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Analysis

Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth

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ABSTRACT

This paper presents a societal level exergy analysis approach developed to analyse transitions in the way that energy is supplied and contributes to economic growth in the UK, the US, Austria and Japan, throughout the last century. We assess changes in exergy and useful work consumption, energy efficiency and related GDP intensity measures of each economy. The novel data provided elucidate certain characteristics of divergence and commonality in the energy transitions studied. The results indicate that in each country the processes of industrialization, urbanisation and electrification are characterised by a marked increase in exergy and useful work supplies and per capita intensities. There is a common and continuous decrease in the exergy intensity of GDP. Moreover for each country studied the trend of increasing useful work intensity of GDP reversed in the early 1970s coincident with the first oil crisis.

1. Introduction

Fundamental changes in patterns of energy supply and use occurring since the onset of the industrial revolution are commonly referred to as the "energy transition". The energy transition has led to alterations in the structure of the energy supply and has entailed a significant growth in overall energy use. It has involved a shift from a solar based energy regime exploiting products of photosynthesis, wind, and water power, to an increasing reliance on fossil fuels. These shifts are linked to the emergence of new energy conversion systems and changes in the energy service demands of final users (Smil, 1991; Podobnik, 2005). Historically, the energy transition has been accompanied by an increase in primary energy demand and per capita energy use. The energy systems of all four industrialized countries in our study underwent such a transition. Evidence indicates that today's industrializing countries are following a similar path (Gales et al., 2007; Marcotullio and Schulz, 2007), while industrialized nations reconsider the structure of their energy supply systems in light of concerns about energy security and climate change and progress in 'clean' energy and energy efficient technologies. Our work in this paper provides evidence for an additional reason to seek efficiency improvements as a means of stimulating sustainable output growth.

Studies analysing long-term trends in energy use typically focus on the quantities of input categories such as total primary energy supply (TPES), which denotes the volume of primary energy inputs into socioeconomic systems, or final energy consumption, the amount of energy supplied to end users in industry and households (e.g. Bartoletto and Rubio 2008; Warde, 2007; Gales et al., 2007; Kander, 2002; Haberl et al., 2006; Krausmann and Haberl, 2002). Exergy analysis deepens this analysis to enable consideration of the quality of energy inputs as well as the breakdown and efficiency of energy use; both important and dynamic characteristics of evolving socioeconomic systems.

Exergy (or useful energy or available work) denotes the ability of energy to perform work and is formally defined as the maximum amount of work that a subsystem can do on its surroundings as it approaches reversible thermodynamic equilibrium. Exergy provides a measure of energy quality. Exergy is usually quantified and measured in energy units (Joules). Unlike energy, which cannot be consumed (a consequence of the first law of thermodynamics), exergy is consumed and lost during any conversion process (Ayres, 1998). In order to

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provide useful work[1] such as heat, light or mechanical power, one or more conversion processes are required and according to the second law of thermodynamics all energy transformation processes result in exergy losses. The size of these losses depends on the way in which they are used.

Exergy analysis has been used to assess the supply, demand and technology characteristics of regional and national economies but the majority of these studies focussed on one single year. Examples include, for the US (Reistad, 1975), Sweden, Japan and Italy (Wall, 1987, 1990; Wall et al., 1994), Canada (Rosen, 1992) and Turkey (Ertesvag and Mielnik, 2000). Fewer studies have examined the historical evolution of resource exergy supply and utilization. Examples include studies for China covering all major sectors of productive activity over the period 1980 to 2002 (Chen and Chen, 2007a,b,c,d,e) and long-term studies that cover the entire 20th century, for the US (Ayres et al., 2003), Japan (Williams et al., 2008) and the UK (Schandl and Schulz, 2002; Warr et al., 2008).

In previous work some of the authors have argued that exergy analysis provides an approach for the better integration of 'productive energy use' in economic growth theory through inclusion of useful work in the production function having shown that useful work supplied to an economy is 'Granger' causal to output growth (Warr and Ayres, 2010). While other studies have used energy as a factor of production, much of the total consumed available energy (exergy) is actually wasted, and therefore does not contribute to growth. Ayres and Warr (2005) concluded that "useful work" delivered to the economy is a more appropriate factor of production to use in representing physical resource flows, than total primary energy (exergy) inputs.[2] The inclusion of useful work as a factor of production representing the productive component of exergy inputs (productive potential) eliminates much of the unexplained Solow residual by effectively accounting for technological progress in energy related processes. Using this work augmented production function, Warr and Ayres (2006) developed a simple yet robust[3] economic forecasting model taking useful work as a factor of production (named REXS). This model has been shown to be able to reproduce observed economic growth in the US economy for the entire of the 20th century and eliminates the assumption of exogenously driven exponential growth along a so-called "optimal trajectory". Instead, the growth trajectory is dependent on endogenous technological change described in terms of the decreasing exergy intensity of output and increasing efficiency of conversion of fuel inputs (exergy) to primary exergy services ("useful work").

In this paper, we present exergy and useful work data for additional countries. The first national data set for useful work used here was published for the US in 2003 (Ayres et al., 2003). Since then, the approach has been standardised and applied to the United Kingdom (Warr et al., 2008), Japan (Williams et al., 2008; Ayres, 2008) and Austria (Eisenmenger et al., 2009). Despite significant variability in the availability and detail of source data we attempt to analyse each country using a standardised methodology to provide comparable data for the last century (1900–2000). Calibrated studies of this length are rare (and by necessity less detailed than static single year analyses), but necessary to test the long-term stability of identified parameters needed for forecasting. The time period studied covers a critical period of the late industrialization process these now mature industrialized economies underwent. The four national case studies provide a unique and novel database enabling us to investigate the trends and dynamics of energy transition. By including useful work we enhance understanding of the relations between technological progress, energy supply and use, and economic growth.

The cross-country comparison of the historical energy transition presented here concentrates on the development of a number of key characteristics of the socioeconomic energy system. In the remainder of the paper we describe the concepts and the methods used to obtain estimates of exergy inputs, the breakdown of exergy inputs to different types of useful work, the efficiency of exergy to useful work conversion, required to obtain estimate of useful work outputs. We highlight similarities and differences in the trends in relation to the development of population, economic growth and carbon dioxide emissions. The paper ends with a comparative summary of the observed characteristics of the energy transition and draws some conclusions on the decoupling of energy use, carbon emissions and economic growth in consideration of the intensity measures generated.

2. Methods and Data[4]

For each economy, the system studied is limited to inflows of domestically exploited and imported energy resources (raw fuels and energy commodities). The methodology comprises three distinct stages. The first requires compilation of natural resource exergy, the second is allocation of exergy to each category of useful work and the third is the estimation of the useful work provided by each. The source dataset was compiled using national statistics on domestic energy production, imports, and exports (of raw fuels and commercial fuel products), energy loss and use in the energy transformation sector, final energy consumption by industry, transport, commercial and public services, and households.[5] The energy input data includes two resource types: (1) conventional non-renewable fuels (coal and coke, crude oil and petroleum products, and natural gas) and (2) non-conventional and renewable fuels (nuclear, hydropower, biomass, solar, and wind). A complete list of sources is provided in Appendix (A.1) and is available together with the data in the online supplementary information.[6] In the following sections we present each stage of the method and data in detail.

3. Accounting for Natural Resource Exergy Inputs

Historical energy data require conversion into exergy values. There are several kinds of exergies: physical (kinetic), thermal (heat) and chemical exergy (embodied) of which the latter is the most significant; the thermophysical exergies of fuels and materials are not considered. Fossil fuels and products of photosynthesis (biomass) –

[1] Useful work was originally conceptualized in the 18th century in terms of a horse pulling a plough or a pump raising water against the force of gravity. The first steam engines were used for pumping water from mines, an application where horses had previously been used. This enabled a direct comparison to be made. Ever since then power has been measured in terms of horsepower or a metric equivalent. In the course of the past two centuries several other types of work have been identified, including thermal, chemical and electrical work. In physics, *power* is defined as work performed per unit of time. Before the industrial revolution there were only four known sources of mechanical power that were of any economic significance. They were human labour, animal labour, water power and wind power. The advent of steam power in the early 18th century led to the first quantification of power in terms of equivalent 'horsepower', by James Watt. Nowadays, mechanical power is mainly provided by *prime movers*, which are either hydraulic or steam turbines (used to generate electrical power) or internal combustion engines. The three major types of internal combustion engines are spark ignition (gasoline) engines, compression ignition (diesel) engines, and gas turbines.

[2] For an extended discussion on exergy and specifically useful work as the engine of growth see Ayres and Warr, (2009).

[3] The model has a simple single sector structure taking capital, labour and useful work as production inputs and generating a single output, Gross Domestic Product. The model is robust having been calibrated using a full century of data having only two free constant parameters to avoid problems of over-fitting.

[4] Data and source description can be found at http://energyuseandeconomicdevelopment.yolasite.com/.

[5] We do not present the results using a sectoral breakdown, but rather a breakdown according to types of (a) resource exergy input and (b) useful work output.

[6] Data for Austria for the period 1900 to 1920 (before the disintegration of the Austro-Hungarian Empire and the formation of the Republic of Austria) refer to Austria based on its current boundaries. Data for this period have to be considered as estimates with considerable uncertainty.

crops and wood – are the major sources of chemical fuel exergy input to the economy.[7] The chemical exergy of fuels and biomass is calculated as the product of the lower heating value (where possible using time dependent values reported in statistical yearbooks to account for changes in the quality of inputs) and a constant energy–exergy ratio.[8] The latter is defined according to an accepted reference environment (Szargut and Morris, 1985; Szargut, 1989; Szargut et al., 1988).

