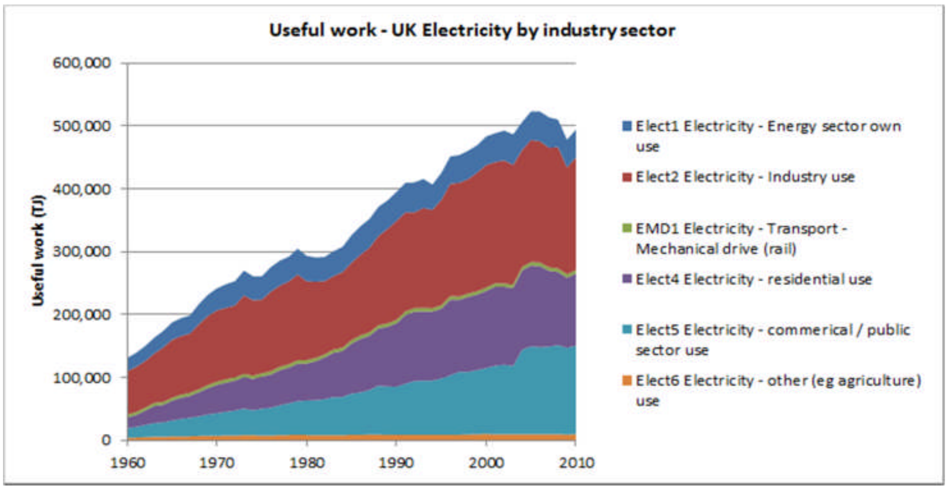


Figure A52: UK useful work by IEA electricity end use category

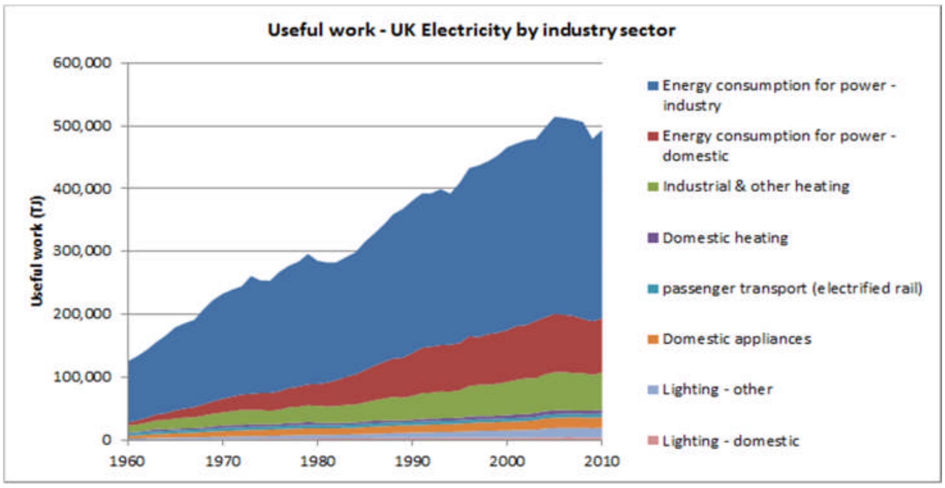


Figure A53: UK useful work by task-level electricity use

A.3.4 Post analysis results

To investigate the causes of the US-UK efficiency divergence, UK task-level exergy efficiencies for 1960-2010 were inserted into the US analysis model to investigate the effect on overall exergy efficiency. Figure A54 shows the impact: US overall efficiency increases from 10% to 14%, close to the UK exergy efficiency, suggesting differences in both task-level efficiencies and structural consumption could play major roles in the causes of the divergence, though further investigation beyond the scope of this paper (e.g. via decomposition analysis) is required.

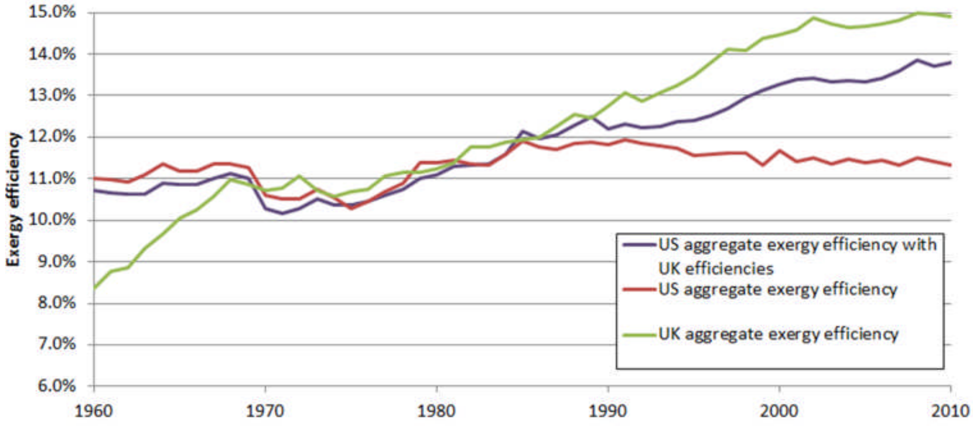


Figure A54: Investigation of effect of adopting UK task-level exergy efficiencies on aggregate US exergy efficiency

Next, the ratios of useful work and exergy to GDP over the period 1960-2010 are calculated (GDP data from The Conference Board (2013)) to provide intensity indicators. The UW/GDP indicator is shown below with the TPES/GDP ratio in Figure A55 and Figure A56, with the UW/GDP indicator values for the US and UK becoming increasingly convergent over time.

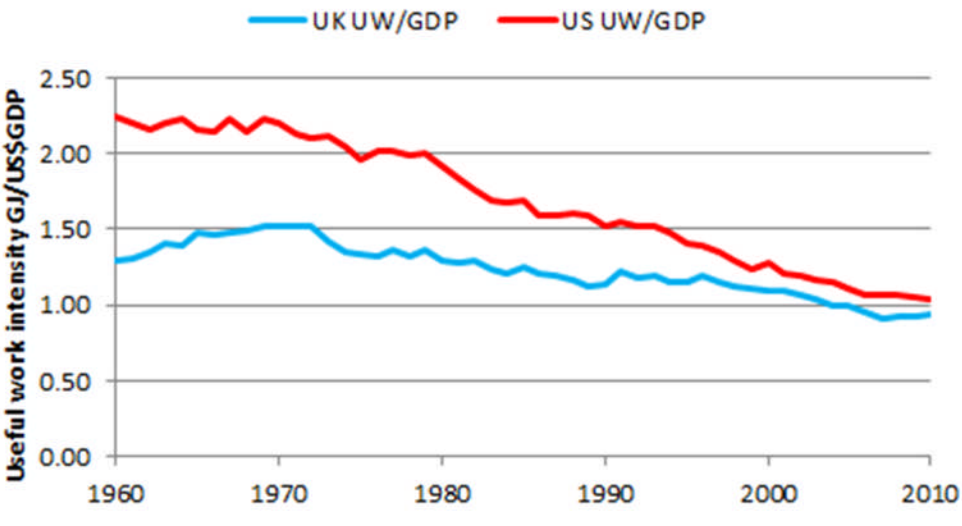


Figure A55: US versus UK useful work intensity (GJ/GDP)

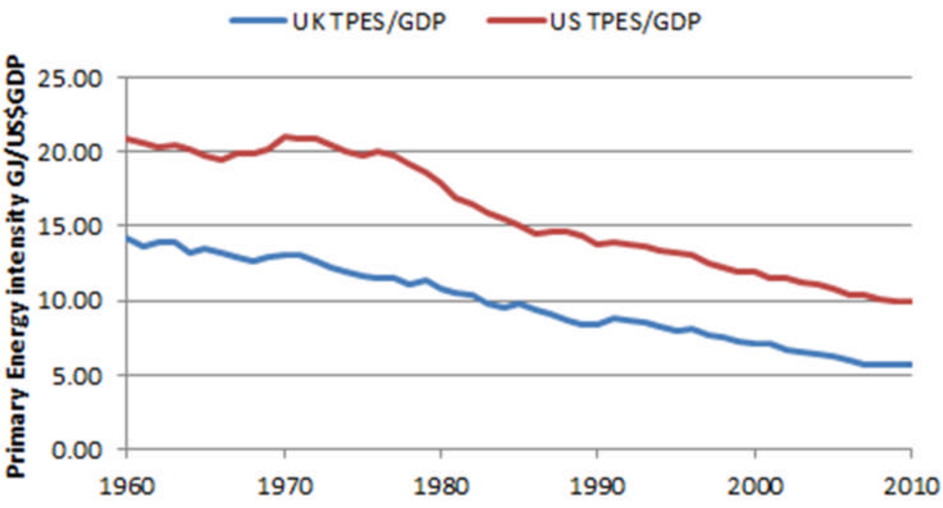


Figure A56: US versus UK primary energy intensity (GJ/GDP)

A.3.5 Non-energy results

Finally, the effect of including non-energy in our analysis was tested, as shown below. US non-energy was selected, since it had a higher proportion (~6%) of TPES than the UK (~4%). The effect was to increase the denominator (input exergy) by around 5%, so exergy efficiency is conversely lower by around 5% than it would otherwise be. This is shown in Figure A57 for the case of the US:

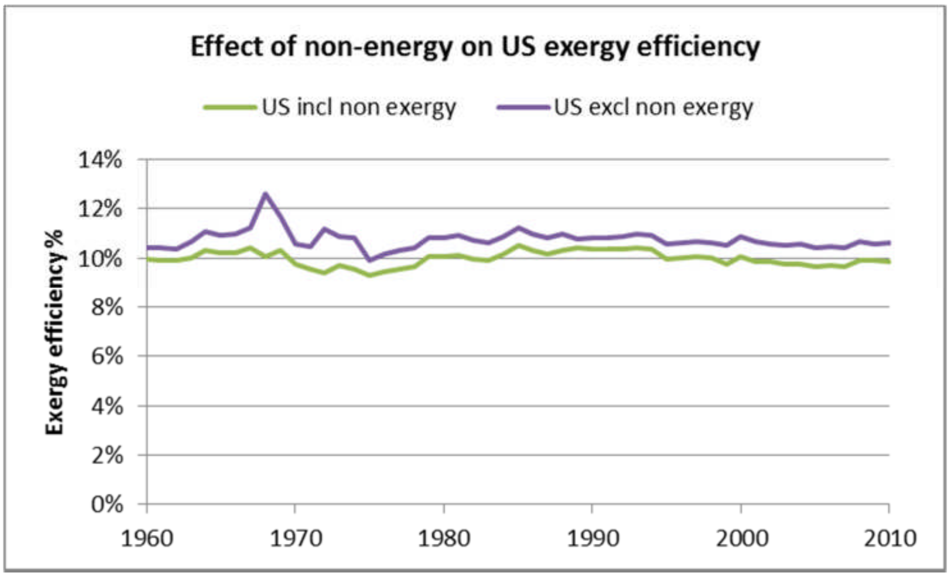


Figure A57: US exergy efficiencies with/without non energy

A.4 References

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Appendix B Supporting information to Chapter 3: Understanding China's past and future energy demand: an exergy efficiency and decomposition analysis

