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

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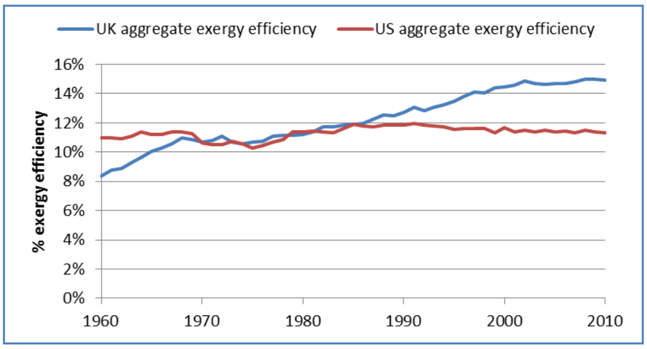
Contents

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 studies use a variety of exergy and useful work calculation methods with sometimes coarse assumptions, which inhibit comparisons. Building on previous work, this paper contributes towards a common useful work accounting framework, by developing more refined methodological techniques for electricity end use and transport exergy efficiencies. Applying these advances to national exergy efficiency analyses for the US and UK for 1960 to 2010 reveals 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" effects, where greater use of lower efficiency processes (e.g. air-conditioning) outweighs device-level efficiency gains. The results demonstrate this is an important area of research, with consequent implications for national energy efficiency policies and our understanding of the mechanisms of economic growth.



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Paul Brockway is on a 3.5 years full-time EPSRC (Engineering and Physical Sciences Research Council) Industrial CASE (Co-operative Awards in Science and Engineering) funded PhD studentship, with the CASE studentship funding co-provided by the EPSRC and industrial supervisor Arup. His research is concerned with exergy, useful work and exergy efficiency, and how these are linked to economic growth, energy use and carbon emissions. Before starting this PhD, Paul worked in consultancy in structural design and corporate sustainability, where he completed many carbon footprint projects in the UK across both public and private sectors.

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1. 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, and prompted seminal research into national energy efficiency (e.g. Carnahan et al., 1975; Reistad, 1975). Other energy issues including industrial efficiency and technology, energy costs, energy transitions, and environmental issues (acid rain and climate change) have joined energy security in subsequent decades to give renewed focus to national energy efficiency research (e.g. American Physical Society, 2008; Belzer, 2013) and multi-lateral cooperation (e.g. the creation of IPEEC - the International Partnership for Energy Efficiency Cooperation in 2009). We distinguish here between energy efficiency, which relates energy inputs and outputs, and energy intensity, which relates energy use to economic output or production (e.g. primary energy / GDP, see Goldemberg & Prado (2011)).

National energy efficiency analysis plays a key role in advancing research into energy issues including future energy projections. Such analysis is either done at the technology/device level or national-scale. Device level energy efficiency studies typically work in 'first law' (of thermodynamics) efficiency definitions using final energy, i.e. energy efficiency, η= useful energy out / energy in. National-scale energy efficiency studies historically used a top-down econometric approach to produce an energy intensity metric (e.g. primary energy consumption / GDP), whilst more recently efforts have gone into developing a bottom-up composite indicator approach (e.g. Ang 2006; International Energy Agency (IEA) 2013a); which combines unit energy consumption across sectors (e.g. transport: litres/km and industry: GJ/tes).

Exergy and useful work analysis extends these approaches beyond final energy to consider work done by end energy uses, whilst linking macro and micro-scale efficiency analysis to give a complete energy picture of an economy, thus providing additional insights to sectoral energy use and drivers of changes alongside traditional methods. Exergy and useful work results have also been used to examine the linkages to economic growth (e.g. Kummel & Strassl 1985; Warr & Ayres 2010).

Exergy, a term introduced by Rant (1956), can be defined as "available energy" (Reistad, 1975) or more formally as "the maximum amount of work that can be done by a subsystem as it approaches thermodynamic equilibrium with its surroundings by a sequence of reversible processes" (Ayres et al. 2003). The second law of thermodynamics means not all input energy is transformed into work, and as such exergy is lost during an energy conversion process. A heat engine provides a classic second law example, where the maximum thermodynamic efficiency is the Carnot temperature ratio ($1-T_2/T_1$), meaning that exergy is lost when a heat engine is used to do work.

With end "useful work" defined as "the minimum exergy input to achieve that task work transfer" (Carnahan et al. 1975a), task level exergy efficiency is defined as follows:

$$\varepsilon_{task} = \frac{Useful\ work}{Primary\ Exergy} = \frac{The\ minimum\ exergy\ input\ to\ achieve\ that\ task\ work\ transfer\ (Bmin)}{Maximum\ amount\ of\ reversible\ work\ done\ as\ system\ reaches\ equlibrium\ (Wmax)} \quad (1)$$

Nine exergy efficiency equations are given in the Supporting Information (SI) for different combinations of end use (work, heat, cooling) and energy source (work, direct combustion and heat), first described by Carnahan et al (1975). Figure 1 shows the case of heat (end use) from direct combustion (source), which helps visualise the difference between first law energy efficiency, η, and second law exergy efficiency, ε. In the example, a gas boiler heats a room to an internal room temperature of 20ºC, with an outdoor temperature of 5ºC. Due to the Carnot temperature ratio penalty, the second law efficiency (calculated in Kelvin temperature values) is given by $\varepsilon = \eta(1 - T_{outside}/T_{room})$ = 4.1%, significantly lower than the 80% first law boiler efficiency (since most of the primary exergy of the energy source does not go into raising the temperature of the room).