There are three further differences to conventional energy accounts. Firstly we include, as well as commonly included fuelwood, biomass for the provision of human and animal power (that is, biomass inputs for food supplied to the working population and feed for draft animals), which enables us to reflect on the transition process from the pre-industrial, where fuelwood, food (and feed) biomass and muscle power were the principle sources of energy and useful work. Estimates of biomass exergy required for food are based on an estimate of the daily intake of food per capita. From this point the calculation goes in two directions; (1) to estimate biomass inputs in the form of food (cereals, vegetables and fruit) and feedstock (requirements for animal products, such as milk and meat); and (2) to estimate the useful muscle work supply from the food and feed energy intake. The second modification to 'standard' methods involves estimating the available energy from falling water, solar radiation and wind required for hydroelectric, solar and aeolian provision of electricity from falling water, solar radiation and wind. An estimate of the total exergy input to renewable energy technologies is provided as the product of the reciprocal of the energy capturing device and the measured electrical or heat output. By so doing we factor in the efficiency of the energy conversion devices such as water driven turbines, solar panels, and wind turbines.[9] The third difference with standard energy accounts is the exclusion of non-fuel uses. Non-fuel energy does not 'activate' either capital (or muscle work) and as such is not suitable for inclusion in the growth model that we use. Moreover, it is not feasible to envisage a commensurate thermodynamic measure of the efficiency of use of non-fuel energy.

Fig. 1a–d plots total exergy inputs by source showing the near continuous and dramatic increase in total exergy inputs, albeit interrupted by several disruptions to the global economy. For discussion we focus on three periods defined by distinct growth rates (Table 1). The first period covers the early decades of the 20th century; influenced by major disruptions caused by the two World Wars and the Great Depression. Exergy inputs grew moderately in the US and Japan but fluctuated around a constant level in Austria and the UK, following WW I, which left the US and Japan relatively unaffected. Not so, the Great Depression, which had the effect of reducing exergy consumption in each, but most notably in the US.[10] In turn, World War II had the greatest impact on the energy systems of Austria, Japan and the UK. Each suffered the wholesale destruction of industrial capital and infrastructure. In contrast, as principal supplier of arms to the Allies, enjoying a degree of geographic isolation, the war years boosted the US economy and with it exergy requirements.

The second distinct period begins post-war; exergy inputs grew at unprecedented rates doubling US and UK demands; tripling Austrian demand, but nearly quadrupling Japanese 1970-demand over pre-war levels. This rapid demand growth matches the development of GDP and reflects the dynamic process of industrial development and economic catch-up which characterized the economies of Austria and Japan in the three decades after World War II where the war-damaged factories and infrastructure were rebuilt and modernized (Sandgruber, 1995; Butschek, 1987; Allen, 1981). The end of this period in the early 70 s with the first oil crisis coincides with a change in dynamics between energy and growth. Exergy inputs display a temporary decline but growth in demand slowed over the subsequent period to the present day.

Fig. 2 shows the changing share of exergy inputs by source. By 1900, in the UK and the US, much of the transition from a biomass (and hence solar powered) economy to one powered by fossil fuels, had already occurred. Coal accounted for more than 50% of all exergy inputs in the US and Austria but as much as 90% in the by then highly industrialized UK. However, biomass (for both heat, and human and animal labour) still dominated the supply mix in less developed Japan, accounting for 80% of total exergy inputs. The share of fossil fuels (principally coal) was at that time still comparatively small.

The transition process from biomass to fossil power is observable for both Austria and Japan. And as Fig. 2 shows, by the late 20th century all four economies are characterized by an energy mix typical of industrialized economies. Oil and gas account for more than 50% of inputs, while the share of biomass (mostly for food and animal feed) amounts to roughly 20%. The importance of coal, the major energy source of earlier periods of industrialization, has declined to less than 20% in all countries. Oil's share in the energy mix increased most rapidly post-war with motorization and the growth of individual transport, to account for approximately 30–40% of total exergy supply by 2000. Natural gas provides anywhere between 10 and 20% of total requirements, the remainder being provided by non-conventional sources, primarily hydroelectric power (HEP) or nuclear, depending upon natural resource endowments and political will. While Japan, the UK and the US draw a significant share of their exergy inputs for electricity production from nuclear heat, Austria (and to a lesser extent Japan) has focussed on the exploitation of abundant hydropower resources for 45% of total exergy input for electricity production.

During the 20th century, all four countries completed the energy regime transition (Krausmann et al., 2008a,b) from biomass to fossil fuels via coal and petroleum, to natural gas and nuclear as main sources for exergy. Overall, exergy inputs per capita grew significantly throughout the 20th century in all four countries (Fig. 3). In particular during the second half of the 20th century, the late-industrializers Austria and Japan caught up with the UK and all three countries finished the 20th century with a remarkably similar level of exergy inputs, at around 200 GJ/cap/yr. The US consistently had the highest exergy inputs per capita throughout the whole century. By the year 2000, exergy inputs in the US economy were twice as high as in the other three economies and had reached over 400 GJ/cap. As we will show in a later section, this may be explained by less efficient energy use in the US, notably in transport and the housing sector, the result of differences in spatial organisation (transport distances), climatic conditions and consumer behaviour (cf. IEA 1997).

4. Allocation of Exergy to Useful Work Categories

The second major task requires allocation of exergy inputs to categories of useful work.[11] Useful work (U) measures energy services such as heat, light or motive power actually available to final users

[7] Most other materials have very little exergy in their original form, but gain exergy from fuels, as occurs in the processes of metal reduction or ammonia synthesis. The available work (exergy) expended increases the kinetic or potential energy of each (sub) system.

[8] Details of the time dependent LHV values and exergy to energy factors used are presented in the supplementary online information. For fuels the LHV differs from the exergy content by a small factor that represents the available work expended in the mixing of the reactants into post-combustion products. For electrical energy, considered as pure work, the exergy–energy ratio is equal to 1 — see later discussion.

[9] For the purposes of the current study we have assumed that the efficiency of conversion from exergy input to electricity is fixed for each non-conventional technology, other than hydro-electric power (HEP), for which we employ time series of Japanese HEP efficiency.

[10] Per capita exergy inputs temporarily slumped by almost 30% from 300 to 220 GJ/cap.

[11] Work increases the kinetic or potential energy of a subsystem (it being understood that the subsystem is contained within a larger system in which energy is always conserved, by definition). Electricity may be regarded as 'pure' useful work because it can be converted into other forms of useful work with very high efficiency, i.e. with very small frictional losses.

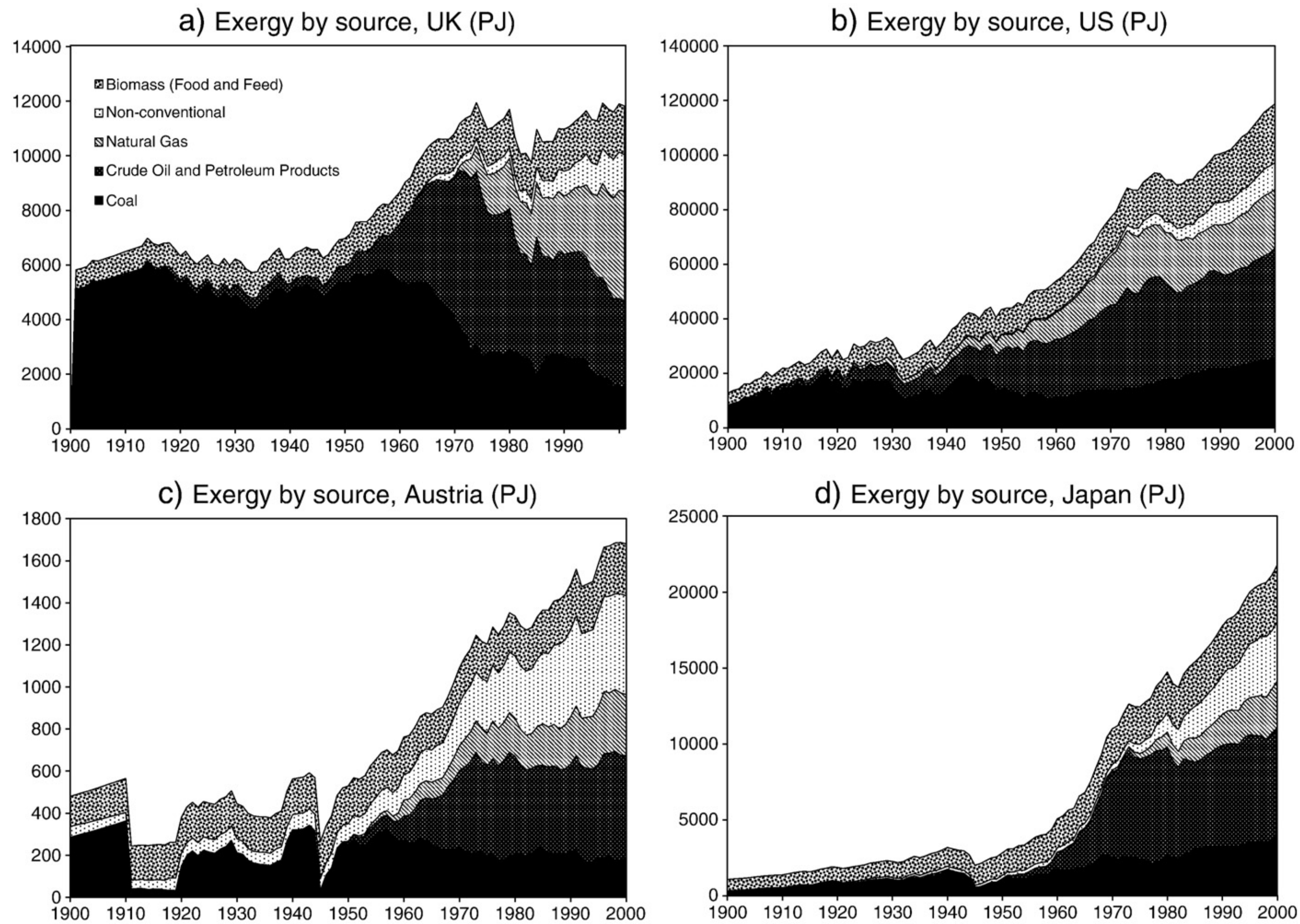

Fig. 1. (a–d). Exergy inputs by source (note: fuelwood is included in biomass grouping).