B.1 Useful work accounting outputs: China - 1971, 2010

Table B1: Useful work accounting outputs: China - 1971, 2010

Main class, i	Task level, j	1971			2010		
		Useful work	Primary exergy	Exergy efficiency	Useful work	Primary exergy	Exergy efficiency
		U_{ij}	E_{ij}	e_{ij}	U_{ij}	E_{ij}	e_{ij}
		PJ	PJ	%	PJ	PJ	%
Heat	LTH (Low Temperature Heating 20'C)	448	10,103	4.4%	1,023	20,281	5.0%
	MTH1 (Medium Temperature Heating 100'C)	30	247	12.1%	592	4,428	13.4%
	MTH2 (Medium Temperature Heating 200'C)	314	2,657	11.8%	1,952	10,506	18.6%
	HTH (High Temperature Heating 600'C)	295	2,362	12.5%	4,034	16,695	24.2%
	Sub total	**1,087**	**15,370**	**7.1%**	**7,602**	**51,910**	**14.6%**
Mechanical Drive	Mechanical Drive - Gas/diesel oil (assume diesel road vehicles	20	114	17.3%	821	3,728	22.0%
	Mechanical Drive - Domestic Aviation fuel, jet fuel	0	0	n/a	158	642	24.6%
	Mechanical Drive - Gasoline fuel (Petrol road vehicles	42	242	17.3%	691	3,920	17.6%
	Mechanical Drive - Diesel/gas oil fuel (Boat engines)	2	17	13.0%	188	915	20.5%
	Mechanical Drive - Industry static motors (diesel engines)	28	118	23.5%	522	1,934	27.0%
	Mechanical Drive - Gas/diesel fuel (diesel trains)	1	8	13.0%	64	310	20.5%
	Mechanical Drive - Gas/diesel fuel (tractors)	26	255	10.2%	88	799	11.0%
	Mechanical Drive - bio-diesel / bio-gasoline (road transport)	0	0	n/a	16	80	n/a
	Mechanical Drive - bio-diesel / bio-gasoline (road transport)	0	0	n/a	0	0	n/a
	Mechanical Drive - Gas/diesel oil (assume diesel cars)	0	1	20.4%	85	385	22.0%
	Mechanical Drive - Gas fired engines (for pipeline transport)	0	0	n/a	2	7	n/a
	Mechanical Drive - Coal (steam powered trains)	7	333	2.2%	0	0	n/a
	Mechanical Drive - Coal (steam powered boats)	0	0	n/a	0	0	n/a
	Mechanical Drive Sub-total	**126**	**1,090**	**11.6%**	**2,633**	**12,720**	**20.7%**
Electricity	lighting	1	84	0.8%	46	2,836	1.6%
	Domestic/commercial - space heating	0	31	1.3%	60	3,303	1.8%
	Domestic - hot water/cooking	1	21	3.0%	47	1,272	3.7%
	Industry - HTH process heating	16	199	7.9%	443	4,537	9.8%
	electrolytic end use - industry	11	153	7.5%	370	3,490	10.6%
	Communications / electric devices	0	0	0.1%	1	267	0.3%
	Refrigeration / air conditioning	4	307	1.4%	144	8,221	1.7%
	Domestic - wet/dry motor driven appliances	0	0	10.0%	17	138	12.6%
	Other mechanical drive motors	123	797	15.4%	3,537	18,442	19.2%
	Electricity - sub-total	**156**	**1,592**	**9.8%**	**4,666**	**42,507**	**11.0%**
Muscle work	Human	26	5,432	0.5%	38	9,626	0.5%
	Draught animals	131	5,229	2.5%	88	3,533	2.5%
	Muscle work - sub-total	**157**	**10,661**	**1.5%**	**127**	**13,159**	**1.0%**
Total	**GRAND TOTAL**	**1,526**	**28,713**	**5.3%**	**15,027**	**120,296**	**12.5%**

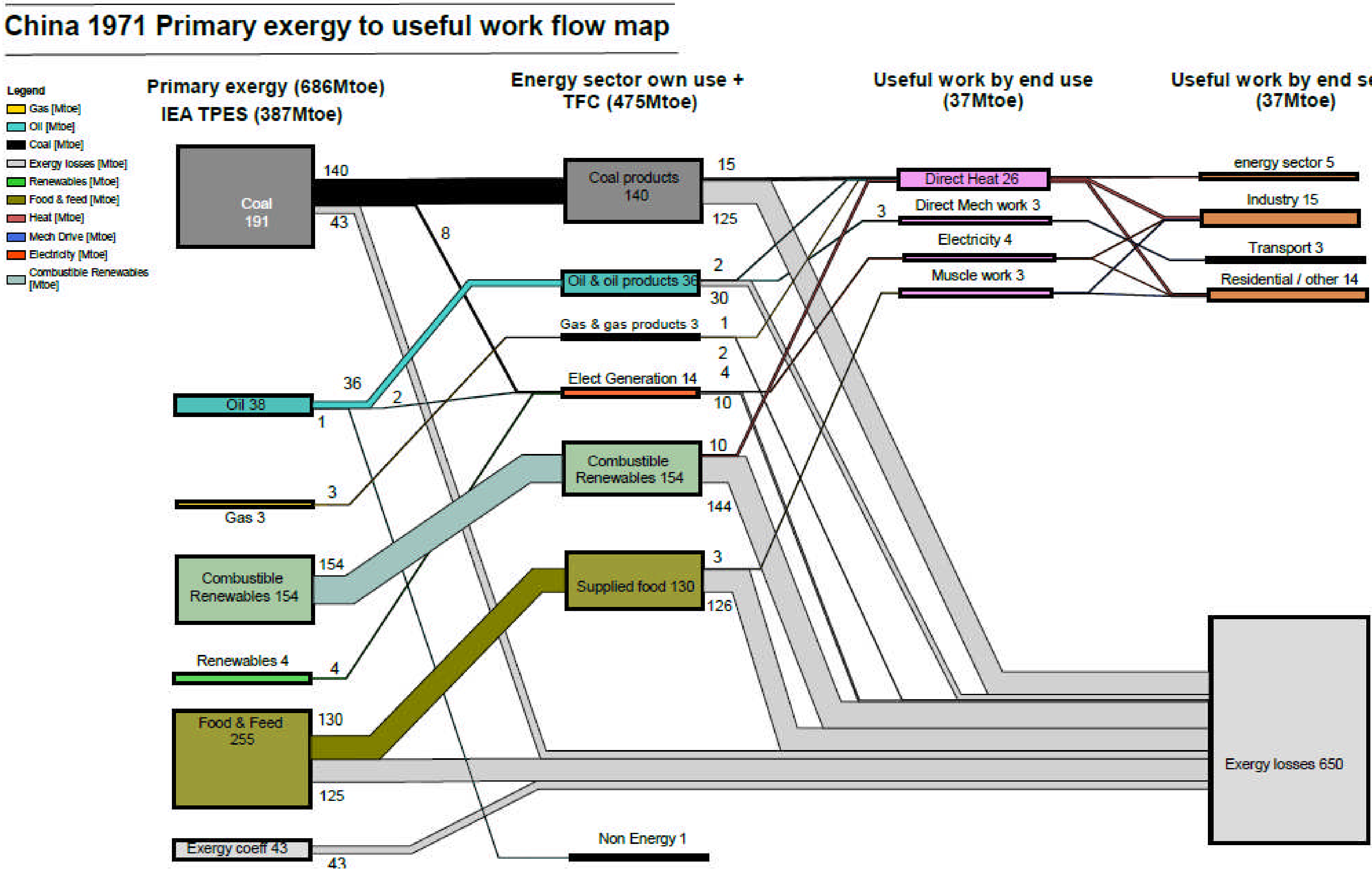

Figure B1: China E-Sankey exergy to useful work flowchart (1971)

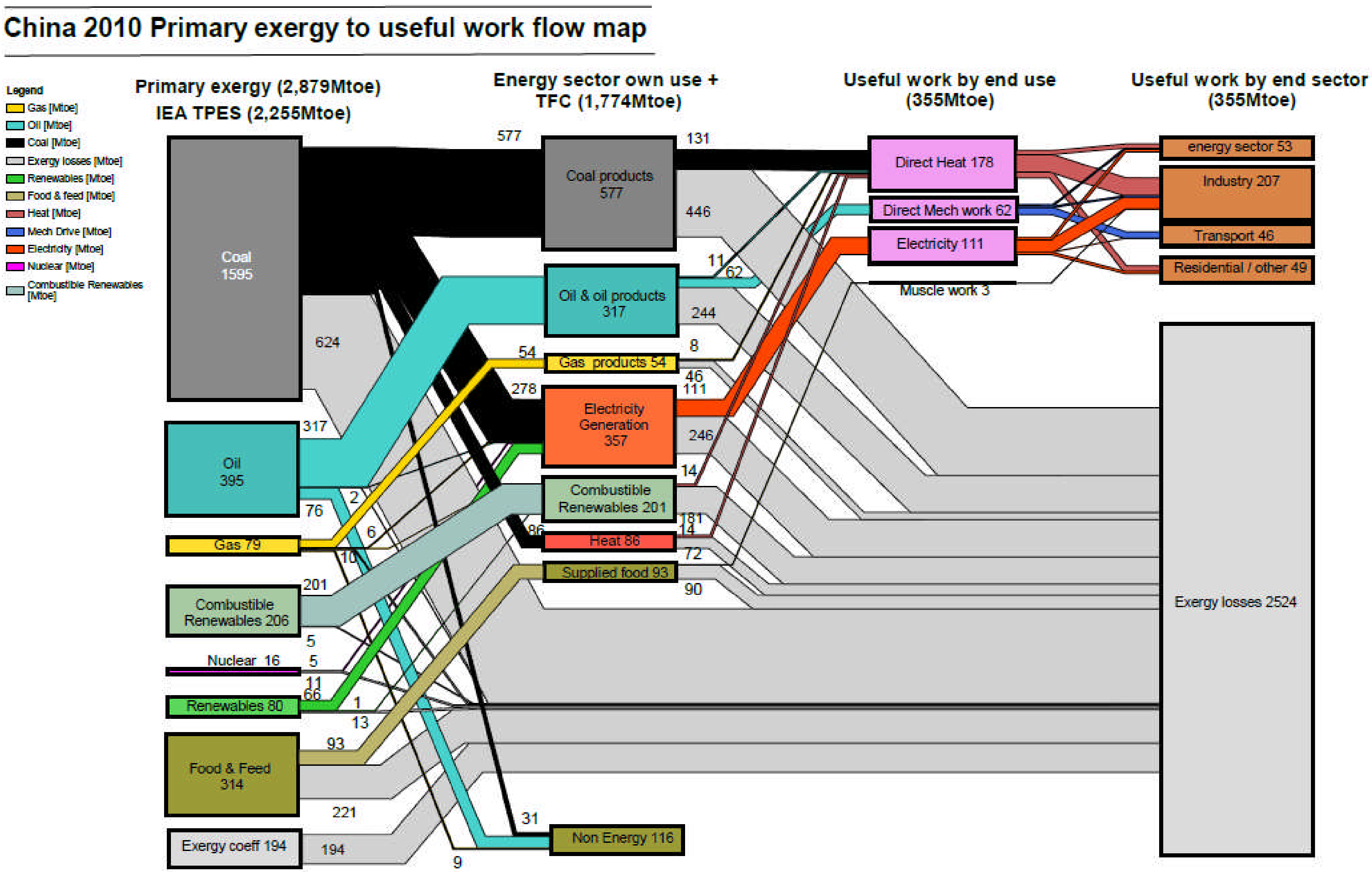

Figure B2: China E-Sankey exergy to useful work flowchart (2010)

B.2 Scenario Analysis: China GDP assumptions to 2030

Table B2 shows the assumed GDP annual growth rate in GDP assumed in our study, using the data from the World Bank (World Bank & The Development Research Center of State Council the People's Republic of China, 2012). For comparison Table B3 shows the assumed GDP growth rate in The IEA's World Energy model, taken from the model documentation document (International Energy Agency (IEA), 2013). They show broadly similar growth rates of 7-8% in 2011-2020, and 4-5% in 2020-2030.