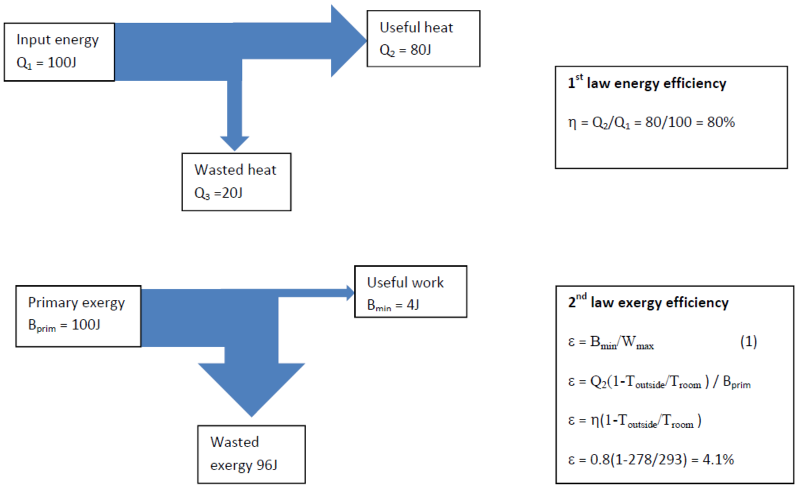


Figure 1: Energy (1st law) versus exergy (2nd law) efficiency for typical domestic boiler heating system

Exergy is therefore lost during each stage of any energy transfer process (e.g. heat, mechanical work or electrical applications) until arriving at its final destination as "useful work". How much exergy remains as useful work depends on the task and the efficiency of the device. Exergy and useful work analysis therefore measures energy quality, in terms of the efficiency with which the exergy content of primary energy sources is converted to useful work, which at an aggregate scale may be seen as a measure of how well an economy converts available energy to valuable uses. This is the focus for this paper, i.e. measuring aggregate exergy efficiency at a national level, which is simply the sum of all task level useful work divided by total input exergy:

$$\varepsilon_{tot} = \frac{\Sigma\, Useful\ work}{\Sigma Primary\ Exergy} \quad (2)$$

Significant work has been done on national exergy analysis, and it remains an active area of research. The first national exergy analysis was by Reistad (1975) who calculated the overall exergy efficiency of the US in 1970 as 22%. Single year exergy analyses followed in other countries including Sweden (Wall, 1987), Japan (Wall, 1990) and the UK (Hammond & Stapleton 2001), plus a global assessment (Nakicenovic et al. 1996). Time-series national exergy analyses are rare due to data availability, but have most notably been undertaken by Ayres and Warr and colleagues who estimated 1900-2000 aggregate efficiencies for the US, UK, Japan and Austria. (e.g. Ayres et al., 2003; Williams et al., 2008; Warr et al., 2010). Most recently, Serrenho et al. (2013a; 2013c) have published work covering Portugal 1859-2009 and EU-15 countries 1960-2010.

At a sub-national level, individual economic sector studies (e.g. Kondo, 2009, Ayres et al., 2011) demonstrate manufacturing processes have higher exergy efficiencies than residential energy consumption, as would be expected due to second law Carnot temperature ratio penalties. Rosen's (2012) analysis of global industry efficiencies obtained a first law energy efficiency of 51% and a second law exergy efficiency of 30%.

We noted earlier how exergy and useful work analysis describe energy quality (i.e. what total exergy losses occur) but as Kanoglu et al note (p.884, 2009) it also "quantifies the locations, types and magnitudes of wastes and losses". These attributes have seen exergy analysis proposed as a candidate to give insights to macro and micro energy efficiency (Cullen et al., 2011); energy transitions (Grubler 2012); economic growth (e.g. Kummel, Strassl, 1985; Warr, Ayres, 2006); energy intensity (Serrenho et al, 2013a), and energy policy (Dincer, 2002).

Despite these advantages, exergy remains the poor relation of energy analysis, with two key issues being methodological consistency and communication of research outputs. This paper seeks to address these issues. Firstly, it builds on recent efforts by Serrenho et al (2013c) towards a common accounting framework using IEA input energy data – which represents the state-of-the-art of comparable worldwide energy data - by developing new methodological techniques for electricity end use and transport (mechanical drive) efficiencies. Secondly, the combined methodology is then used to undertake an exergy and useful work analysis for the US and UK for the period 1960-2010, and the sectoral and aggregate results reviewed to determine if any observable trends or notable features exist. The US and UK are chosen as they have been previously analysed for the period 1900-2000 by Warr et al. (2010), so comparisons of results help to study the effects of the different methodological approaches. Also, since the 1960-2010 timeline aligns to input IEA energy data availability and they are both mature industrialised countries, such comparisons may yield insights into patterns of post-industrial energy use.