after the conversion of exergy inputs in a wide variety of technological processes. For the purposes of this study the exergy input of each energy source was divided across the following useful work categories: heat (high [HTH], medium [MTH] and low temperature [LTH]), mechanical drive [MD], electrical power [ELEC], muscle work [MW] and light [LGHT].[12]

In the early years of the 20th century firewood was a primary fuel for cooking in rural areas as well as space heating by means of fireplaces or stoves. Some firewood was used on farms for smoking meats and by small brewers, distillers and bakers. Firewood is now utilized principally for residential housing, as a supplementary fuel for heating, in fireplaces or stoves.[13] Each of these uses is grouped within the category low temperature space heat [LTH]. Available charcoal use in the iron and steel industry was also considered, with exergy flows being allocated to the high temperature heat [HTH] category.

Coal allocated to electric power production was (and is) used for steam turbines. Fuel requirements per kwh are independently published. Coal used in transportation and allocated to Mechanical Drive [MD] category was exclusively for steam locomotives and ships, both phased out by mid-century. High quality (coking) coal, mainly used in the iron and steel industry with minor uses for other metallurgical furnaces, is allocated to the High Temperature Heat [HTH] category. Coal was used to manufacture "synthetic town gas", (by steam-reforming) which was used by commercial and residential buildings for gas–light at the beginning of the century and later for cooking. Coal exergy flows to town gas manufacture are allocated across useful work categories in the same manner as natural gas exergy. Other coal allocated to industry was either for the cement industry or for boilers generating "process steam" for a variety of uses from laundries to chemicals. Process steam can be assumed to have a temperature in the range of 150–300 °C, referred to here as the Mid Temperature Heat [MTH] category. Residential and commercial uses of coal were restricted to heating purposes and were therefore allocated to the Low Temperature Heat [LTH] category.

Unlike coal, crude oil must be refined before use. Exergy losses in the domestic refining process were allocated to the HTH category of useful work. The range and diversity of petroleum products complicate the accounting process. For each country, the labelling, level of aggregation and structure of the historical databases varied. Each petroleum product was allocated to the appropriate exergy service flow on the basis of its inherent properties and dominant uses in each economy. For example, illuminating kerosene could be allocated to lighting [LGHT] and burning

Table 1
Average exergy demand growth rates (%).

Period	UK	US	Austria	Japan
1900–1940	0.2	2.5	0.6	2.7
1940–1970	1.9	3	3.4	4.3
1970–2000	0.3	1.5	1.5	2.3

[12] Details of the allocations are presented in the country-specific notes provided in the supplementary information online.

[13] Use of firewood (and other biomass) for electricity production is increasingly common, however the total energy supply from this source remains negligible compared to the totals.

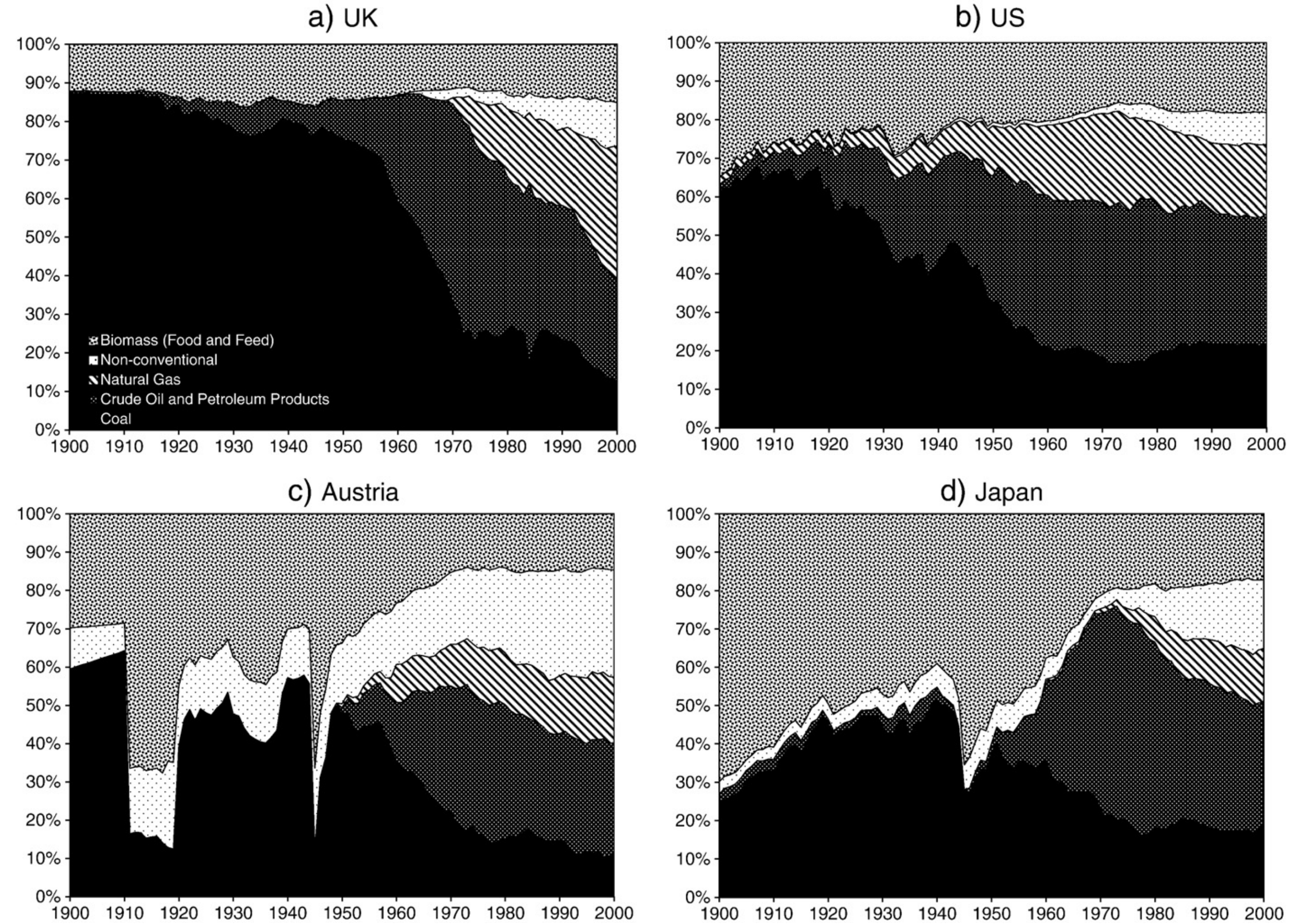

Fig. 2. (a–d). Exergy inputs as share of total by type.

oil kerosene to low temperature heating [LTH] while aviation kerosene, similarly gasoline, diesel and refinery own use for steam driven mechanical drive could all be allocated to the Mechanical Drive [MD] category. Furnace oil (also referred to as heavy oil or residual fuel) is used primarily as a fuel for boilers, furnaces and for heating (as well as for bunkering and as a feedstock in fertiliser plants), but increasingly for electric power generation. Where statistics indicate the quantity flowing to the latter [ELEC] the remainder was allocated to the Low Temperature Heat [LTH] category. Similarly statistics describing gas consumption are broken down by sector and were allocated accordingly: industrial uses of gas were allocated to HTH direct firing; residential and commercial to LTH space heating; power generation to ELEC; and minimal transport uses to the MD category.

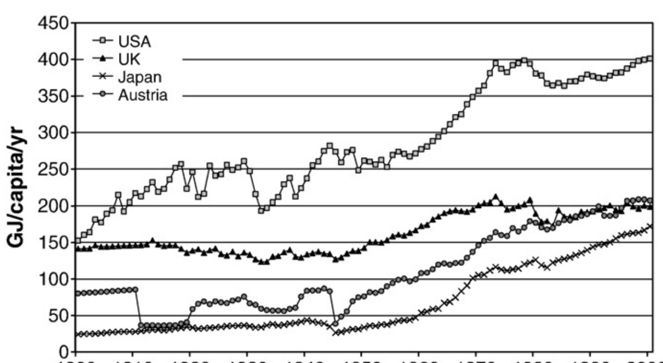

Fig. 3. Exergy inputs per capita (GJ/cap/yr).