Table B2: World Bank GDP growth rate projections for China 2011-2030 (World Bank & The Development Research Center of State Council the People's Republic of China, 2012)

Table 1 China: Projected growth pattern assuming steady reforms and no major shock

Indicator	1995–2010	2011–15	2016–20	2021–25	2026–30
GDP growth (percent per year)	9.9	8.6	7	5.9	5
Labor growth	0.9	0.3	−0.2	−0.2	−0.4
Labor productivity growth	8.9	8.3	7.1	6.2	5.5
Structure of economy (end of period percent)					
Investment/GDP ratio	46.4	42.0	38.0	36.0	34.0
Consumption/GDP ratio	48.6	56.0	60.0	63.0	66.0
Industry/GDP ratio	46.9	43.8	41.0	38.0	34.6
Services/GDP ratio	43.0	47.6	51.6	56.1	61.1
Share of employment in agriculture	38.1	30.0	23.7	18.2	12.5
Share of employment in services	34.1	42.0	47.6	52.9	59.0

Source: Development Research Center of the State Council (DRC).

Table B3: IEA GDP growth rate projections for China 2011-2030 (International Energy Agency (IEA), 2013)

Table 3: Real GDP growth by region (compound average annual growth rates)

	1990-2000	2000-11	2011-20	2020-35	2011-35
OECD	**2.8%**	**1.6%**	**2.2%**	**2.0%**	**2.1%**
Americas	3.4%	1.7%	2.9%	2.3%	2.5%
United States	3.4%	1.6%	2.8%	2.2%	2.4%
Europe	2.4%	1.6%	1.5%	1.8%	1.7%
Asia Oceania	2.1%	1.6%	2.1%	1.7%	1.8%
Japan	1.1%	0.6%	1.4%	1.1%	1.2%
Non-OECD	**3.3%**	**6.5%**	**5.8%**	**4.2%**	**4.8%**
E. Europe/Eurasia	-3.8%	5.0%	3.5%	3.1%	3.3%
Russia	-3.9%	4.8%	3.6%	3.2%	3.4%
Asia	7.0%	8.0%	7.1%	4.7%	5.6%
China	9.9%	10.1%	8.1%	4.4%	5.7%
India	5.6%	7.4%	6.5%	6.2%	6.3%
Middle East	3.9%	5.3%	3.7%	3.7%	3.7%
Africa	2.6%	4.9%	5.0%	3.4%	4.0%
Latin America	2.9%	3.9%	3.7%	3.1%	3.3%
Brazil	2.5%	3.5%	3.6%	3.7%	3.7%
World	**2.9%**	**3.5%**	**4.0%**	**3.3%**	**3.6%**
European Union	2.1%	1.5%	1.3%	1.8%	1.6%

Note: Calculated based on GDP expressed in year-2012 dollars in PPP terms.

Source: IEA (2013a).

B.3 Scenario Analysis: Useful work allocations to 2030

Figure B3 to B6 show the % allocations given to the main categories of useful work (Heat, Mechanical Drive, Electricity, and Muscle Work), together with their sub-allocations, i.e. task-level allocations. The basis for the allocations is to best-fit three trends in each dataset:

1. **Historical China useful work % allocations**: i.e. ensure a smooth trends approach without discontinuity
2. **Historical US and UK useful work % allocations**: by looking at the time-series US and UK allocations, we get a sense of the split of useful work in a mature / service sector orientated economies, which is China's long-term direction of travel. For example, the overall % split of electricity in both UK and US is below 40% of total useful work. Therefore this has been placed as a asymptotic limit for China, and the allocation is smoothed to fit that boundary.
3. **Mega trends**: i.e. China moving from industrial to service based economy in the future. Thus we see in our projections by 2030 a growing share for transport and non-industry electricity uses, whilst conversely there is a peaking and decline in HTH share. This view is supported by GDP projections (e.g. (World Bank & The Development Research Center of State Council the People's Republic of China, 2012)) and primary energy forecasts (e.g. (International Energy Agency (IEA), 2010)).

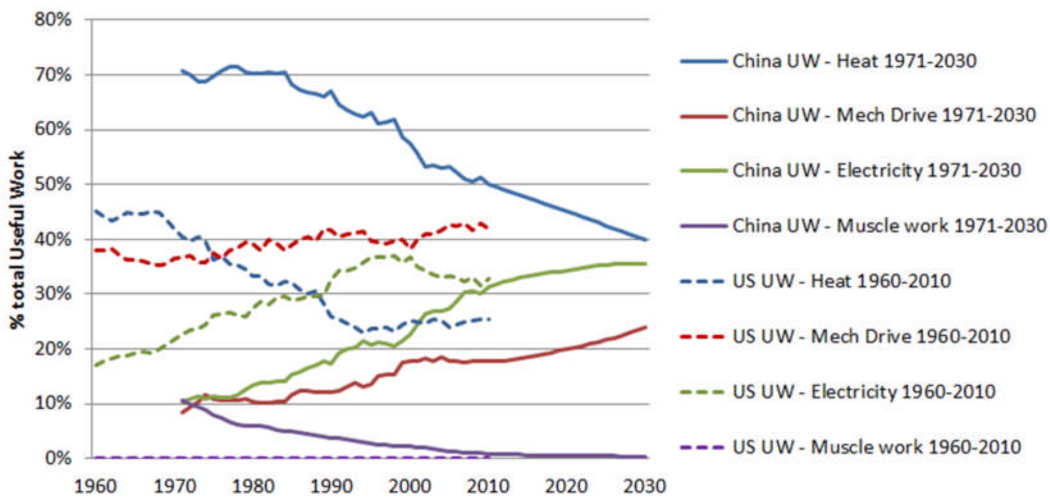

Figure B3: useful work allocations China & US

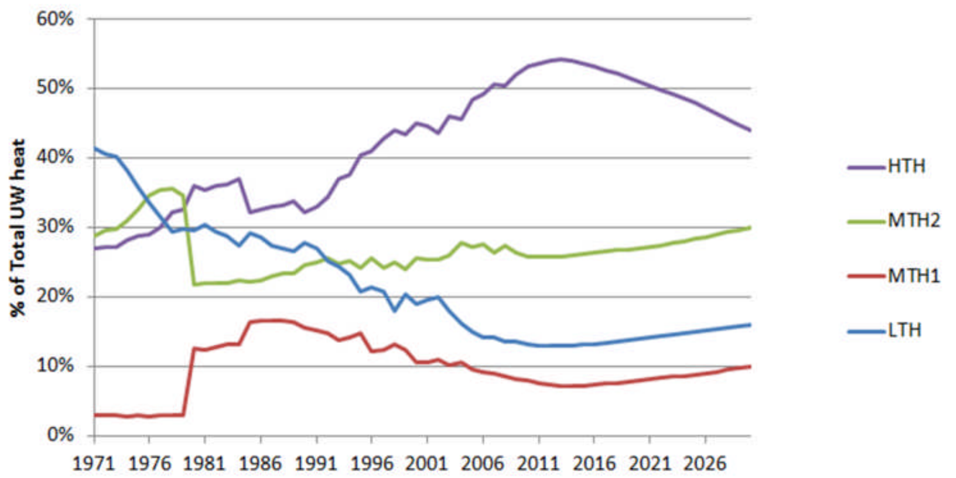

Figure B4: China useful work allocation 2010-2030 – Heat

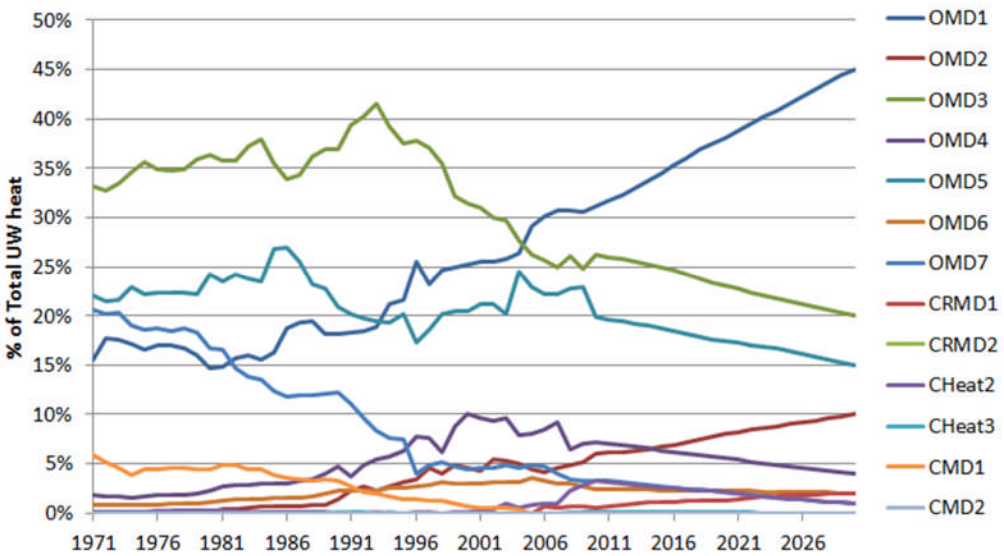

Figure B5: China useful work allocation 2010-2030 – Mechanical Drive

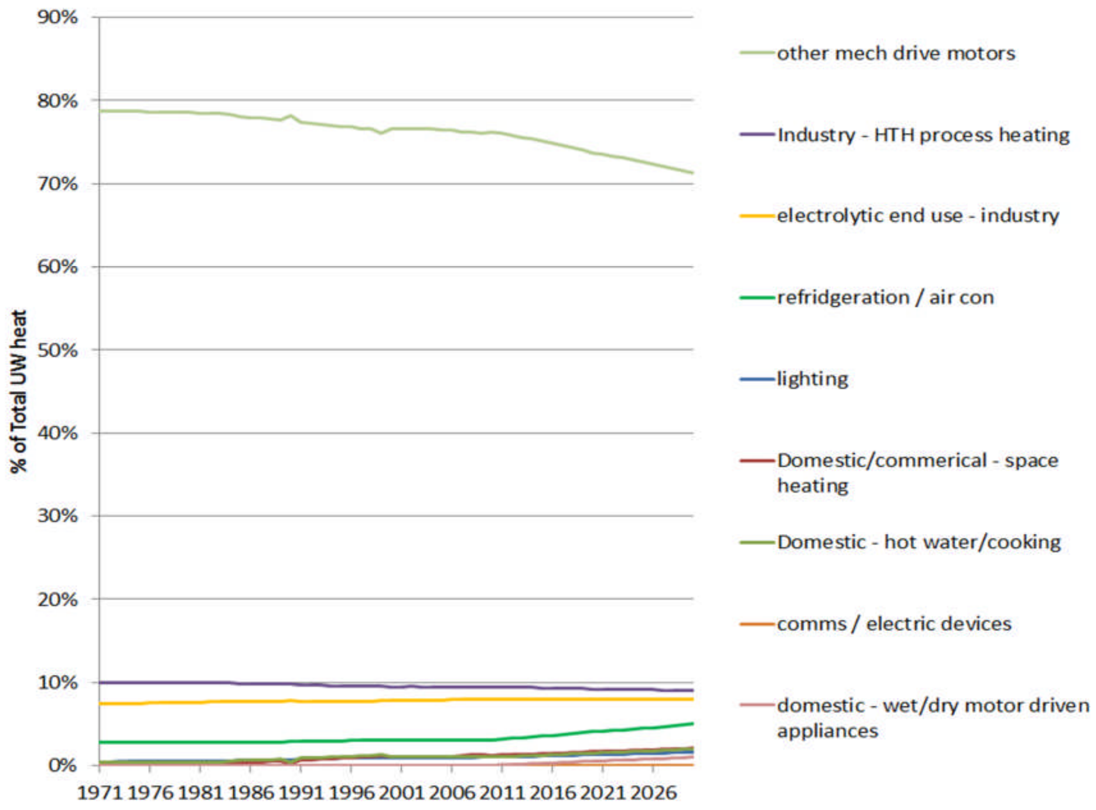

Figure B6: China useful work allocation 2010-2030 – Electricity

As we have already estimated the total useful work value for China 2011-2030 via econometric U/GDP approach (see main paper), with a known total useful work values and % allocation, we can calculate the estimated absolute useful work values for each main category and task-level. This is shown in Figures B7 to B10, in TJ/year.