Lastly, a note on boundaries. Sciubba (2001) and others take an extended exergy accounting (EEA) approach, where a bio-physical analysis framework includes embedded exergy in all material flows. Krausmann et al. (2008) also consider material flows in their socio-metabolism framework. However, material flows which are not "energy carriers for energy services" (e.g. cotton, iron ores) are very small (~2% for Chen et al. 2006 analysis of China, excluding food/feed for general population), and so are not accounted for in this paper. Therefore we align our work with the energy carriers boundary taken by Ayres et al (2003) and Serrenho et al. (2013b). This means the principle energy flows appropriated for "energy services" are considered, i.e. coal, gas, oil, nuclear, combustible renewables, hydro, other renewables and food (for manual labour).

The paper is structured as follows: Methods are given in section 2, Results are in section 3, and a Discussion is given in section 4. Supporting Information (SI) is referenced at the end, which contains more detail on the mapping categories to useful work, exergy to useful work calculations and post-results analysis.

2. METHODS

The basic approach to useful work accounting follows that of Ayres and Warr (e.g. Warr et al., 2010). Their method is well documented in sections 3 and 4 of their book "The Economic Growth Engine" (Ayres & Warr 2010), and is based on five key steps. In step 1, national-level primary energy data (i.e. oil, coal, gas, nuclear, renewables, food and feed) is collated and then converted back to primary exergy via 'chemical equivalent' conversion factors for fossil fuels (e.g. Szargut et al., 1988) and technology conversion values for renewables. For step 2, the primary exergy values (by energy type) are then mapped to task levels (e.g. cars, trucks, aircraft, rail for the transport sector) within each main useful work category (heat, transport, electricity and muscle work). Step 3 establishes task level conversion factors, based on published values or new estimations. In step 4, the individual task level useful work by energy source is then calculated by multiplying task level values from steps 2 and 3. Finally, step 5 calculates the overall national exergy efficiency value by summing the end useful work values and dividing by total primary exergy inputs (Equation 2).

Serrenho et al. (2013a) 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) 2013b). This paper follows this IEA mapping approach for the US and UK analyses shown in SI. Though the IEA datasets may differ from local country energy data, the differences are typically small (<5%) and as the IEA dataset is based on one methodology, greater benefits come from cross-country comparisons. This paper proposes methodological advances for task level exergy efficiencies within step 3, which may help efforts towards building a common analytical useful work accounting framework. The main features are given below, with a more detailed description in SI.

The first major revision has been to electricity end uses, giving a more granular treatment to exergy efficiencies of electricity end uses. Originally electricity was taken as pure work (Ayres & Warr, 2003), so electrical end uses had exergy efficiencies approximately equal to the electricity generation efficiency (~35%). Later, work on electrical end use efficiency (Ayres et al. 2005) estimated task-level end use efficiencies including motors, heating, cooling and cooking, and these were subsequently incorporated in national exergy analyses (Ayres, Warr, 2010, Serrenho et al., 2013a). We largely follow this approach, with the exception of two important electrical end uses - high temperature heat and air-conditioning, where we include Carnot temperature ratio penalties - an approach also taken by others including Rosen and Buluce (2009) and Reistad (1975). This has the effect of reducing the overall electricity exergy efficiency. Two other electricity revisions are to map IEA electricity consumption in main sectors (e.g. industry, commerce, residential) to main end uses (e.g. heat, electrical appliances, computers, lighting) based on local country end use consumption data (DECC, 2013, US Department of Energy, 2011), and add granularity to residential electricity use (which is a significant and growing proportion of total electricity consumption – see SI) via exergy efficiency calculations for household appliances. This is important, as it shows that different end uses have significantly different electrical exergy efficiencies. Efficiencies for different end uses have changed over time, and the mix of end uses within the economy has changed over time. This is shown for the US in Figure 2, where aggregate electricity exergy efficiency has declined, because of an expansion of low efficiency air conditioning use.:

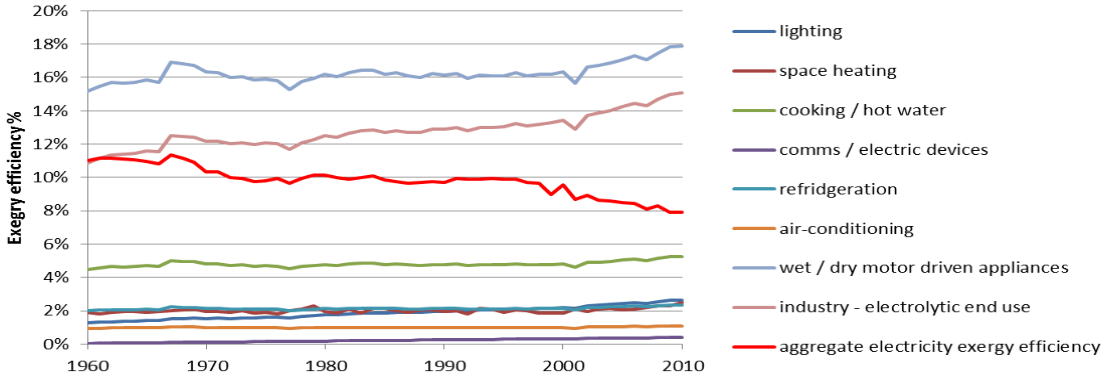


Figure 2: US electrical exergy efficiencies 1960-2010

Secondly, a novel approach is developed for mechanical drive (transport) to improve the estimation of time-series exergy efficiency in this important sector, which uses around 30% of total input primary exergy. Traditional techniques (e.g. Warr et al., 2010, Hammond, Stapleton, 2001) follow Carnahan et al's (1975a) method, where overall exergy efficiency is derived from the thermal engine efficiency (~30%) multiplied by assumed (~30%) post-engine losses (e.g. heat, friction and drag), leaving the estimated exergy efficiency at 8%-10% for a typical car. The key limitation in this method are the loss factors, which firstly ignore all other changes in vehicle design and performance, and secondly have generally taken the same values as the 1975 Carnahan analysis. Ayres et al (2003) acknowledge this limitation, and as a remedy adopted an exergy efficiency equation of $\varepsilon = 0.52 \times \text{mpg}$. This linear relationship weakens above 70mpg, which some cars can now achieve, since exergy efficiency becomes (impossibly) higher than the engine thermal efficiency.

To address this, and in the absence of time-series exergy efficiency estimations, we developed a new calculation method to estimate exergy efficiency based on vehicle fuel economy for each major transport mode (road, rail, air). A detailed investigation was done for US gasoline cars (the dominant US transport mode), using Oak Ridge National Laboratory data for 68 tested vehicles (Thomas 2014). Dynamometer power-train force values therefore enabled useful work (power-train force x distance travelled) and thus exergy efficiency to be calculated. Adding the (Carnahan et al. 1975b) c.1970 value, and an estimated terminal exergy efficiency of 35% for gasoline cars (we assume current best engine thermal efficiency = future limiting exergy efficiency), we derived a best-fit declining exponential function to relate fuel economy to exergy efficiency, as shown in Figure 3 below. This approach was then extended to diesel-road, rail and air sectors using the same principles. The family of declining exponential functions (plotted in SI) then enable exergy efficiencies (and hence end useful work) to be estimated based on 1960-2010 vehicle fuel economy data.

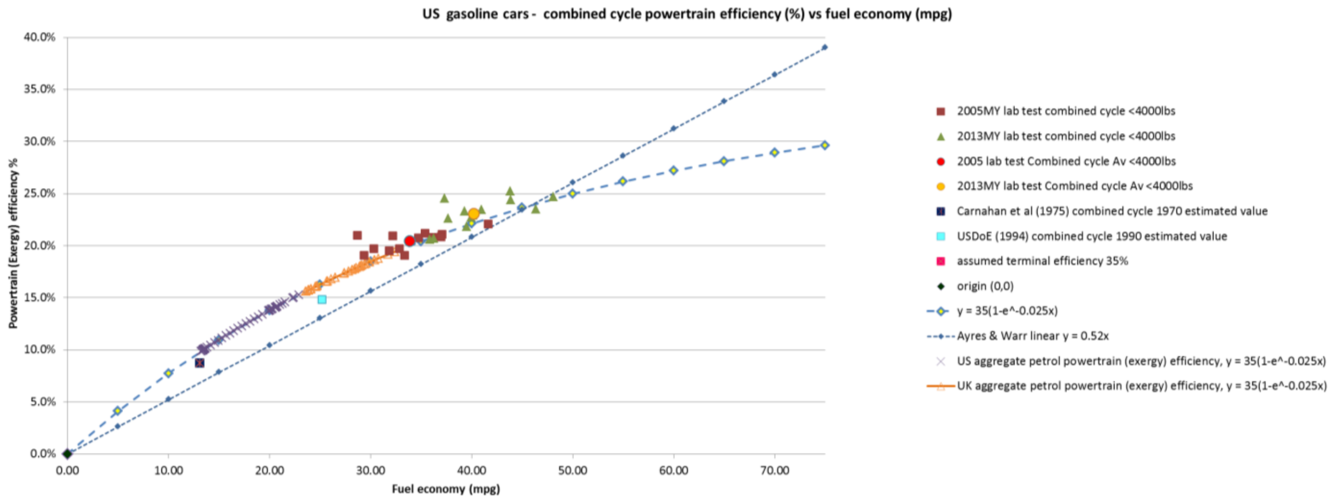


Figure 3: US gasoline cars (mechanical drive) exponential function exergy efficiency plot