The final task requires allocation of electricity flows. Electric power is used for several purposes, of which the most important is for electric motors (including refrigeration and air-conditioning), followed by lighting, electric furnaces (for metallurgical purposes and making carbides), electrolysis (aluminium, chlorine), electric water heating, electric space heating, electric stoves and microwave ovens for cooking and electronics and telecommunication.

Fig. 4 plots the exergy allocation to different types of useful work, revealing how changes in the structure of energy supply were accompanied by changes to the way in which energy is used. For the catch-up countries (Austria and Japan) we observe the declining importance of muscle work and the growing prevalence of energy activated capital. This trend is also observable for the US, albeit to a lesser extent. For the UK, however, by 1900, the substitution process was to all intents complete; the (biomass) exergy required to power human (and draft animal) labour remains a constant fraction throughout the century. Indeed, the UK can be seen as a precursor. Observable trends in the UK are repeated, with a delay first in the US, then Austria and finally Japan. Perhaps the most revealing indication of this is the 'growth' and 'decline' of exergy uses for high temperature heat [HTH], which relate directly to uses in heavy industry. In the UK the importance of this exergy use shows evidence of continuous decline. However, for the US, Austria and Japan, arguably 'delayed' in the industrialization process relative to the UK, we observe growth

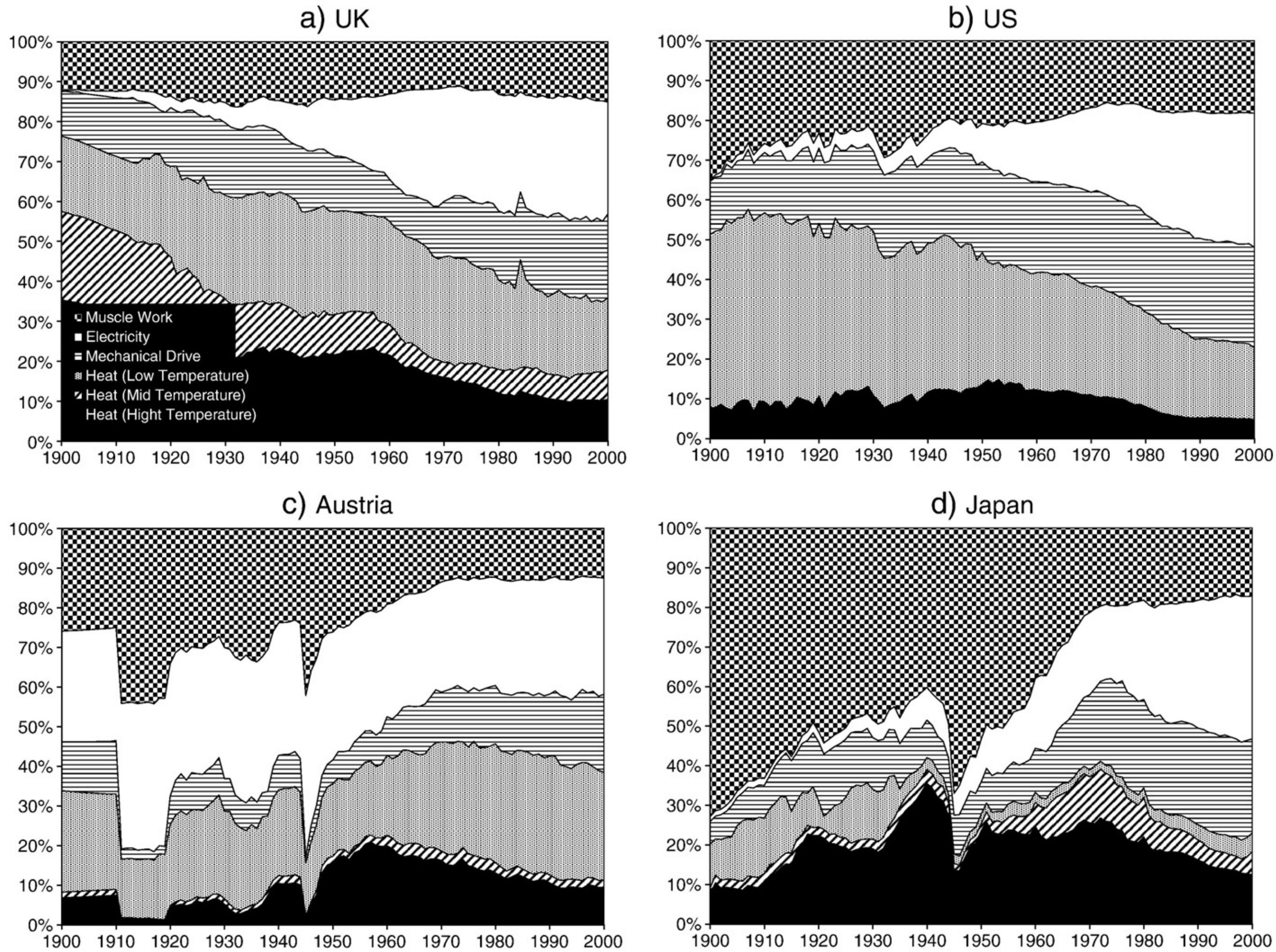

Fig. 4. (a–d). Exergy allocation to useful work categories.

and subsequent decline in HTH uses of exergy as heavy industry waxed then waned as the service sector and a reliance on imports of processed commodities from elsewhere grew in importance.

Other important features to note are the increasing fraction of exergy devoted to (a) mechanical drive and (b) electricity generation. The growing importance of mechanical drive is most notable in Japan where the exergy fraction grew from 6% in 1900 to 20%. By 2000 a similar fraction of total exergy (approx. 20%) is devoted to mechanical drive (transport) in each country. This observation together with the fact that for the UK this figure remained quite constant over the entire century indicates an 'upper limit' to the share of total exergy devoted to surface transport in industrialized economies.[14] Post-war electrification is common to each economy, and by the end of the century electricity generation accounted for between 29 to 36% of all energy requirements.[15] The dominance of electricity as an energy carrier is likely to increase in the future as renewable energy supplies increase, new uses for electricity are invented and as electric power substitutes for existing uses (e.g. as the internal combustion engine is replaced by electric alternatives).

5. Exergy Efficiency and Intensity Measures

To obtain useful work values requires estimation of the efficiency of exergy to useful work conversion for each end-use category over time. Exergy inputs were converted into useful work outputs by applying country-specific technical conversion coefficients that represent the conversion efficiency for each fuel/use combination. The method used depends on the resource flow type and the available data. Wherever possible, the conversion efficiency used reflects changes over time. The aggregate exergy to useful work conversion efficiency is then simply the ratio of useful work outputs to exergy inputs: exergy input, E, useful work output, U and exergy efficiency f, are described by the relation:

$$f = \frac{U}{E} \tag{1}$$

Exergy efficiency changes with (a) improvements in the efficiency of existing technologies and (b) the innovation and adoption of new technologies which either improve the performance of existing process, or (c) cause a shift in the structure of energy service (the type of useful work) demanded. Additional country-specific details on the method of conversion of exergy to useful work are provided in

[14] Exergy requirements for surface transport are strongly linked to the process of urbanisation, which was largely complete in the UK. In contrast air travel is growing with total exergy consumption in 2000 almost double 1990 levels in each country studied. There is little evidence to suggest indicating at what level this growth will stabilise. The UK Department of Transport forecasts that between 2010 and 2030 passenger numbers at UK airports will double again.

[15] Note that electricity is subsequently used to provide heat, light, and mechanical drive, not shown in this figure.

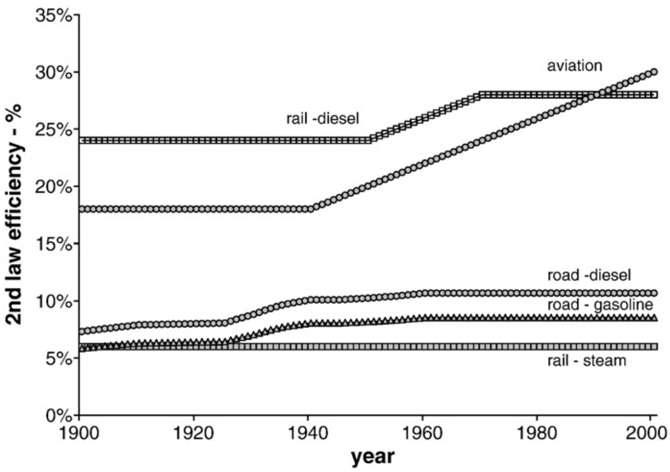

Fig. 5. Estimated efficiencies of transport devices.

previous research (Ayres et al., 2003; Warr et al., 2008; Williams et al., 2008; Ayres, 2008; Eisenmenger et al., 2009).

Fig. 5a–d plots the exergy to useful work conversion efficiency for the principle useful work categories. The exergy efficiency of electricity generation from fossil fuels (Fig. 5a) is obtained by taking the ratio of electricity output at the facility to the exergy content of the fuels. The natural resource exergy input required to generate electricity from renewable and nuclear resources is provided as the product of the reciprocal of the energy capturing device and the measured electrical or heat output (Table 2). By so doing we factor in the efficiency of the energy conversion devices such as water driven turbines, solar panels, wind and steam turbines.[16]

Fig. 5a reveals the S-shaped trajectory of electricity generation efficiency from fossil fuels.[17] The timing and trend of improvements for the UK, US and Austria are similar: significant improvements do not occur until post 1920 with the introduction of centralised large-scale turbines and transmission–distribution infrastructure, replacing smaller reciprocating engines. Major investments in state-of-the-art high efficiency natural gas and oil thermal power stations occurred only after the WWII in Japan. For a period in the late 70s Japan was able to attain very high efficiencies by relying on oil and gas rather than coal.