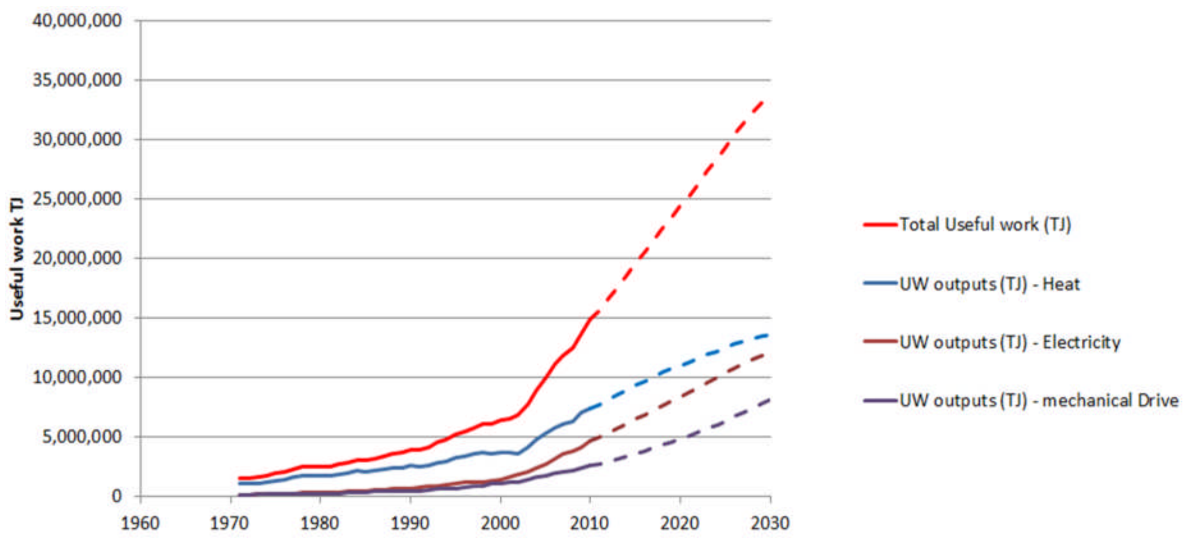

Figure B7: China useful work projection 2010-2030 – Total

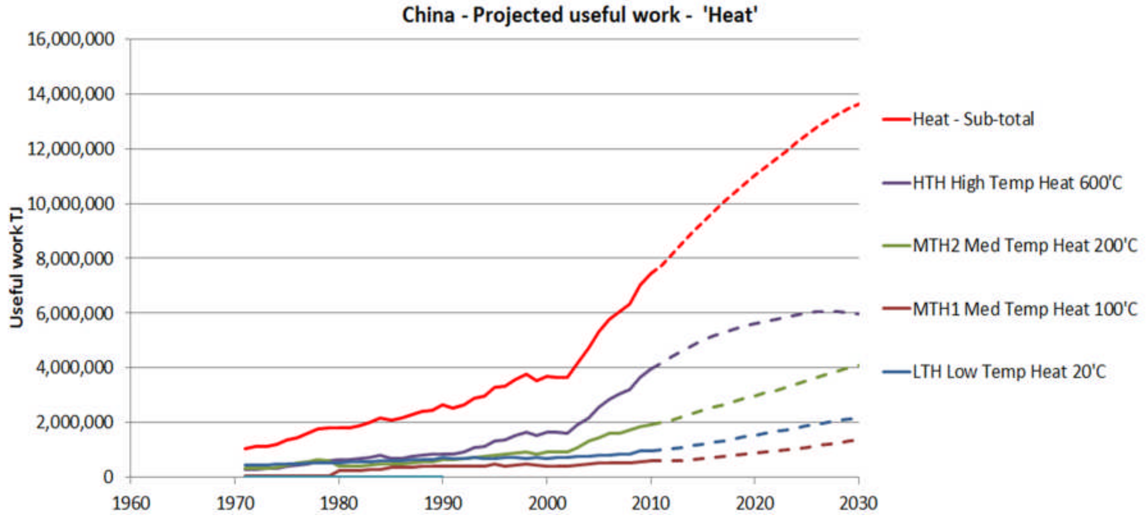

Figure B8: China useful work projection 2010-2030 – Heat

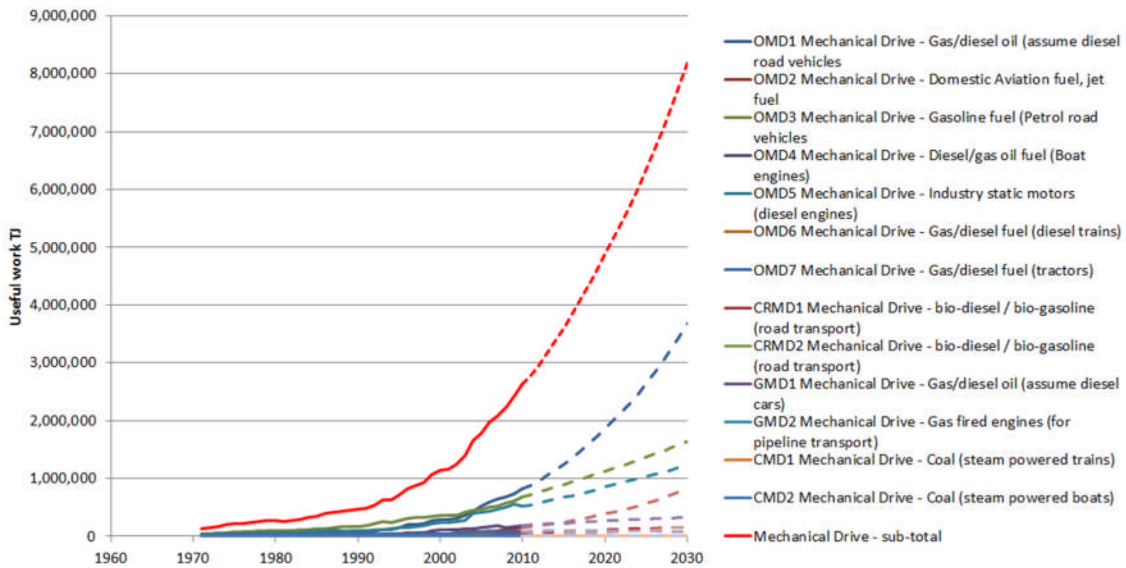

Figure B9: China useful work projection 2010-2030 – Mechanical Drive

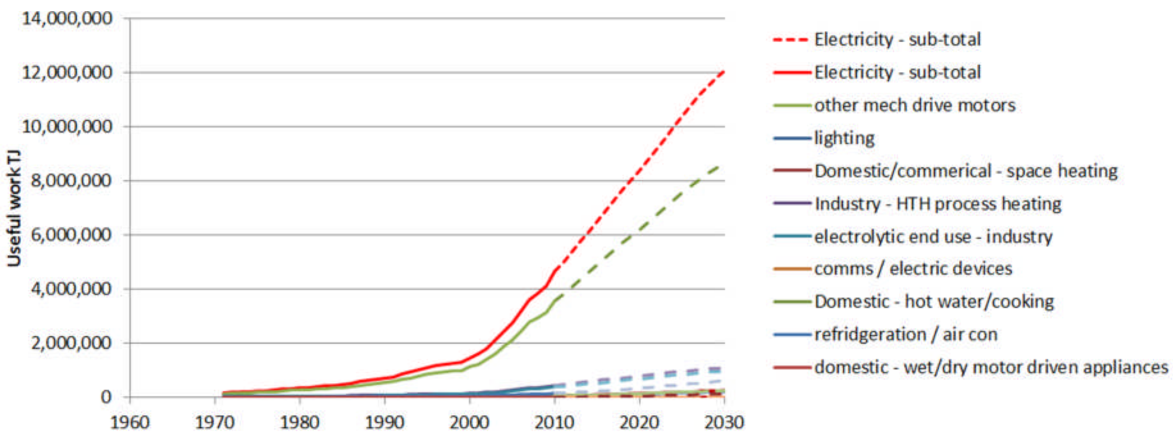

Figure B10: China useful work projection 2010-2030 – Electricity

B.4 Scenario Analysis: Exergy efficiency scenarios to 2030

The following graphs show the assumed exergy efficiency under the two scenarios:

- **Scenario 1:** the change in each task-level efficiency 1990-2010 is applied to the task-level efficiency for 2010-2030. So for example a rise in task-level efficiency from 10% (1990) to 12% (2010) is a 20% rise in efficiency, so the efficiency in 2030 would be 1.2 * 12% = 14.4%.
- **Scenario 2:** 50% of the change in task-level efficiency 1990-2010 is applied to 2010 – 2030, with two thirds of this change occurring in 2010-2020, and one third in 2020-2030. So for example a rise in task-level efficiency from 10% (1990) to 12% (2010) is a 20% rise in efficiency, so half (10%) is taken for 2010-2030, resulting in a value of 12%*1.1 = 13.2% in 2030. The value in 2020 is 12+0.667*1.2% = 12.8%. This scenario mimics a declining gains scenario, where the rate of growth of task-level efficiency gains slows by 2030.

Tables B4 to B6 show the exergy efficiencies under Scenario 1. It highlights that in some cases the rise in exergy efficiencies at a task-level may not follow this linear trajectory, due to approaching asymptotic limits – for example the HTH efficiency in 2030 is over 30% which is higher than current US or UK HTH efficiencies. This underlines the thinking behind Scenario 2, whose tables were derived in a similar manner as just described.

Table B4: Scenario 1 Heat Efficiencies 2010-2030

Task-level	1990	2010	2020	2030
LTH	4.60%	4.80%	4.90%	5.00%
MTH1	14.59%	13.37%	12.76%	12.15%
MTH2	14.51%	18.21%	20.06%	21.91%
HTH	17.36%	23.74%	26.93%	30.12%

Table B5: Scenario 1 Mechanical Drive Efficiencies 2010-2030

Task-level	1990	2010	2020	2030
OMD1	22.55%	22.01%	21.75%	21.48%
OMD2	22.65%	24.64%	25.63%	26.63%
OMD3	18.88%	17.62%	16.99%	16.36%
OMD4	17.14%	20.52%	22.21%	23.90%
OMD5	25.20%	27.00%	27.90%	28.80%
OMD6	17.14%	20.52%	22.21%	23.90%
OMD7	11.28%	11.01%	10.87%	10.74%
CRMD1	n/a	19.82%	19.91%	20%
CRMD2	n/a	n/a	n/a	n/a
GMD1	n/a	22.01%	21.01%	20%
GMD2	22.68%	24.30%	25.11%	25.92%
CMD1	2.91%	n/a	n/a	n/a
CMD2	n/a	n/a	n/a	n/a

Table B6: Scenario 1 Electricity Efficiencies 2010-2030

Task – level	**1990**	**2010**	**2020**	**2030**
Lighting	1.24%	1.85%	2.15%	2.45%
Domestic/commercial - space heating	1.52%	1.95%	2.16%	2.38%
Domestic - hot water/cooking	3.42%	4.20%	4.59%	4.98%
Industry - HTH process heating	9.08%	11.10%	12.10%	13.11%
electrolytic end use - industry	9.25%	12.05%	13.46%	14.86%
comms / electric devices	0.18%	0.33%	0.41%	0.48%
refridgeration / air con	1.62%	1.99%	2.17%	2.35%
Domestic - wet/dry motor driven appliances	11.60%	14.27%	15.61%	16.95%
other mech drive motors	17.76%	21.80%	23.81%	25.83%

Figures B11 to B13 give the task-level efficiencies and outturn overall main class efficiencies under Scenario 1