The other analysis elements are largely similar to Ayres and Warr (2010) and Serrenho et al (2013a) approaches. Heat follows the Ayres and Warr split into various sub-categories of High Temperature Heat (HTH) at 600'C; Medium Temperature Heat (MTH1) at 100'C and (MTH2) at 200'C, and Low Temperature Heat (LTH) at ~20'C. For HTH, a weighted average of the two largest HTH consuming industrial sector efficiencies (steel and petro-chemicals) is taken. MTH2 is lower temperature (~200'C) industrial heat, which in the absence of further data was taken as the Carnot temperature pro-rata of the HTH efficiency. For LTH and MTH1, the exergy efficiency is the device conversion ratio (70-90%) multiplied by the Carnot temperature ratio. Next, the electrical generation efficiency is calculated based on IEA main producer plant data (GWh produced versus fuel inputs). Last, manual labour takes the same approach as Serrenho et al (2013a) in that it is the amount of manual labour that is of key interest as this is essentially human 'mechanical drive' outputs (UK and US draught animals have negligible useful work contribution post-1960 so are ignored). Thus the additional manual labour calories are carried forward into the exergy and useful work calculations.

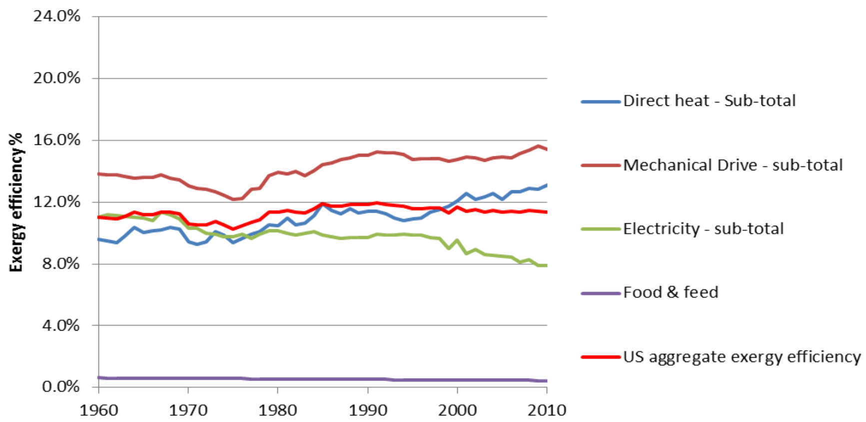
Finally, we also remove non-energy uses of primary exergy from our analysis (e.g. bitumen or petrochemical feedstocks) as others including Ayres and Warr (2010) and Ertesvag (2001) have done. Starting from useful work, and working back to primary exergy inputs (to derive exergy efficiency), the exergy contained in non-energy products is therefore excluded. Serrenho et al. (2013a) also excludes non-energy, but sets out an open question as to whether it should be included. Therefore, as non-energy is a small but growing sector, currently taking 6% of US and 4% and UK primary energy demand, to investigate its effect we have included it in SI, to prompt further discussion on whether exclusion is the appropriate way to address non-energy use.

Incorporating these methodological advances, 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), following the five step approach defined above (and set out in detail in SI). The exergy efficiency is calculated on a primary-to-useful basis (as done also by Warr et al. (2010), Nakicenovic et al. (1996) and Reistad (1975), as opposed to the final-to-useful basis of (Serrenho et al, 2013c). The latter approach

gives higher quoted efficiency values, since typical primary to final conversion efficiencies are around 65-70%.
Finally, the results are then reviewed and discussed. Further analysis is also completed (refer to SI for detailed results) as follows. First, US and UK task-level exergy efficiencies are swapped for cross-country comparison, to examine if their aggregate differences are due to structural or exergy efficiency differences. Second, to investigate economic insights, plots are obtained of useful work intensity (UW/GDP), and contrasted to the traditional Total Primary Energy Supply energy intensity ratio (TPES/GDP).

3. UK AND US EXERGY EFFICIENCY 1960-2010: RESULTS

Figures **Error! Reference source not found.** and 5 show the results of the aggregate exergy efficiency analyses for the US and UK over the period 1960-2010. The aggregate US exergy efficiency has remained stable at around 11%. This stability is due to gains in heat efficiency (9% to 13%) being offset by reductions in electricity end use efficiency (11% to 8%), whilst mechanical drive efficiency remains at around 12%. Food and feed (for muscle work) has a negligible impact on the US (and UK) results due to the very small size of the exergy and useful work contribution versus that from heat, mechanical drive and electricity sectors (see SI).
For the UK, aggregate exergy efficiency has risen from 8% to 14%, with gains across all three main sectors: heat has risen from 8% to 12% (due to significant gains in all task level efficiencies: i.e. LTH, MTH and HTH efficiencies); electricity end use 8% to 14% (due largely 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 (i.e. LTH, MTH, HTH for heat sector) and electricity



generation efficiencies are shown for both the US and UK in SI.