The mechanical drive category includes all uses of exergy to provide mechanical drive for vehicles, airplanes and static machines in factories. Transport accounts for the greater part of the exergy flows in this grouping. The service, or the minimal exergy requirement for gaining speed and overcoming air resistance, is a function of total mass, total distance, mass per single transport and average speed. The delivered service declines as the mass per voyage and the total distance decrease. It declines as the average voyage speed increases but increases with the total distance travelled. Clearly for shorter voyages any gain in kinetic exergy has to be attributed to a smaller distance. In practice, for long-term historical studies, estimation of the service provided for each mode of transport using the method proposed by Dewulf et al. (2008), while elegant is not feasible. While macro-statistics are available to describe the useful work (electricity) generated by electricity installations, work delivered to move vehicles is not measured empirically at the national scale. Our approach is to build a model of how the net output to the driving mechanism (i.e. wheel, propeller, and turbine) of different transport technologies has evolved over time based on technological considerations (see Fig. 6 and Appendix).

[16] To provide a coherent aggregate measure of exergy efficiency it is necessary to account for the substitution of electricity for direct fuel use. The detailed data required to do this for the entire century for each country is not available for each country, so we use an estimate of the electricity end-use efficiency for the US (Ayres et al., 2005). This value evolved little from 45 to 52% over the entire period.

[17] An evaluation of the efficiency of renewable and nuclear electricity generation is presented in Fig. 7d.

Table 2
Exergy inflow coefficients for renewable and non-conventional energy sources.

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 useful work delivered is estimated as the efficiency times the total exergy input to each mode, provided by national statistics.[18] The aggregate exergy efficiency for the whole group is then simply the ratio of the total useful work delivered to the total exergy consumed by all modes (Fig. 5b). Major differences between countries in the early part of the century reflect the relative importance of rail versus road transport. So in 1900 efficiencies are highest in the United Kingdom where the rail system was heavily developed. Subsequent efficiency improvements reflect (a) improvements in the individual transport technologies, (b) shifts toward more efficient transport modes. The most dramatic improvements occur in two periods, the first from 1950 to 1960 with the introduction of diesel-(electric) rail, the second post 1985 with the increased adoption of diesel ICEs and increased prevalence of air travel.

Process improvements that exploit improvements in heat transfer and utilization may also be classed as thermodynamic efficiency gains. There is little published data describing the breakdown of heat requirements. Energy statistics tend only to distinguish total industrial use from residential/commercial uses. For practical purposes industrial uses can be broken down into high temperature (>600 °C) uses to drive endothermic processes such as metal smelting, casting and forging, cement and brick manufacture, glass-making, ammonia synthesis and petroleum refining. Mid-temperature uses (100–600 °C) include food processing where the heat is mostly delivered to the point of use by steam (typically ~200 °C). The third group is low temperature heat at temperatures <100 °C for space heat and hot water required by the residential and commercial sector.

There are very many high and mid temperature industrial uses of exergy. It is possible in some cases to calculate the minimum theoretical exergy requirements for the process or end-use in question and compare with the actual consumption in current practice. The ratio of theoretical minimum to actual exergy consumption – for an endothermic process – is equal to the 'second law efficiency'. Estimating each is not practicable for the principle reason that data do not exist to describe the input flows of exergy to each for the entire period under consideration. To provide results that are coherent with previous analyses we use the efficiency of steel smelting as a proxy for this category. We define the work done in making one kg of crude steel from ore as the amount of chemical enthalpy change in effecting the reaction $Fe_2O_3 > 3\,Fe + 3/2\,CO_2$, plus the amount of heat input to bring the ore to its melting point (1813K). The total of these two steps is 10.9 MJ/kg (Fruehan et al., 2000).

A substantial portion of the steel production indicated in statistics is made from recycled steel scrap, usually done by re-melting in electric arc furnace (EAF). The minimum work required to re-melt scrap is much less than for reducing ore. Via similar arguments as above, the minimum energy needed to make steel from scrap is 1.3 MJ/kg (Fruehan et al., 2000). While it would be desirable to separate the efficiency trends in both kinds of steel making, in practice

[18] This definition is a limited representation of the actual service delivered, but permits us to use a combination of engineering information, describing the performance of the transport technology and national transport statistics of fuel economy to provide approximate estimates of efficiency for each mode (see Appendix for details).

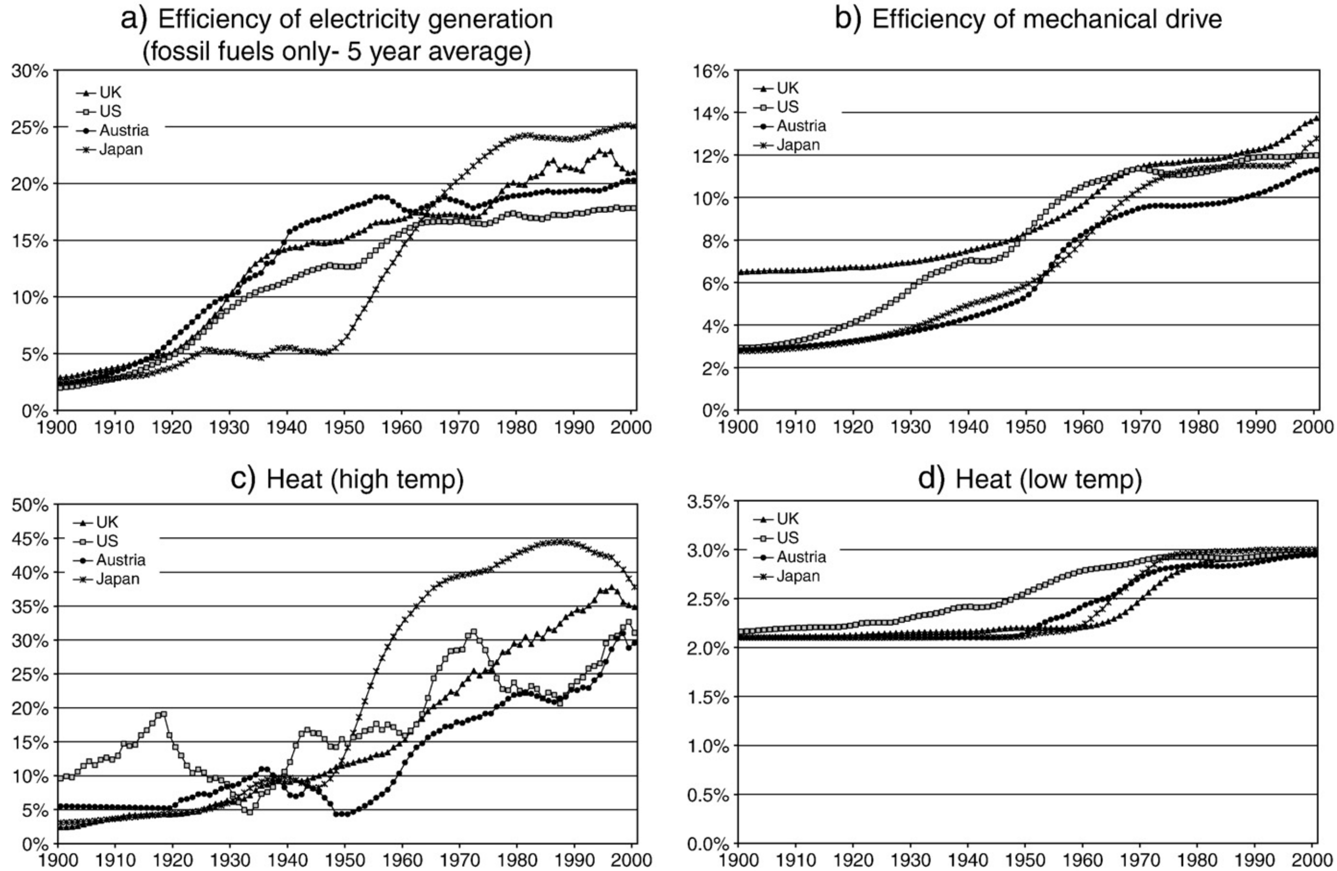

Fig. 6. (a–d). Exergy efficiency of useful work categories.

historical statistics only describe the net consumption of fuels and electricity by the iron/steel sector. We thus take the approach of defining a lower limit that depends on the relative production of steel from ore versus scrap:

$$\textit{Efficiency of steel}-\textit{making} = (1.3\,\textit{EAF share} + 10.9\,(1-\textit{EAF share})). \quad (2)$$

For assessing the actual energy intensity of steel production we apply this framework to estimate trends in the national average efficiency by using statistics describing total crude steel production and energy use in the sector. For these estimations, we separate energy use into consumed fossil fuels and purchased electricity. The exergy content of the latter is estimated by dividing electricity consumed by the national efficiency of electricity generation. The results, plotted in Fig. 5c, show the dramatic post-WWII 'global' increase in steel manufacture efficiency, but perhaps most importantly the considerable advance and relative out-performance of the Japanese steel making industry, made possible by the more widespread effective use of by-product gases and energy-saving facilities such as coke dry quenching (CQD) and top pressure recovery (TRT), (RITE, 2008). Efficiency declines post 1990 reflects changes in the efficiency of electricity generation, the quality of raw materials and pollution control mechanisms.