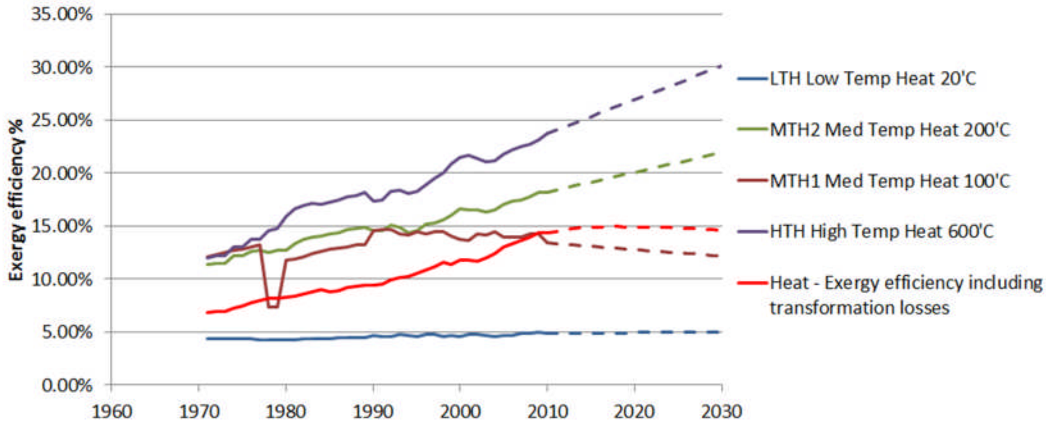

Figure B11: China – Scenario 1 exergy efficiencies – Heat

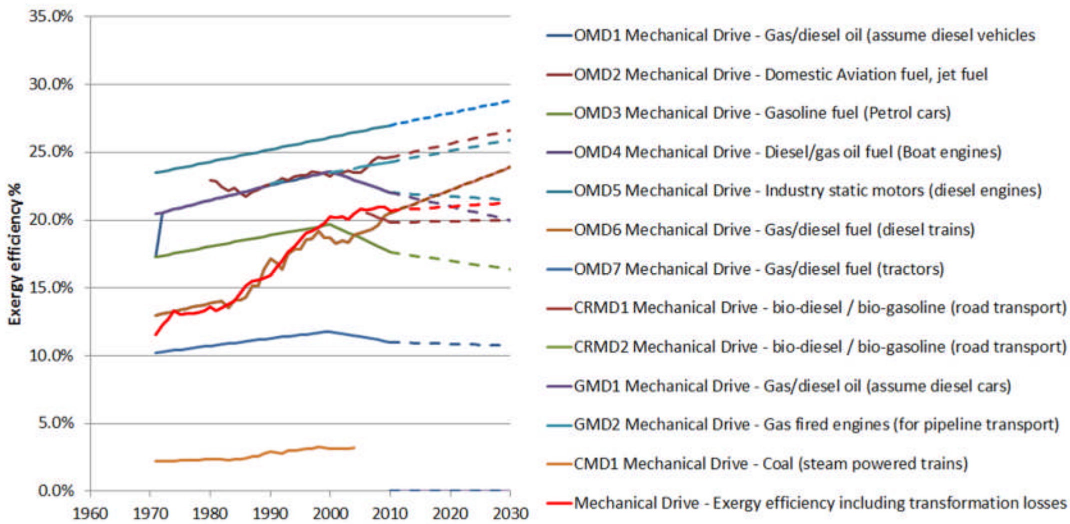

Figure B12: China – Scenario 1 exergy efficiencies – Mechanical Drive

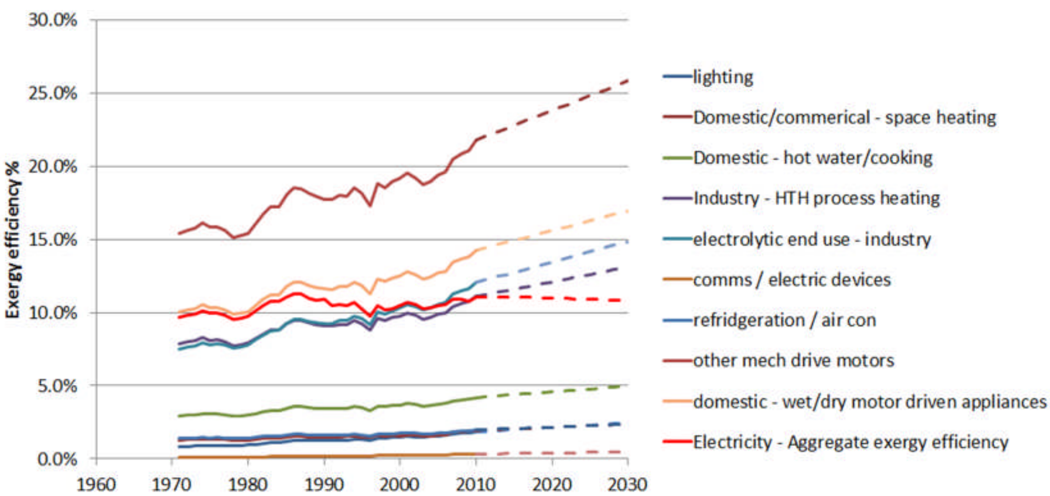

Figure B13: China – Scenario 1 exergy efficiencies - Electricity

Figures B14 to B16 give the task-level efficiencies and outturn overall main class efficiencies under Scenario 2.

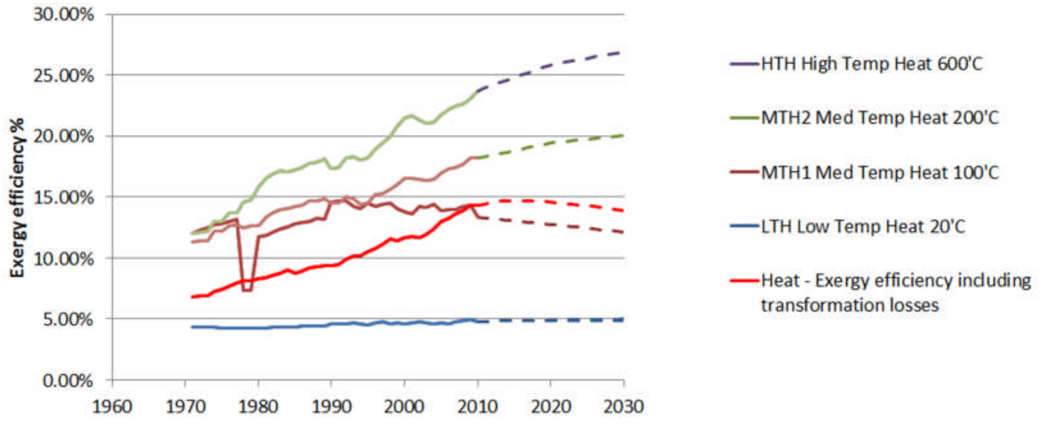

Figure B14: China – Scenario 2 exergy efficiencies – Heat

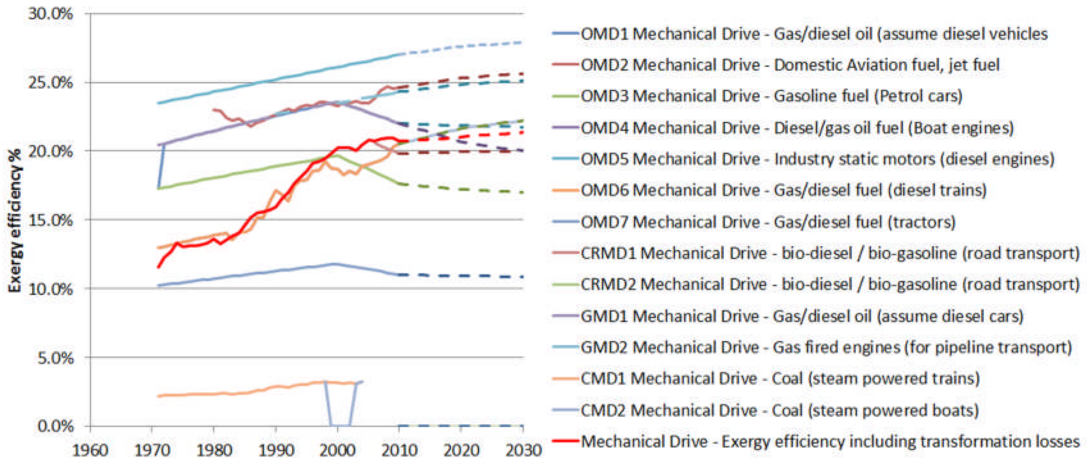

Figure B15: China – Scenario 2 exergy efficiencies – Mechanical Drive

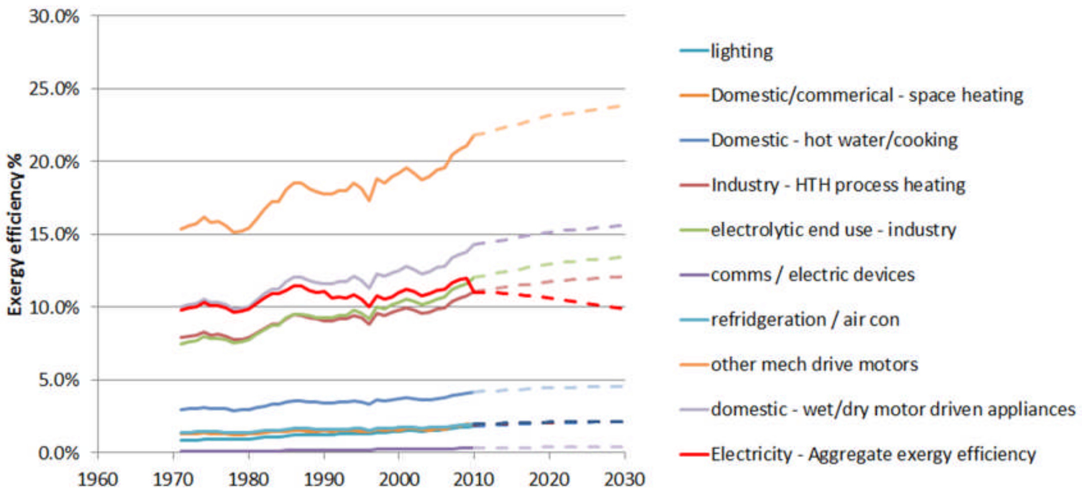

Figure B16: China – Scenario 2 exergy efficiencies – Electricity

B.5 References

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International Energy Agency (IEA), 2013. World Energy Model Documentation 2013 Version, Available at http://www.worldenergyoutlook.org/media/weowebsite/2013/WEM_Documentation_WEO2013.pdf.

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Appendix C Supporting information to Chapter 5: A new approach to estimating total economy-wide energy rebound: An exergy efficiency based study of the UK, US and China

C.1 Extended CES Function – Long-term rebound condition

C.1.1 Setup

We need to develop the expressions $\frac{\tau}{Y}\frac{\partial Y}{\partial \tau}$ and $\frac{\tau}{F}\frac{\partial F}{\partial \tau}$ to deliver the output and intensity rebound elasticities (long-term) expressed in a form employing (ideally measured) parameters of the particular production function being examined:

$$\begin{aligned} \eta_{\tau}^{F_{Output}} &= \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} \\ \eta_{\tau}^{F_{Intensity}} &= \frac{\tau}{F}\frac{\partial F}{\partial \tau} - \eta_{\tau}^{F_{Output}} \end{aligned} \tag{1}$$

In this case we're using an extended version of the CES production function, of the form:

$$Y = \gamma A \left\{ \delta \left[\delta_1 K^{-\rho_1} + \left(1-\delta_1\right) L^{-\rho_1} \right]^{\rho/\rho_1} + \left(1-\delta\right)\left(\tau F\right)^{-\rho} \right\}^{-1/\rho}; A = e^{\lambda(t-t_0)} \tag{2}$$

Solving for the needed rebound elasticities requires appeal to the Implicit Function Theorem. This is because the introduction of an energy technology gain τ affects the Y and F terms in (1) in multiple complex ways, requiring setting up a series of equations. And it happens that the variables required to develop expressions for the $\frac{\partial Y}{\partial \tau}$ and $\frac{\partial F}{\partial \tau}$ terms of (1) are embedded in the equation structure in such a way that they cannot be isolated directly. The Implicit Function Theorem allows us to ask how any endogenous variables (here we mean Y and F) will change, while honoring these equations, if some exogenous variable (here we mean τ) changes .