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

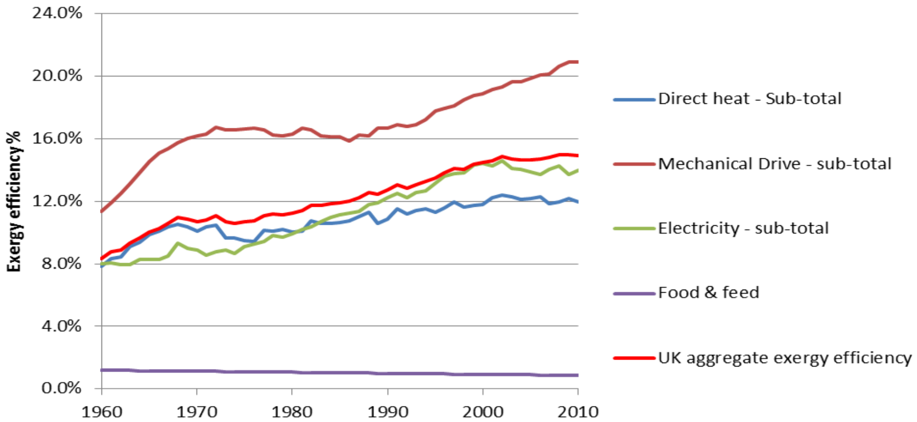


Figure 5: UK exergy efficiency 1960-2010 by end use

By simply swapping US and UK task level efficiencies, the divergence between US and UK aggregate efficiencies can be seen to arise mainly from differences in sectoral efficiencies rather than structural consumption. Error! Reference source not found. shows how US exergy efficiency (with UK task level efficiencies) increases from 10% to 14%, similar to actual UK exergy efficiency. Similarly, Figure 7 shows how UK efficiency (with US task level efficiencies) remains close to actual US exergy efficiency .

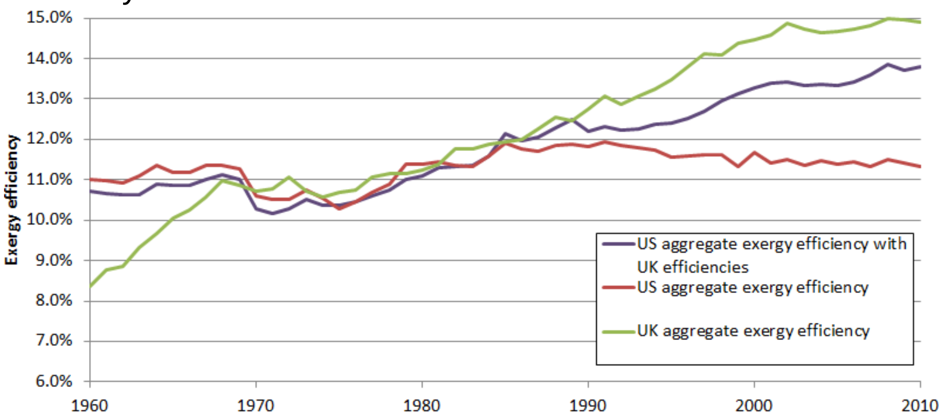


Figure 6: US efficiency with UK task-level exergy efficiencies

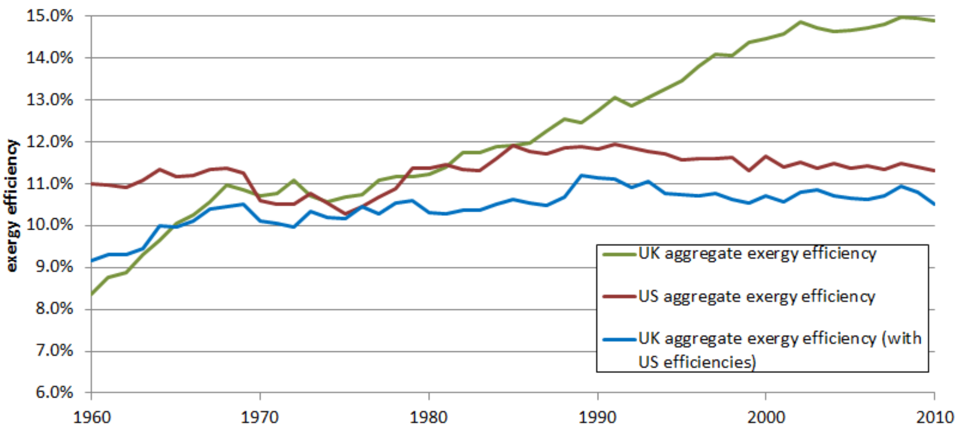


Figure 7: UK efficiency with US task-level exergy efficiencies

Figure 8 shows the Sankey diagram of overall exergy and useful work for the UK. It shows how 86% of the input exergy is lost and only 14% remains as final useful work. Direct heat (~30%); mechanical drive (~20%) and electricity generation (~20%) losses are the largest components of the exergy losses.