Residential and commercial heat requirements are largely for space heating. The work performed to heat a room is defined as that required by an ideal Carnot engine to move heat from outside to the inside. The basic equation for a Carnot cycle is

$$W\,/\,Q = \;(1-T_c\,/\,T_h) \quad (3)$$

where W is work performed by the engine (or heat pump), Q is the amount of heat delivered to the room, and T_c and T_h are the temperatures of the ambient and source. For the case of direct heating by combustion of a fuel, Q is the portion of heat of combustion that reaches the room and directly gives the 2nd law efficiency of space heating. This varies according to the indoor and outdoor temperatures. In practice it is difficult to know the actual operating conditions for heating systems, which depend on both on climate and the operating practices in residences that in turn vary as a function of geography, season and social/economic context. Given the lack of data on usage patterns of heating systems, we take a simplified approach and assume average, time-independent values[19] of $T_c = 7$ °C and $T_h = 20$ °C. For direct combustion-based heating (such as a natural gas furnace), the exergy efficiency is

$$\textit{Exergy efficiency}\;(\textit{combustion heater}) = \textit{first law efficiency}^{*}\;(1-T_c\,/\,T_h) \quad (4)$$

where the first law efficiency is the share of heat of combustion actually entering the room. Table 3 lists 1st and 2nd law efficiencies for different heating technologies and Fig. 5d plots the aggregate efficiency ranges from 2% in 1900 to 3% in 2000.

It is worth noting that historical improvements in space heating efficiency arise mainly from better insulation and variable ventilation conditions which are taken into account in our approach. For purposes of second law analysis, the reference case can be defined as a container with perfect insulation (no heat loss through walls or windows) and just enough ventilation to compensate for the build-up of carbon dioxide and water vapour from respiration by occupants. But the calculation of minimum losses versus actual losses from a

[19] These values are those required for the European EN 255 Standard to calculate the Coefficient of Performance (COP) for heat pumps, and reflect the understanding of industry of typical operating conditions.

Table 3
1st and 2nd law efficiencies of space heating technologies ($T_h = 20$ °C, $T_c = 7$ °C).

Technology	1st law efficiency	2nd law efficiency
Hand fired coal fire	45%	2.1%
Wood fire	80%	3.5%
Oil or gas fired furnace	60%–75%	2.6–3.3%
Kerosene/gas stove	100%	4.4%
Electric resistance heater (40% electricity generation efficiency)	100%	4.4%(1.8%)
Heat pump (COP = 3.2, 40% electricity efficiency)	300%	14.2% (5.7%)

realistic house or apartment as a function of occupancy, frequency of coming and going, desired temperature/humidity and local climate conditions (degree days) is extremely difficult in principle and beyond the scope of this present study.

5.1. Resource Specific Exergy Efficiency

Fig. 7a–e plots the efficiency of exergy to useful work conversion for each exergy source (coal, oil, gas, commercial renewables (excluding nuclear) and food and feed biomass). There are distinct country-to-country differences that are defined primarily by the end-use given general similarities in the task dependent efficiencies by country. For example, coal exergy conversion efficiencies in the US, UK and Austria grow linearly throughout the century to converge towards an efficiency of ~30%. The reason is the declining use of coal for space heating and transport and its increasing use for electricity generation (~80% by 2000), the remainder being used for high temperature uses. In Japan, the situation is reversed. When efficiency peaked in Japan electricity uses only accounted for 10% of coal consumption, the remainder being used for more efficient industrial heat.

Country-specific efficiencies for crude oil and petroleum products also vary primarily with differences in the amount used for electricity generation relative to less efficient uses for mechanical drive and space heating, but secondly with country-level differences in the efficiency of transport devices. The observable peak of oil use efficiency in Japan corresponds (~1960–70) to a period when over 25% of all oil consumed was used to generate electricity: space heating uses accounted for less than 5% (US and UK: 10–15%) and transport uses for less than 10–15% (US and UK: 40%–60%). The aggregate declined in Japan post 1980 as car ownership proliferated. For natural gas the aggregate efficiency is again a function of the fraction used for electricity generation, being over 90% in Japan and approximately 40% in the UK, the US and Austria. The particularly low US efficiency reflects the ~20% used for residential space heating–cooling, compared to the UK and Austria (<10%).

Fig. 7d plots the efficiency of non-fossil exergy resources (renewables and nuclear power), revealing the declining aggregate efficiency for those countries adopting nuclear power.[20] The effect is most clearly observable for the UK, where prior to 1962 the dominant renewable energy source was HEP. In nuclear power free Austria, the stable efficiency post 1960 reflects the dominance of HEP and geothermal exergy sources. Finally with (a) increasing average daily food intake, and hence biomass exergy requirements, (b) the slowly declining ratio of hours worked to hours at rest and (c) the near complete substitution of commercial fuel powered machinery for draft animals we observe the declining aggregate efficiency of food and feed biomass (Fig. 7e). Longer working hours and lower food energy intake the efficiency mean that muscle work from Japanese labour is the most efficient.

[20] For which the efficiency of conversion is fixed equal to the efficiency of a typical steam turbine (33%).

5.2. Aggregate Exergy Efficiency

Fig. 8 plots the development of the aggregate exergy conversion efficiency. Efficiencies in 1900 ranged between 3% and 5%. Throughout the 20th century improvements varied by a factor of 3 to 5. By 2000, economy-wide efficiency had increased to 11% in the US, 14% in the UK and 16% in Austria and 18% in Japan. Alarmingly, wasted available energy ubiquitously exceeded 80%. Aggregate efficiencies grew fastest between 1950 and 1970 with annual efficiency gains ranging from 2% to 4% coinciding with the period of most rapid economic growth. In the 1970s, exergy to work conversion efficiency gains lost momentum: annual improvements decreased to 1% in the following decade 1970 to 1980, and have further declined to 0.5% or less since then.

Nevertheless, the UK and Austria demonstrate a continuous improvement in aggregate conversion efficiency throughout the last century, characteristic of incremental improvements to existing infrastructure. The US and Japan reveal a more S-shaped trend: efficiency improvements were slower during the first half of the century and more rapid during post-war industrial reconstruction with the introduction of state-of-the-art technologies, integrated processing and transport facilities, urbanisation and electrification; but post 1970 efficiency gains peaked and either stagnated or slowly declined since. We refer to this as ‘efficiency dilution’ (Williams et al., 2008). The effect is most evident in Japan where opportunities to exploit highly efficient energy supplies such as HEP became exhausted in the mid 60s; but there are other causes not least wealth effects that have led to the increased use of personal transport, comfort heating and air-conditioning, as well as technology asymptotes, health, safety and pollution controls.

5.3. Exergy and Useful Work Intensities

Fig. 10 plots the exergy and useful work intensity of CO_2 and GDP. These indicators describe the energy (or work) input required per unit of GDP (CO_2) produced and as such provide an intensive measure of progress on the economic ‘efficiency’ of energy use (GHG emissions). Fig. 9a,b reveals the relatively constant exergy:CO_2 ratio but a rapidly increasing useful work:CO_2 ratio. The former remains relatively constant once the shift from ‘traditional’ exergy sources is ‘complete’. This is evident for Japan, where we observe the rapid decline in exergy: CO_2 intensity from 1900 to 1915, the period over which the share of biomass exergy inputs declined most rapidly. Only since 1970 is there any evidence that the exergy intensity of CO_2 is improving. In contrast the useful work intensity of CO_2 increases for each country (post 1910) with the increasing aggregate efficiency. Evidently, improving the efficiency of resource use (via improved exergy to useful work conversion efficiency) does not directly address the problem of reducing the carbon intensity of exergy inputs. To achieve an overall reduction in carbon emissions it is necessary to shift to low carbon exergy sources.

The exergy intensity of GDP shows a continuous decrease starting in the 1920s reflecting a relative ‘decoupling’ of economic growth and energy use. The trend for the US is reminiscent of the ‘Kuznets curve’, implying that as industrialization strengthened energy productivity initially declined[21] — or alternatively waste emissions per unit of output increased (Bruyn et al., 1998). No such relationship is clearly observable for the other countries, where there is evidence of a near continuous decline in the energy required per unit of output measured as GDP. Indeed, if we remove biomass inputs from the exergy aggregate the U-shaped trend is no longer visible for the US, implying that the upward trend may reflect the process of infrastructure development.

[21] The decline in productivity with the introduction of new systems of production and consumption is typically attributed to the process of investing in and building necessary capital infrastructure, from which, once installed, the full productivity benefits may be reaped.