C.1.2 Equations Needed

We need three equations to describe how an economy with three factor inputs (here K, L, F) behaves when there is a change in τ.

We can construct the following three equations:

$$\begin{aligned} \psi_1 &= g\left(Y, f(K, L, \tau F)\right) = 0 \\ \psi_2 &= h\left(s_F, \frac{\partial f(K, L, \tau F)}{\partial F}\frac{F}{Y}\right) = 0 \\ \psi_3 &= k\left(s_K, \frac{\partial f(K, L, \tau F)}{\partial K}\frac{K}{Y}\right) = 0 \end{aligned} \tag{3}$$

The first equation is essentially the production function itself, and so looks like:

$$\psi_1 = Y - \gamma A\left\{\delta\left[\delta_1 K^{-\rho_1} + \left(1-\delta_1\right)L^{-\rho_1}\right]^{\rho/\rho_1} + \left(1-\delta\right)\left(\tau F\right)^{-\rho}\right\}^{-1/\rho} = 0 \tag{4}$$

The second and third equations are developed from the value shares of energy and capital:

$$\begin{aligned} & s_F Y = \frac{p_F}{c}F \\ & s_K Y = \frac{p_K}{c}K \\ & \Rightarrow s_F Y - \frac{p_F}{c}F = 0 \\ & \Rightarrow s_K Y - \frac{p_K}{c}K = 0 \\ & \Rightarrow Y - \frac{p_F}{c s_F}F = 0 \\ & \Rightarrow Y - \frac{p_K}{c s_K}K = 0 \end{aligned} \tag{5}$$

So we choose the second and third equations to be

$$\begin{aligned} \psi_2 &= Y - \frac{p_F}{c s_F}F = 0 \\ \psi_3 &= Y - \frac{p_K}{c s_K}K = 0 \end{aligned} \tag{6}$$

C.1.3 Implicit Function Theorem and the Jacobian

To measure rebound, we need to know how Y and F respond to changes in the energy technology gain τ. To accomplish this, we form the Jacobian matrix of

$\Psi = (\psi_1, \psi_2, \psi_3)$, namely $J = \left[\frac{\partial \psi_i (Y_0, F_0, \tau_0)}{\partial X_j} \right]$, where $X_j = Y, F, K$. Then it will be true that

$$\begin{bmatrix} \frac{\partial Y}{\partial \tau} \\ \frac{\partial F}{\partial \tau} \\ \frac{\partial K}{\partial \tau} \end{bmatrix} = -J^{-1} \begin{bmatrix} \frac{\partial \psi_1}{\partial \tau} \\ \frac{\partial \psi_2}{\partial \tau} \\ \frac{\partial \psi_3}{\partial \tau} \end{bmatrix} \tag{7}$$

From the terms $\frac{\partial Y}{\partial \tau}$ and $\frac{\partial F}{\partial \tau}$ we can determine the components of long-term rebound.

The Jacobian matrix is

$$J = \begin{pmatrix} \frac{\partial \psi_1}{\partial Y} & \frac{\partial \psi_1}{\partial F} & \frac{\partial \psi_1}{\partial K} \\ \frac{\partial \psi_2}{\partial Y} & \frac{\partial \psi_2}{\partial F} & \frac{\partial \psi_2}{\partial F} \\ \frac{\partial \psi_3}{\partial Y} & \frac{\partial \psi_3}{\partial F} & \frac{\partial \psi_2}{\partial F} \end{pmatrix} \tag{8}$$

C.1.4 Calculating the Jacobian Elements

To develop the first row of the Jacobian, we need to calculate $\frac{\partial \psi_1}{\partial Y}, \frac{\partial \psi_1}{\partial F}, \frac{\partial \psi_1}{\partial K}$.

The first element is easy: From (4) we have that $\frac{\partial \psi_1}{\partial Y} = 1$.

Calculating the second two elements is trivial as these are essentially the first-order conditions on energy and capital:

$$\begin{aligned} \frac{\partial \psi_1}{\partial F} &= -\frac{\partial f(K, L, \tau F)}{\partial F} = \frac{p_F}{c} \\ \frac{\partial \psi_1}{\partial K} &= -\frac{\partial f(K, L, \tau F)}{\partial K} = \frac{p_K}{c} \end{aligned} \tag{9}$$

To develop the second row of the Jacobian, we need to calculate $\frac{\partial \psi_2}{\partial Y}, \frac{\partial \psi_2}{\partial F}, \frac{\partial \psi_2}{\partial K}$

.

Looking at (4) and (6), we see that

$$\begin{aligned} \frac{\partial \psi_2}{\partial Y} &= 1 \\ \frac{\partial \psi_2}{\partial F} &= -\frac{p_F}{cs_F} \\ \frac{\partial \psi_2}{\partial K} &= 0 \end{aligned} \tag{10}$$

To develop the third row of the Jacobian, we need to calculate $\frac{\partial \psi_3}{\partial Y}, \frac{\partial \psi_3}{\partial F}, \frac{\partial \psi_3}{\partial K}$.

Looking at (4) and (6), we see that

$$\begin{aligned} \frac{\partial \psi_3}{\partial Y} &= 1 \\ \frac{\partial \psi_3}{\partial F} &= 0 \\ \frac{\partial \psi_3}{\partial K} &= -\frac{p_K}{cs_K} \end{aligned} \tag{11}$$

So the Jacobian matrix becomes

$$J = \begin{pmatrix} \frac{\partial \psi_1}{\partial Y} & \frac{\partial \psi_1}{\partial F} & \frac{\partial \psi_1}{\partial K} \\ \frac{\partial \psi_2}{\partial Y} & \frac{\partial \psi_2}{\partial F} & \frac{\partial \psi_2}{\partial F} \\ \frac{\partial \psi_3}{\partial Y} & \frac{\partial \psi_3}{\partial F} & \frac{\partial \psi_2}{\partial F} \end{pmatrix} = \begin{pmatrix} 1 & \frac{p_F}{c} & \frac{p_K}{c} \\ 1 & -\frac{p_F}{cs_F} & 0 \\ 1 & 0 & -\frac{p_K}{cs_K} \end{pmatrix} \tag{12}$$

Interestingly, this matrix appears to be independent of the particular form of the production function.

C.1.5 Calculating the Efficiency Gain Vector Elements

Prior to inverting the above Jacobian matrix, we need to develop the partials of the three equations with respect to the energy efficiency gain parameter, τ , as called for in equation (7). The three elements are $\frac{\partial \psi_1}{\partial \tau}$, $\frac{\partial \psi_2}{\partial \tau}$, and $\frac{\partial \psi_3}{\partial \tau}$. We start by invoking some substitutions to make the derivatives easier. Specifically, let

$Q=\delta\left[\delta_1K^{-\rho_1}+\left(1-\delta_1\right)L^{-\rho_1}\right]^{\rho/\rho_1}+\left(1-\delta\right)\left(\tau F\right)^{-\rho}$. Let $R=\delta_1K^{-\rho_1}+\left(1-\delta_1\right)L^{-\rho_1}$. And let $S=\tau F$. Then, $Q=\delta R^{\rho/\rho_1}+\left(1-\delta\right)S^{-\rho}$.

C.1.5.1 Partial of First Equation

So beginning with $\frac{\partial\psi_1}{\partial\tau}=Y-\gamma A\left\{\delta\left[\delta_1K^{-\rho_1}+\left(1-\delta_1\right)L^{-\rho_1}\right]^{\rho/\rho_1}+\left(1-\delta\right)\left(\tau F\right)^{-\rho}\right\}^{-1/\rho}$ and noting that $Y=\gamma A\left[Q\left(S\left(\tau\right)\right)\right]^{-1/\rho}$, from the chain rule we have

$$\frac{\partial f(K,L,\tau F)}{\partial\tau}=\frac{\partial Y}{\partial Q}\frac{\partial Q}{\partial S}\frac{\partial S}{\partial\tau} \tag{13}$$

The three partials are

$$\frac{\partial Y}{\partial Q}=-\frac{1}{\rho}\gamma A\frac{Q^{-1/\rho}}{Q}=-\frac{1}{\rho}\frac{Y}{Q}=-\frac{1}{\rho}\frac{Y}{\left(\frac{Y}{\gamma A}\right)^{-\rho}}=-\frac{1}{\rho}\left(\gamma A\right)^{-\rho}Y^{1+\rho}$$

$$\frac{\partial Q}{\partial S}=-\rho\left(1-\delta\right)\frac{S^{-\rho}}{S}=-\rho\left(1-\delta\right)\frac{\left(\tau F\right)^{-\rho}}{\tau F}=-\rho\left(1-\delta\right)\tau^{-\rho-1}F^{-\rho-1} \tag{14}$$

$$\frac{\partial S}{\partial\tau}=F$$

To get us part way, we substitute (14) into (13), yielding

$$\frac{\partial f(K,L,\tau F)}{\partial\tau}=\frac{\partial Y}{\partial Q}\frac{\partial Q}{\partial S}\frac{\partial S}{\partial\tau}$$

$$\frac{\partial f(K,L,\tau F)}{\partial\tau}=\left[-\frac{1}{\rho}\left(\gamma A\right)^{-\rho}Y^{1+\rho}\right]\left[-\rho\left(1-\delta\right)\tau^{-\rho-1}F^{-\rho-1}\right]F \tag{15}$$

$$\frac{\partial f(K,L,\tau F)}{\partial\tau}=\left(\gamma A\right)^{-\rho}\left(1-\delta\right)\frac{1}{\tau^{\rho+1}}\left(\frac{Y}{F}\right)^{1+\rho}F$$

So the first partial becomes

$$\frac{\partial\psi_1}{\partial\tau}=-\left(\gamma A\right)^{-\rho}\left(1-\delta\right)\frac{1}{\tau^{\rho+1}}\left(\frac{Y}{F}\right)^{1+\rho}F \tag{16}$$

Further simplification comes if we derive the first-order condition on energy and introduce the value share s_F. The development is identical to (13) except for the last term:

$$\frac{\partial f(K,L,\tau F)}{\partial F}=\frac{p_F}{c}=\frac{\partial Y}{\partial Q}\frac{\partial Q}{\partial S}\frac{\partial S}{\partial F} \tag{17}$$

where $\frac{\partial S}{\partial F}=\tau$, meaning (17) can be re-written as

$$\begin{aligned}\frac{\partial f(K,L,\tau F)}{\partial F}&=\frac{p_F}{c}=\left[-\frac{1}{\rho}(\gamma A)^{-\rho}Y^{1+\rho}\right]\left[-\rho(1-\delta)\tau^{-\rho-1}F^{-\rho-1}\right]\tau\\ \frac{\partial f(K,L,\tau F)}{\partial F}&=\frac{p_F}{c}=(\gamma A)^{-\rho}(1-\delta)\frac{\tau}{\tau^{\rho+1}}\left(\frac{Y}{F}\right)^{1+\rho}\end{aligned} \tag{18}$$

This equation can be rearranged to enable substitution into (16). That is,

$$\frac{p_F}{c\tau}=(\gamma A)^{-\rho}(1-\delta)\frac{1}{\tau^{\rho+1}}\left(\frac{Y}{F}\right)^{1+\rho} \tag{19}$$

Substituting (19) into (16) yields:

$$\frac{\partial \psi_1}{\partial \tau}=-\frac{p_F}{c\tau}F \tag{20}$$

But observing from the energy share equation that

$$\begin{aligned}s_F&=\frac{p_F}{c}\frac{F}{Y}\\ \Rightarrow\frac{p_F}{c}&=s_F\frac{Y}{F}\end{aligned} \tag{21}$$

substituting (21) into (20) yields:

$$\begin{aligned}\frac{\partial \psi_1}{\partial \tau}&=-\frac{1}{\tau}s_F\frac{Y}{F}F\\ \frac{\partial \psi_1}{\partial \tau}&=-\frac{s_F Y}{\tau}\end{aligned} \tag{22}$$

C.1.5.2 Partial of Second Equation

The second equation is $\psi_2=Y-\frac{p_F}{cs_F}F=0$.