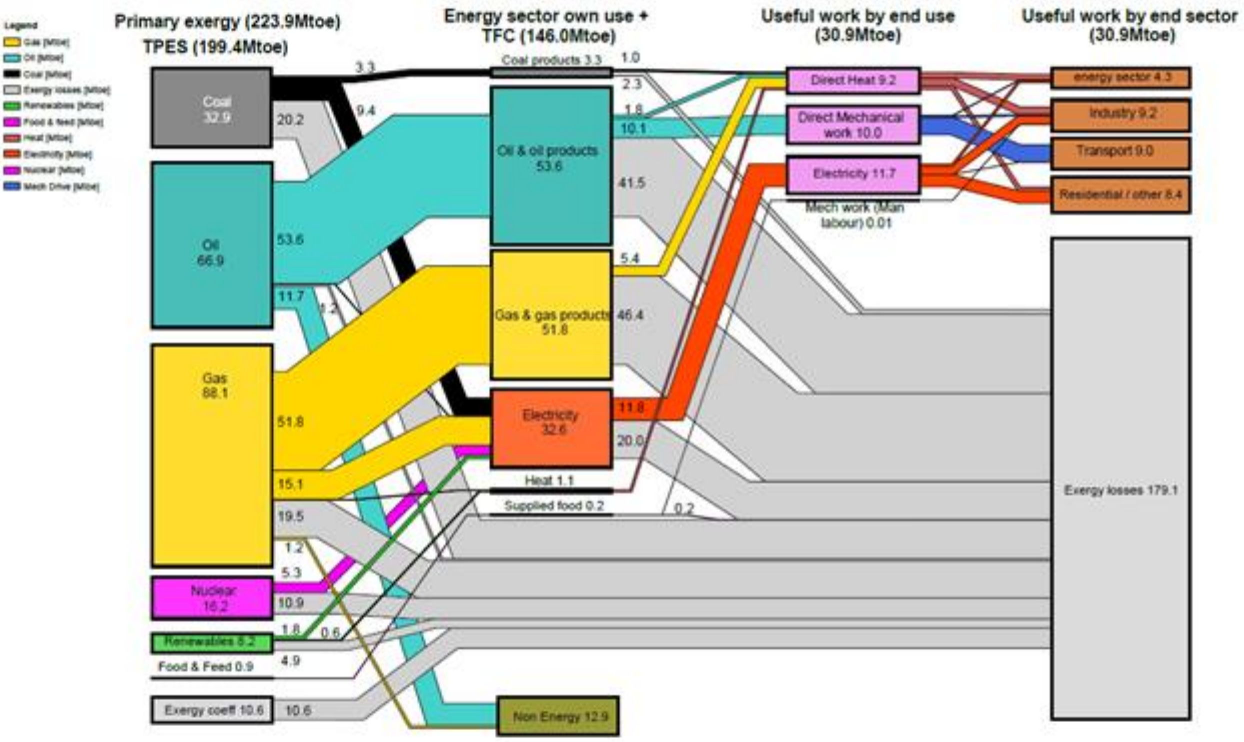
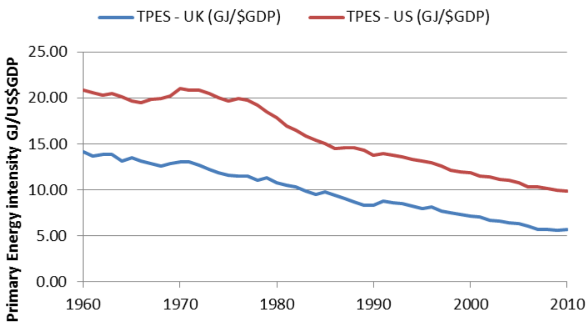


Figure 8: UK exergy Sankey flowchart (2010)

Lastly, 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 **9** and

Figure **10**, with the UW/GDP indicator values for the US and UK becoming increasingly convergent over time.



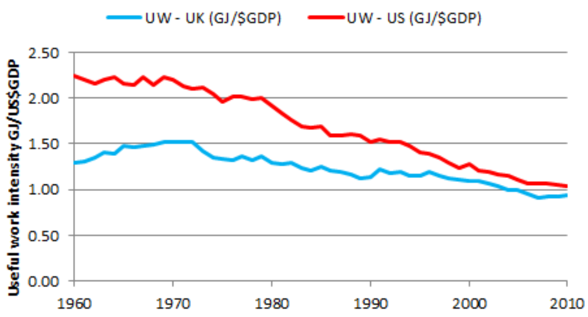


Figure 9: US versus UK useful work intensity (GJ/$GDP)

Figure 10: US versus UK primary energy intensity (GJ/$GDP)

4. UK AND US EXERGY EFFICIENCY 1960-2010 - DISCUSSION

The 50 year stagnation in overall US exergy efficiency is a striking and hitherto unexpected result: our novel analysis suggests 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%. The divergence in US-UK overall exergy efficiencies is because the UK has become much more efficient in all three main useful work categories: heat, electricity and mechanical drive, whereas in the US efficiency made significant gains in only in one category - heat efficiency, which was then offset by a large reduction in electricity efficiency.