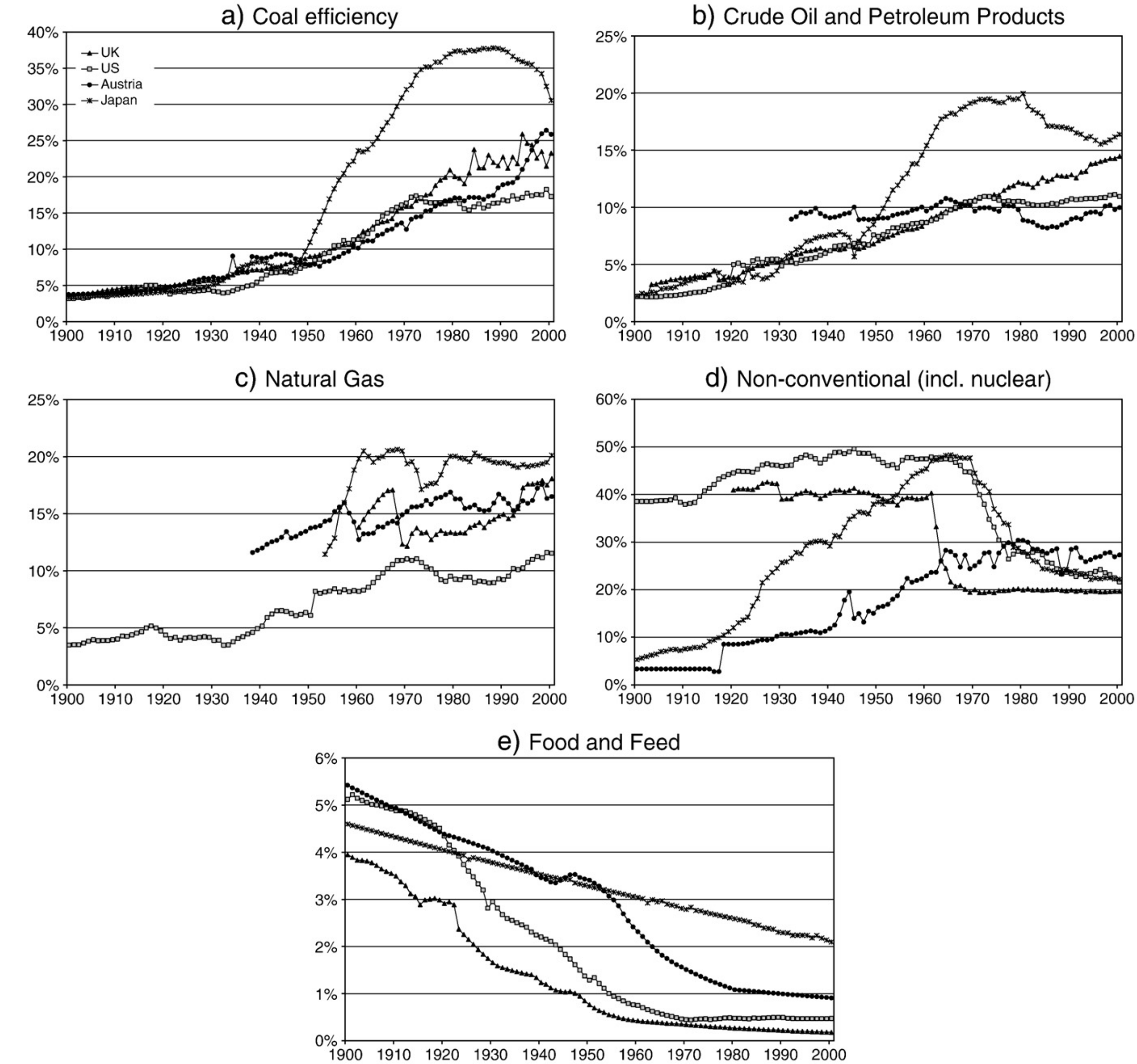

Fig. 7. (a–e). Exergy to useful work efficiency by source.

Throughout the post-war period the exergy intensity of GDP declined at a near constant rate; the fractional rate of exergy intensity decline equalled 1.53% (US), 1.51% (UK), 1% (Austria) and 0.74% (Japan). The decline rate is highest for the countries having the largest exergy:GDP ratio, suggesting that incremental improvements in energy 'productivity' either by the introduction of improved energy conversion processes or quite simply through off-shoring of heavy industry are 'easier' or 'more common' where productivities are comparatively lower, namely in the US and UK. However, despite continual improvements to energy productivity (E:GDP ratio) – evidence of energy decoupling – total exergy consumption actually increased.

Inspection of the useful work intensity of GDP (Fig. 9a exergy and (b) useful work intensities of CO_2 (GJ/ton CO_2).

Fig. 10b contradicts the picture of near 'continuous improvement' in energy productivity provided by the more usual measure and described above. In stark contrast the useful work intensity of GDP grew in each country at an increasing rate until 1970. Supplies of useful work, which inflate with efficiency improvements and increasing demand for exergy, outstripped GDP growth. Effectively year-on-year each unit of useful work delivered to the economy became less 'productive' in generating output. Pre-war the intensities were relatively constant, although remarkably variable by country. The largest productivity losses were post-war and coincided with a convergence of the intensity measures of Japan, Austria and the UK (1970 approx. 2 GJ/\$1000 US). Interestingly we note that by 2000 the useful work intensity of GDP measures are remarkably similar (at 1.5 GJ/\$1000 US), yet the exergy intensity measures vary by a magnitude of 2. This implies that there is a common relationship between useful work consumption and output that is typical of industrialized economies and determined largely by the dominant systems of production and consumption technologies employed. In

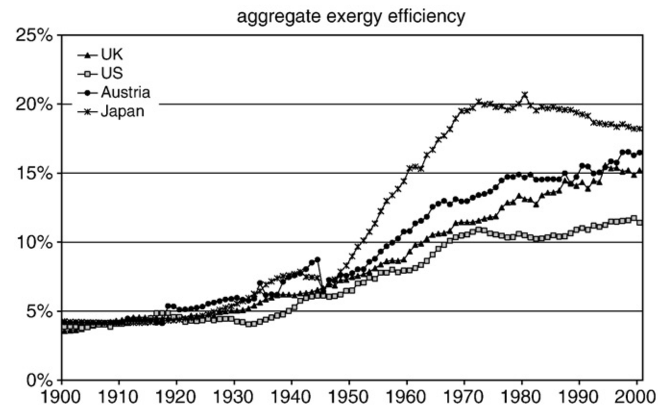

Fig. 8. Aggregate exergy efficiency.

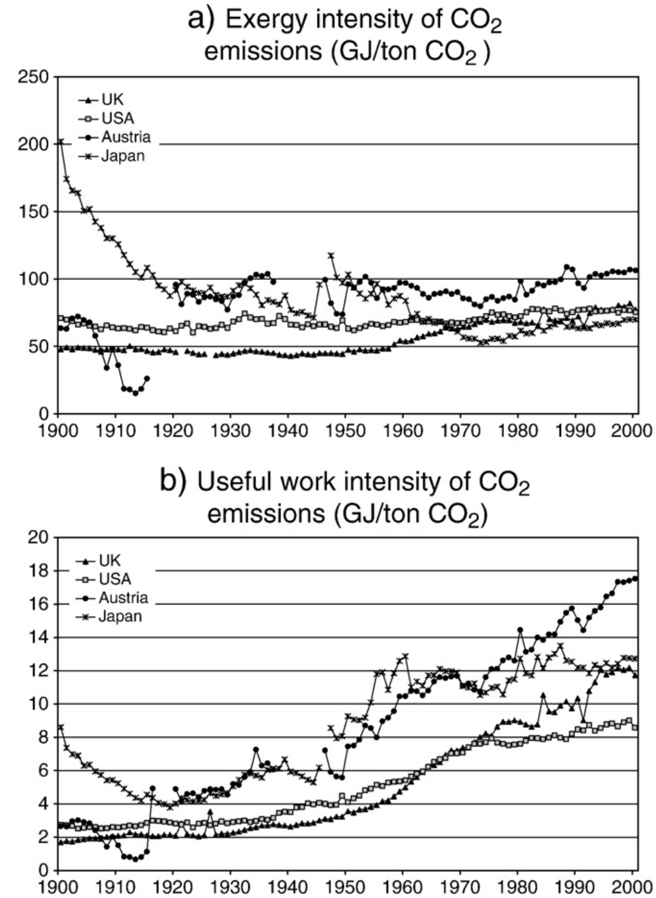

Fig. 9. (a) Exergy and (b) useful work intensities of CO_2 (GJ/ton CO_2).

contrast, the variability of the exergy:GDP ratio reflects the characteristic of the exergy resource supply and associated exergy to useful work efficiency of each country.

A second startling feature of Fig. 9a exergy and (b) useful work intensities of CO_2 (GJ/ton CO_2).

Fig. 10b is the abrupt change of trend that occurs in the late 1960s and early 1970s. The turning point occurred more or less synchronously in all four countries. Useful work intensities peaked in the US in 1972, in the UK in 1971, in Austria in 1969, and in Japan in 1970. Two fundamental and global changes happened around the same time. On one hand, oil price shocks provoked measures to achieve process improvements and behavioural changes in energy consumption (energy conservation and efficiency) which had important effects in subsequent years.[22] On the other, the domestic growth of highly productive but less energy intensive service sectors (such as those reliant on information communication technologies, such as finance) and competition from less developed countries for the products of energy intensive heavy industry have led to off-shoring contributing to a relative decoupling of economic growth and energy use in the long run (Podobnik, 2005). Because GDP grew faster than useful work outputs, declines in useful work intensities were achieved in the period 1970 to 2000 and ranged between 36% in the UK and 18% in Austria. Through the 1980s useful work intensities converged and stabilized at 1.49–1.67 GJ/\$1000 since the late 1980s.