But we need to re-state this equation in a form that is explicit in τ . For this we return to the first-order condition (18):

$$(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}\left(\frac{Y}{F}\right)^{1+\rho} = \frac{p_F}{c}$$

$$\left(\frac{Y}{F}\right)^{1+\rho} = \frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}}$$

$$\frac{Y}{F} = \left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}}\right)^{\frac{1}{1+\rho}} \tag{23}$$

$$\Rightarrow Y = \left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}}\right)^{\frac{1}{1+\rho}} F$$

$$\Rightarrow Y = \left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)}\right)^{\frac{1}{1+\rho}} \tau^{\frac{\rho}{1+\rho}} F$$

So ψ_2 can now be written as:

$$\Psi_2 = Y - \left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)}\right)^{\frac{1}{1+\rho}} \tau^{\frac{\rho}{1+\rho}} F = 0 \tag{24}$$

Now we can differentiate wrt τ :

$$\frac{\partial \Psi_2}{\partial \tau} = -\left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)}\right)^{\frac{1}{1+\rho}} F \frac{\partial}{\partial \tau}\tau^{\frac{\rho}{1+\rho}}$$

$$\frac{\partial \Psi_2}{\partial \tau} = -\frac{\rho}{1+\rho}\left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)}\right)^{\frac{1}{1+\rho}} F \frac{\tau^{\frac{\rho}{1+\rho}}}{\tau}$$

$$\frac{\partial \Psi_2}{\partial \tau} = -\frac{\rho}{1+\rho}\left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}}\right)^{\frac{1}{1+\rho}} \frac{F}{\tau} \tag{25}$$

We can simplify by invoking the share equation for energy:

$$s_F = \frac{p_F}{c}\frac{F}{Y}$$
$$\Rightarrow \frac{Y}{F} = \frac{p_F}{cs_F} \tag{26}$$

But from (23) we know that

$$\frac{Y}{F} = \left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}}\right)^{\frac{1}{1+\rho}} \tag{27}$$

Comparing (27) with (26), we see that

$$\left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}}\right)^{\frac{1}{1+\rho}} = \frac{p_F}{cs_F} \tag{28}$$

Therefore we can rewrite equation (25) as

$$\frac{\partial\Psi_2}{\partial\tau} = -\frac{\rho}{1+\rho}\left(\frac{p_F}{c(\gamma A)^{-\rho}(1-\delta)\tau^{-\rho}}\right)^{\frac{1}{1+\rho}}\frac{F}{\tau} \tag{29}$$

$$\frac{\partial\Psi_2}{\partial\tau} = -\frac{\rho}{1+\rho}\frac{p_F}{cs_F}\frac{F}{\tau}$$

C.1.5.3 Partial of Third Equation

The first order of business is to derive the first-order condition on capital:

Let $Q = \delta\left[\delta_1 K^{-\rho_1} + (1-\delta_1)L^{-\rho_1}\right]^{\rho/\rho_1} + (1-\delta)(\tau F)^{-\rho}$. Let $R = \delta_1 K^{-\rho_1} + (1-\delta_1)L^{-\rho_1}$.

Then $Y = \gamma A\left[Q(R(K))\right]^{-1/\rho}$, so from the chain rule

$$\frac{\partial f(K,L,\tau F)}{\partial K} = \frac{p_K}{c} = \frac{\partial Y}{\partial Q}\frac{\partial Q}{\partial R}\frac{\partial R}{\partial K} \tag{30}$$

Also note that $Q = \delta R^{\rho/\rho_1} + (1-\delta)(\tau F)^{-\rho}$.

Taking each component of (30) in turn,

$$\frac{\partial Y}{\partial Q} = -\frac{1}{\rho}\gamma A \frac{Q^{-1/\rho}}{Q} = -\frac{1}{\rho}\gamma A(\gamma A)^{\frac{1-\rho}{\rho}} Y^{1+\rho} = -\frac{1}{\rho}(\gamma A)^{\frac{1-\rho}{\rho}+\frac{\rho}{\rho}} Y^{1+\rho}$$

$$\frac{\partial Y}{\partial Q} = -\frac{1}{\rho}(\gamma A)^{\frac{1}{\rho}} Y^{1+\rho}$$

$$\frac{\partial Q}{\partial R} = \delta \frac{\rho}{\rho_1} \frac{R^{\rho/\rho_1}}{R} \tag{31}$$

$$\frac{\partial R}{\partial K} = -\delta_1 \rho_1 \frac{K^{-\rho_1}}{K}$$

We need to express Q in terms of Y:

$$Q = \frac{Y^{-\rho}}{\gamma A}$$

$$Q^{\frac{-1}{\rho}} = \left(\frac{Y^{-\rho}}{\gamma A}\right)^{\frac{-1}{\rho}} = \left(\frac{1}{\gamma A}\right)^{\frac{-1}{\rho}} Y$$

$$\frac{Q^{\frac{-1}{\rho}}}{Q} = \frac{\left(\frac{1}{\gamma A}\right)^{\frac{-1}{\rho}} Y}{\frac{Y^{-\rho}}{\gamma A}} = \left(\frac{1}{\gamma A}\right)^{\frac{-1}{\rho}} \gamma A Y^{1+\rho} = \left(\frac{\gamma A}{1}\right)^{\frac{1}{\rho}} \gamma A Y^{1+\rho} \tag{32}$$

$$\frac{Q^{\frac{-1}{\rho}}}{Q} = (\gamma A)^{\frac{1-\rho}{\rho}} Y^{1+\rho}$$

So the expression (30) becomes:

$$\frac{\partial f(K,L,\tau F)}{\partial K} = \left[-\frac{1}{\rho}(\gamma A)^{\frac{1}{\rho}} Y^{1+\rho}\right]\left[\delta \frac{\rho}{\rho_1}\frac{R^{\rho/\rho_1}}{R}\right]\left[-\rho_1\delta_1 \frac{K^{-\rho_1}}{K}\right]$$

$$\frac{\partial f(K,L,\tau F)}{\partial K} = \frac{1}{\rho}(\gamma A)^{\frac{1}{\rho}} \delta\rho_1\delta_1 \frac{\rho}{\rho_1}\left[Y^{1+\rho}\right] R^{\rho/\rho_1 - \frac{\rho_1}{\rho_1}} K^{-\rho_1-1} \tag{33}$$

$$\frac{\partial f(K,L,\tau F)}{\partial K} = (\gamma A)^{\frac{1}{\rho}} \delta\delta_1 R^{\frac{\rho-\rho_1}{\rho_1}} K^{-\rho_1-1} Y^{1+\rho}$$

We know the first-order condition on capital is

$$\frac{\partial f(K,L,\tau F)}{\partial K} = \frac{p_K}{c} \tag{34}$$

Therefore, from (33)we have

$$\frac{p_K}{c} = (\gamma A)^{\frac{1}{\rho}} \delta\delta_1 R^{\frac{\rho-\rho_1}{\rho_1}} K^{-\rho_1-1} Y^{1+\rho}$$
$$\frac{p_K}{c} = (\gamma A)^{-\rho} \delta\delta_1 R^{\frac{\rho-\rho_1}{\rho_1}} \frac{Y^{\rho}}{K^{\rho_1}} \frac{Y}{K} \tag{35}$$

We can solve this for Y in terms of K:

$$\frac{p_K}{c} = (\gamma A)^{-\rho} \delta\delta_1 R^{\frac{\rho-\rho_1}{\rho_1}} \frac{Y^{\rho+1}}{K^{\rho_1}} \frac{1}{K}$$
$$\Rightarrow Y^{\rho+1} = \frac{p_K}{c} \frac{1}{(\gamma A)^{-\rho} \delta\delta_1 R^{\frac{\rho-\rho_1}{\rho_1}}} K^{\rho_1} K \tag{36}$$
$$\Rightarrow Y = \left(\frac{p_K}{c} \frac{1}{(\gamma A)^{-\rho} \delta\delta_1 R^{\frac{\rho-\rho_1}{\rho_1}}} K^{\rho_1} K \right)^{\frac{1}{\rho+1}}$$

We can see that the first-order condition will be a complex function of K. However, we can also see that none of the terms of (36) involve τ . K does not explicitly depend on τ . Therefore the partial derivative for the third term will be zero.

When this is used to formulate the third equation forcing the capital first-order condition to be met, it will look as follows.

$$\psi_3 = Y - (\gamma A)^{-\rho} \delta\delta_1 R^{\frac{\rho-\rho_1}{\rho_1}} \frac{Y^{\rho}}{K^{\rho_1}} \frac{Y}{K} = 0 \tag{37}$$

And, from the argument above, we will have that

$$\frac{\partial \psi_3}{\partial \tau} = 0 \tag{38}$$

C.1.6 Summary to this Point

We have calculated the Jacobian matrix (but have not yet inverted it for equation (7)). We have also calculated the vector of partials, so we have

The Jacobian is

$$J = \begin{pmatrix} 1 & \frac{p_F}{c} & \frac{p_K}{c} \\ 1 & -\frac{p_F}{cs_F} & 0 \\ 1 & 0 & -\frac{p_K}{cs_K} \end{pmatrix} \tag{39}$$

And the efficiency gain vector of the technology partials is

$$\Psi = \begin{bmatrix} \frac{\partial \Psi_1}{\partial \tau} \\ \frac{\partial \Psi_2}{\partial \tau} \\ \frac{\partial \Psi_3}{\partial \tau} \end{bmatrix} = \begin{bmatrix} -\frac{s_F Y}{\tau} \\ -\frac{\rho}{1+\rho} \frac{p_F}{cs_F} \frac{F}{\tau} \\ 0 \end{bmatrix} \tag{40}$$

Notably, the parameter ρ_1 is absent from the system of equations. In fact, the equations are identical to the equations developed in [ref] for the simpler CES production function: $Y = \left[a\left(K^{\alpha} L^{1-\alpha}\right)^{\rho} + b\left(\tau F\right)^{\rho} \right]^{\frac{1}{\rho}}$.

It seems possible that the Jacobian may be identical for any production function (CRS required, probably). For one thing, it is derived from share equations only (equations (5) and (6)), which are agnostic as to production function form (the energy derivative of equation (4) is highly related to the energy value share). But, unlike the Jacobian, the efficiency gain vector will depend on the functional form.

Nonetheless, the energy efficiency gain vector is the same for the current production function as for the simpler CES form in Saunders (2008).

Therefore, the only real difference between the LT rebound equation in Saunders (2008), and the one that applies here, is the difference in the production function specification in how it treats ρ .

Nonetheless, we take the derivation through from here to get the exact rebound equation given this function's treatment of the ρ and ρ_1 parameters and certain other parameters that differ from that used in the Saunders (2008) formulation.

C.1.7 Inverting the Jacobian Matrix

We need to develop the inverse matrix of the Jacobian J in (39). We do this using Cramer's rule.

Inverting J first requires calculating the determinant of J, here specified as $\Delta = \det(J)$.