This divergence has been revealed due to our methodological changes to electrical end use efficiencies and mechanical drive. First, the added granularity of electricity end use task-level efficiencies has revealed that US electricity aggregate efficiency has decreased from 11.0% in 1960 to 7.9% in 2010. Second, mechanical drive efficiencies using the exponential mpg-exergy efficiency function have not significantly increased in the US, where average road-based fuel economy has remained static since 1980 (Figure 6, American Physical Society, 2008).

The reductions in US electricity efficiency and its impact of stagnating US national exergy efficiency suggests that the 'efficiency dilution' effects described first for Japan by Williams et al. (2008) – where greater use of lower efficiency processes (e.g. air conditioning has risen from 10% to 20% of electricity end use) outweigh device level efficiency gains - are also occurring in the US. The efficiency dilution effects in the UK's electricity sector have not been as pronounced due to the significant rise in electricity generation efficiency (30% in 1960; 43% in 2010), meaning electricity exergy efficiency rose from 8.0% in 1960 to 14.4% in 2000, but this has decreasing slightly since then to 14.0% in 2010 due to reductions in electricity and heat exergy efficiencies, which suggest the UK may be slowing if not peaking in its national efficiency. Comparing our results to earlier studies, Reistad (1975) estimated US exergy efficiency to be 22% in 1970, which is double our result due to Reistad's higher calculated transport and heating efficiencies. Ayres and Warr's (2010) US analysis for 1900-2000 and Laitner's (2013) subsequent 2000-2010 extension estimated overall 1960-2010 US efficiency rose from 7% (1960) to 14% (2010). Whilst heat and transport efficiencies were broadly similar, the main difference arises because we include Carnot temperature ratios in all our electrical end uses which provide heating or cooling, which reduces our overall efficiency. Warr et al (2010) found UK exergy efficiency to rise from 8% to 15% from 1960-2010, which compares well at the aggregate scale to our results, due largely to a much smaller use of electrical heating and cooling in the UK, and hence a smaller difference (than the US) from the inclusion of Carnot temperature ratios.

This paper shows the benefits of using a common methodology such that comparisons can be made. First, cross country swapping of end use exergy efficiencies suggest the US and UK have predominant differences in sectoral efficiencies rather than structural consumption. Second, risks and opportunities can be identified: for example US road transport is a particular sector for potential improvement through fuel economy measures, whilst in the UK gains in UK exergy efficiency may be constrained by a stalling electricity generation factor coupled to any future increase to air-conditioning and other low efficiency electrical end use efficiencies.

Traditional energy-economic analysis uses TPES/GDP as a yardstick of energy intensity. This has several limitations as has been discussed in the literature which "confirm the doubts about both the meaning and usefulness of the indicator itself" (p.465, Fiorito, 2013). Recently (Serrenho et al 2013b; Serrenho et al 2013a) have tested the benefits of using useful work / GDP, as this potentially offers more insights into the links between (end) energy use and economic output, and the approaching convergence of US and UK useful work intensities (UW/GDP) from our paper is an interesting result.

Overall, the results have important implications which are the basis for suggested further work. First, comparability between results was a key feature of this paper, and so further work standardising the IEA-based calculation approach would be useful, including a consistent treatment of renewables, electricity end uses and non-energy. Second, the prevalence of these dilution effects suggest that despite implementing various energy efficiency measures in industry, residential and transport sectors, aggregate exergy efficiency is no longer rising in either US or UK, and so the concepts of exergy efficiency dilution and stagnation need deeper investigation. Are these effects replicated in other countries and does this indicate the UK (due to dilution) is close to a practical maximum for national energy efficiency, or at least has limited options for future efficiency gains? Perhaps high efficiency processes are “offshored” through exergy trade flow, in a similar way to consumption-based emissions (Wiedmann et al. 2013). Dilution may also provide some evidence of energy rebound (e.g. Brookes & Saunders 2000; Sorrell 2009), whilst if exergy efficiency stagnation continues, future growth in useful work would come wholly from primary exergy (energy) supply. Thus both dilution and stagnation effects could have impacts on energy efficiency and energy supply policies. Thirdly, the links between exergy and economic growth are worthy of continued study, not least because stagnation may threaten the engine of economic growth (Ayres & Warr 2010). Fourth 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, and whilst conversely threatening the engine of economic growth.

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. As others (e.g. American Physical Society, 2008) have noted, there are limits to insights that can be gained from a purely first law energy efficiency approach, and as Hammond and Stapleton (2001) suggest exergy and useful work approaches should be seen as complementary to traditional energy analysis techniques.

ASSOCIATED CONTENT

Supporting Information (SI): Additional material, results, and cited literature is in three sections: S1: IEA mapping to useful work categories; S2 Detailed input data; S3 Detailed outputs. This material is available free of charge via the Internet at http://pubs.acs.org.

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