This in turn requires specifying "cofactor" matrices in J associated with expansion along one row or column of J. For us, it is convenient to choose the first column of J as the selected basis. Then, the cofactors of J become:

$$
\begin{aligned}
J_{11} &= \begin{vmatrix} -\dfrac{p_F}{cs_F} & 0 \\ 0 & -\dfrac{p_K}{cs_K} \end{vmatrix} \\
J_{21} &= -\begin{vmatrix} \dfrac{p_F}{c} & \dfrac{p_K}{c} \\ 0 & -\dfrac{p_K}{cs_K} \end{vmatrix} \\
J_{31} &= \begin{vmatrix} \dfrac{p_F}{c} & \dfrac{p_K}{c} \\ -\dfrac{p_F}{cs_F} & 0 \end{vmatrix}
\end{aligned}
\tag{41}
$$

These determinants are calculated as

$$
\begin{aligned}
J_{11} &= \frac{p_F}{cs_F}\frac{p_K}{cs_K} \\
J_{21} &= \frac{p_F}{c}\frac{p_K}{cs_K} \\
J_{31} &= \frac{p_F}{cs_F}\frac{p_K}{c}
\end{aligned}
\tag{42}
$$

So the determinant is

$$\begin{aligned}
\Delta &= 1\cdot\frac{p_F}{cs_F}\frac{p_K}{cs_K}+1\cdot\left(\frac{p_F}{c}\frac{p_K}{cs_K}\right)+1\cdot\frac{p_F}{cs_F}\frac{p_K}{c}\\
\Delta &= \frac{p_F}{cs_F}\frac{p_K}{cs_K}+\frac{p_F}{c}\frac{p_K}{cs_K}+\frac{p_F}{cs_F}\frac{p_K}{c}\\
\Delta &= \frac{p_F\,p_K}{c^2}\left(\frac{1}{s_F s_K}+\frac{1}{s_K}+\frac{1}{s_F}\right)\\
\Delta &= \frac{p_F\,p_K}{c^2}\left(\frac{1+s_F+s_K}{s_F s_K}\right)
\end{aligned} \tag{43}$$

Then, the elements of J^{-1} rely on the other cofactors:

$$\begin{aligned}
J_{12} &= -\begin{vmatrix} 1 & 0 \\ 1 & -\frac{p_K}{cs_K} \end{vmatrix} = \frac{p_K}{cs_K}\\
J_{13} &= \begin{vmatrix} 1 & -\frac{p_F}{cs_F} \\ 1 & 0 \end{vmatrix} = \frac{p_F}{cs_F}\\
J_{22} &= \begin{vmatrix} 1 & \frac{p_K}{c} \\ 1 & -\frac{p_K}{cs_K} \end{vmatrix} = -\frac{p_K}{cs_K}-\frac{p_K}{c} = -\frac{p_K}{c}\left(\frac{1}{s_K}+1\right) = -\frac{p_K}{c}\left(\frac{1+s_K}{s_K}\right)\\
J_{23} &= -\begin{vmatrix} 1 & \frac{p_F}{c} \\ 1 & 0 \end{vmatrix} = \frac{p_F}{c}\\
J_{32} &= -\begin{vmatrix} 1 & \frac{p_K}{c} \\ 1 & 0 \end{vmatrix} = \frac{p_K}{c}\\
J_{33} &= \begin{vmatrix} 1 & \frac{p_F}{c} \\ 1 & -\frac{p_F}{cs_F} \end{vmatrix} = -\frac{p_F}{cs_F}-\frac{p_F}{c} = -\frac{p_F}{c}\left(\frac{1}{s_F}+1\right) = -\frac{p_F}{c}\left(\frac{1+s_F}{s_F}\right)
\end{aligned} \tag{44}$$

The inverse of J is then

$$J^{-1} = \frac{1}{\Delta}\begin{pmatrix} J_{11} & J_{21} & J_{31} \\ J_{12} & J_{22} & J_{32} \\ J_{13} & J_{23} & J_{33} \end{pmatrix} \tag{45}$$

So plugging in the values from (42) and (44), the inverse becomes

$$J^{-1} = \frac{1}{\Delta}\begin{pmatrix} \frac{p_F}{cs_F}\frac{p_K}{cs_K} & \frac{p_F}{c}\frac{p_K}{cs_K} & \frac{p_K}{c}\frac{p_F}{cs_F} \\ \frac{p_K}{cs_K} & -\frac{p_K}{c}\left(\frac{1+s_K}{s_K}\right) & \frac{p_K}{c} \\ \frac{p_F}{cs_F} & \frac{p_F}{c} & -\frac{p_F}{c}\left(\frac{1+s_F}{s_F}\right) \end{pmatrix} \tag{46}$$

C.1.8 Solution

The Solution Vector is now:

$$\begin{bmatrix} \frac{\partial Y}{\partial \tau} \\ \frac{\partial F}{\partial \tau} \\ \frac{\partial K}{\partial \tau} \end{bmatrix} = -\frac{1}{\Delta}\begin{bmatrix} \frac{p_F}{cs_F}\frac{p_K}{cs_K} & \frac{p_F}{c}\frac{p_K}{cs_K} & \frac{p_K}{c}\frac{p_F}{cs_F} \\ \frac{p_K}{cs_K} & -\frac{p_K}{c}\left(\frac{1+s_K}{s_K}\right) & \frac{p_K}{c} \\ \frac{p_F}{cs_F} & \frac{p_F}{c} & -\frac{p_F}{c}\left(\frac{1+s_F}{s_F}\right) \end{bmatrix}\begin{bmatrix} -\frac{s_F Y}{\tau} \\ -\frac{\rho}{1+\rho}\frac{p_F}{cs_F}\frac{F}{\tau} \\ 0 \end{bmatrix} \tag{47}$$

Substituting in Δ,

$$\begin{bmatrix} \frac{\partial Y}{\partial \tau} \\ \frac{\partial F}{\partial \tau} \\ \frac{\partial K}{\partial \tau} \end{bmatrix} = -\frac{c^2 s_F s_K}{p_F p_K(1+s_F+s_K)}\begin{bmatrix} \frac{p_F}{cs_F}\frac{p_K}{cs_K} & \frac{p_F}{c}\frac{p_K}{cs_K} & \frac{p_K}{c}\frac{p_F}{cs_F} \\ \frac{p_K}{cs_K} & -\frac{p_K}{c}\left(\frac{1+s_K}{s_K}\right) & \frac{p_K}{c} \\ \frac{p_F}{cs_F} & \frac{p_F}{c} & -\frac{p_F}{c}\left(\frac{1+s_F}{s_F}\right) \end{bmatrix}\begin{bmatrix} -\frac{s_F Y}{\tau} \\ -\frac{\rho}{1+\rho}\frac{p_F}{cs_F}\frac{F}{\tau} \\ 0 \end{bmatrix} \tag{48}$$

For the first equation we need to remove F from the second element of the efficiency vector (but we'll need it in this form later). Noting that $s_F = \frac{p_F}{c}\frac{F}{Y}$ and substituting this into the second element of the efficiency gain vector yields

$$-\frac{\rho}{1+\rho}\frac{p_F}{cs_F}\frac{F}{\tau} = -\frac{\rho}{1+\rho}\frac{Y}{F}\frac{F}{\tau} = -\frac{\rho}{1+\rho}\frac{Y}{\tau} \tag{49}$$

So the first equation becomes

$$\frac{\partial Y}{\partial \tau} = -\frac{c^2 s_F s_K}{p_F p_K(1 + s_F + s_K)}\left(-\frac{p_F}{cs_F}\frac{p_K}{cs_K}\frac{s_F Y}{\tau} - \frac{p_F}{c}\frac{p_K}{cs_K}\frac{\rho}{1+\rho}\frac{Y}{\tau}\right)$$

$$\Rightarrow \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} = -\frac{c^2 s_F s_K}{p_F p_K(1 + s_F + s_K)}\left(-\frac{p_F}{cs_F}\frac{p_K s_F}{cs_K} - \frac{p_F}{c}\frac{p_K}{cs_K}\frac{\rho}{1+\rho}\right)$$

$$\Rightarrow \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} = \frac{c^2 s_F s_K}{(1 + s_F + s_K)}\left(\frac{1}{cs_F}\frac{s_F}{cs_K} + \frac{1}{c}\frac{1}{cs_K}\frac{\rho}{1+\rho}\right)$$

$$\Rightarrow \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} = \frac{s_F}{(1 + s_F + s_K)}\left(1 + \frac{\rho}{1+\rho}\right)$$

$$\Rightarrow \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} = \frac{s_F}{(1 + s_F + s_K)}\left(\frac{1+2\rho}{1+\rho}\right) \qquad (50)$$

For the second equation, we need to remove Y from the first element of the efficiency vector. As before, noting that $s_F = \frac{p_F}{c}\frac{F}{Y}$ and substituting this into the first element of the efficiency gain vector yields

$$-\frac{s_F Y}{\tau} = -\frac{p_F}{c}\frac{F}{Y}\frac{Y}{\tau} = -\frac{p_F}{c}\frac{F}{\tau} \qquad (51)$$

So the second equation becomes

$$\frac{\partial F}{\partial \tau} = -\frac{c^2 s_F s_K}{p_F p_K(1 + s_F + s_K)}\left(-\frac{p_K}{cs_K}\frac{p_F}{c}\frac{F}{\tau} + \frac{p_K}{c}\left(\frac{1+s_K}{s_K}\right)\frac{\rho}{1+\rho}\frac{p_F}{cs_F}\frac{F}{\tau}\right)$$

$$\Rightarrow \frac{\tau}{F}\frac{\partial F}{\partial \tau} = -\frac{c^2 s_F s_K}{(1 + s_F + s_K)}\left(-\frac{1}{cs_K}\frac{1}{c} + \frac{1}{c}\left(\frac{1+s_K}{s_K}\right)\frac{\rho}{1+\rho}\frac{1}{cs_F}\right)$$

$$\Rightarrow \frac{\tau}{F}\frac{\partial F}{\partial \tau} = \frac{s_F}{(1 + s_F + s_K)}\left(1 - \left(\frac{1+s_K}{1}\right)\frac{\rho}{1+\rho}\frac{1}{s_F}\right)$$

$$\Rightarrow \frac{\tau}{F}\frac{\partial F}{\partial \tau} = \frac{1}{(1 + s_F + s_K)}\left(\frac{(1+\rho)s_F - \rho(1+s_K)}{(1+\rho)}\right)$$

$$\Rightarrow \frac{\tau}{F}\frac{\partial F}{\partial \tau} = \frac{1}{(1 + s_F + s_K)}\left(\frac{\rho(s_F - s_K - 1) + s_F}{(1+\rho)}\right) \qquad (52)$$

Thus the long-term rebound equation from Equation 52 is:

$$\mathrm{Re} = 1 + \eta_{\tau}^{F} \quad = 1 + \frac{\tau}{F}\frac{\partial F}{\partial \tau} \tag{53}$$

$$= 1 + \frac{1}{(1 + s_F + s_K)}\left(\frac{\rho(s_F - s_K - 1) + s_F}{(1 + \rho)}\right)$$

$$Re = \frac{(1 + s_F + s_K)(1 + \rho) + (\rho(s_F - s_K - 1) + s_F)}{(1 + s_F + s_K)(1 + \rho)} \tag{54}$$

In addition, from (50) and (52) we can state the elasticity components for rebound calculations as follows:

$$\eta_{\tau}^{F_{Output}} = \frac{\tau}{Y}\frac{\partial Y}{\partial \tau} = \frac{s_F}{(1 + s_F + s_K)}\left(\frac{1 + 2\rho}{1 + \rho}\right) \tag{55}$$

$$\eta_{\tau}^{F_{Intensity}} = \frac{\tau}{F}\frac{\partial F}{\partial \tau} - \eta_{\tau}^{F_{Output}}$$

$$\eta_{\tau}^{F_{Intensity}} = \frac{1}{(1 + s_F + s_K)}\left(\frac{\rho(s_F - s_K - 1) + s_F}{(1 + \rho)}\right)$$

$$- \frac{s_F}{(1 + s_F + s_K)}\left(\frac{1 + 2\rho}{1 + \rho}\right)$$

$$\eta_{\tau}^{F_{Intensity}} = \frac{(\rho(s_F - s_K - 1) + s_F) - (s_F)(1 + 2\rho)}{(1 + s_F + s_K)(1 + \rho)} \tag{56}$$

C.2 References

Saunders, H.D., 2008. Fuel conserving (and using) production functions. Energy Economics, 30, pp.2184–2235.