The period of most rapid work 'productivity' decline – as measured by increasing U:GDP – 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'. There are many examples where efficiency gains have enabled new 'growth' and have led to overall resource use growth (Herring, 2004). We argue that energy efficiency improvements drive economic growth through a similar rebound effect. *Ceteris paribus* efficiency improvements provide more useful work per unit of energy purchased and hence drive down the costs of products and services. Lower prices stimulate demand enabling economies of scale and R&D. The resultant product, process and price improvements increase revenues and further stimulate growth (Ayres and Warr, 2008; Warr and Ayres, 2010).

6. Summary and Conclusion

We have presented a methodology for exergy analysis of national economies suitable for the estimation of long run trends in exergy and useful work consumption, and energy efficiency. The methodology is theoretically based on the principles of thermodynamics and specifically consideration of the 2nd law (the 'entropy law') and as such bears many similarities to those used by others for single year, single country assessments cited previously. Our analysis is arguably less exhaustive. This is a necessary compromise to ensure that a consistent approach is applied to source data that differs in detail and quality over time and between countries. Where historical statistics are consistent with our approach the analysis is relatively straightforward. Such is the case for electricity. However, more commonly the essential information (exergy input, useful work allocation or efficiency) was not available and needed to be estimated.[23] The greatest uncertainty involves industrial uses of energy for heat which are multiple and complex. We present a means of assessing the energy efficiency of industrial use with a simple three category division of exergy use into high, medium and low temperature heat. The division is based on reported flows to industry, residential and commercial uses. The efficiency coefficients, required to estimate useful work output were obtained by standardised methods; in the case of high temperature heat, steel manufacture was used as a proxy; for mid and low temperature heat 2nd law efficiencies appropriate to the energy conversion device considered were approximated using the Carnot equation for the relevant temperature differentials.

[22] With current concerns over global climate change and recent energy prices it is hard to argue that either awareness or efforts to increase energy efficiency or conserve energy are any less prevalent in the minds of industry leaders.

[23] For a period of 30 years the Australian Bureau of Agricultural and Resource Economics (ABARE) required large industrial energy consumers to provide yearly information on quantities of energy used by device (i.e. boiler, and direct heat), in much the same way as capital formation data is collected. This practice was discontinued 1980s. We strongly recommend that such an information service be (re)inaugurated more widely.

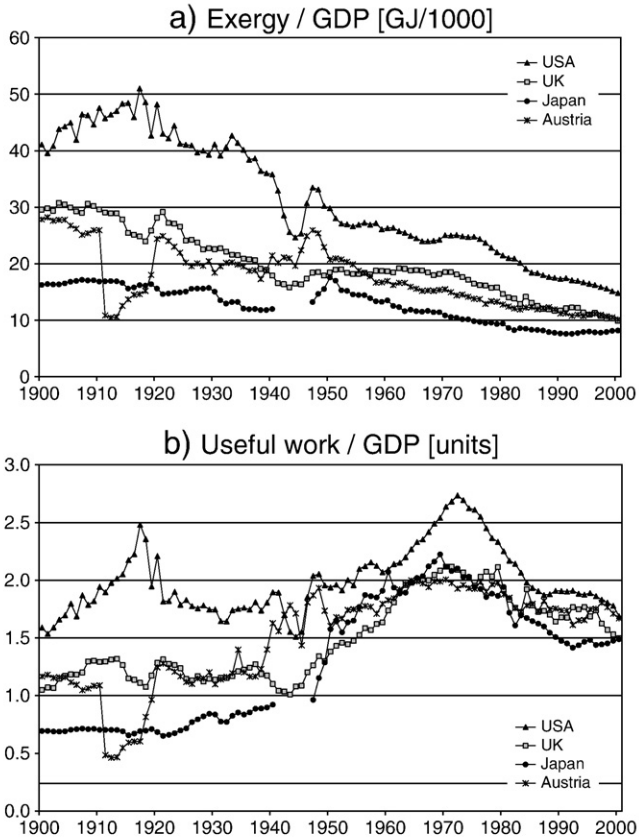

Fig. 10. (a) Exergy and (b) useful work intensity of GDP ($ PPP/cap/yr).

This last point highlights perhaps not only the major strength but also the limitation of the approach. The exergy efficiencies we estimate are specifically task related. Perhaps the clearest example of this is with regard mobility. A 'complete' assessment of the efficiency of the service provided must consider the distance and the speed of the voyage and the load of the vehicle. In practice as we discuss this is not feasible. We are restricted to providing estimates of the task efficiency specific to a given device or technology. By so doing we avoid issues of non-technical tradeoffs. For example, we do not consider the relative efficiency of wearing warm clothing over resistance domestic space heating of a room to a comfortable temperature. We are limited to consideration of the technical aspects of service delivery and do not consider qualitative preferences. The power of the exergy approach is that it enables us to compare general physical performance, by considering the actual device used in relation to the task, "such analysis delineates the limitations and inefficiencies of the devices we now have, and indicates where they should either be improved or replaced or integrated to form new systems which perform joint tasks more efficiently than either could separately accomplish", (AIP, 1975).

The concept of exergy allows us to define a theoretical maximum efficiency (or a minimum exergy requirement) to complete any given task. It follows from the definition of exergy that the actual amount of useful work delivered to all economic activities is less than the theoretical maximum or alternatively that the exergy input exceeds the minimum requirement. The ratio of the actual to the theoretical maximum can be described as the *technical efficiency* (as opposed to economic efficiency) with which the economy converts raw materials into finished materials. This, in turn, can be regarded as a reliable measure of the state of technology of energy conversion devices and systems. Given the prevalence and importance of such systems in industrialized economies, and the rigorous theoretical foundations of the energy-to-work framework[24] we propose in this paper that the change in efficiency, over time is a reasonable proxy measure of technical progress.

The data presented has enabled us to compare the impacts of a century of unparalleled change on energy consumption. The energy transition experienced in each country has dramatically altered the structure of the energy system in each country. Common characteristics of the transition process include a rapid growth in exergy consumption accompanied by a shift from a biomass to a fossil fuel powered system. The former was constrained in size by our ability to capture energy from the sun and convert this into useful forms of energy, notably muscle work. The latter is limited only by our supplies of fossil fuels and the capacity for assimilation of wastes without catastrophic change. Useful work output shows a characteristic shift from muscle work and low temperature heat in the early phases of the energy transition, to a period of high and medium temperature heat dominating the energy system (coal-iron/steel-railroad technology regime), to a dominance of electricity-consuming services (by businesses and households) and petroleum-based transportation services.

The drivers of change have been many and include industrialization, urbanisation and electrification, but specifically growth itself. The data we provide will permit examination of the relationship between these drivers of change and efficiency improvements in the way that energy is used and most importantly economic growth. We have qualitatively described a process whereby efficiency improvements provide more useful work per unit of energy purchased and hence drive down the costs of products and services (*ceteris paribus)*. Subsequent research will seek to quantitatively assess the importance of energy efficiency improvements as a source of growth and the potential for decoupling of energy use from growth in the future.

Acknowledgments

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Appendix A

A.1. Data sources

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[24] The thermodynamic efficiency with which a system (such as a society) or device (for example a boiler) can provide a given service is constrained to lie between zero and one independent of the state of the system. Hence the proposed efficiency measure is unique and remains valid for all societies from the past to the far future. The same cannot be said for measures of progress in education, and particularly to price based measures of progress that have no unique scale or upper or lower bound.

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A.2. Efficiency of transport modes

A.2.1. Road

Our simple model for road transport takes as its starting point the theoretical ideal gas air-cycle Otto engine (Table 4), the single largest energy user in the transportation sector. Energy losses within the engine decline – as the compression ratio r increases, according to the formula,

$$\eta_{\text{road}} = 1 - \left(\frac{1}{r}\right)^{\gamma - 1} \tag{A1}$$

where γ is the adiabatic compressibility ($\gamma = 1.4$) (American Institute of Physics, 1975). Much of the efficiency improvements have been the result of using higher compression ratios. The maximum compression ratio achievable without 'knocking' depends on the fuel octane rating. A small increase in the octane number results in a larger increase in the compression ratio. A compression ratio of 4 was typical of cars during the period 1910 to 1930. Between 1940 and 1980 the average compression ratio for gasoline driven cars increased from 4 to 8.5, with the addition of tetra–ethyl lead to increase the fuels octane rating (Shelton, 1982). Compression ratios have not improved significantly since the discontinuation of this practice. We estimate the net efficiency of diesel engines at full load to be 20 to 30% greater than that of a comparable Otto-cycle engine. Other efficiency losses listed in Table 4, and estimated as constant were accounted for to obtain the net output to the rear wheels (Kummer, 1974).

A.2.2. Rail

The thermal efficiency of steam locomotives remained relatively constant being estimated at 8% in 1950, whereas diesel-electric locomotives reached 35% (Ayres and Scarlott, 1952). For electric locomotives the efficiency of conversion of electric power to rotary motion has always been significantly higher ranging from 50% at the start of the century rising to 90% efficiency in the present day. However, the combined efficiency of the generator-motor is lower and presently does not exceed the efficiency of diesel–electric locomotion. We estimate internal losses due to internal friction, transmission and variable load losses to be a constant 30% for all locomotives (Ayres and Warr, 2003).

Table 4
Example efficiency factors for ICE.

Fuel available work	Efficiency factor	100%
Fuel energy (heat of combustion)	0.96	96%
Ideal gas air-cycle Otto engine ($r = 8$, $\gamma = 1.4$)	0.56	54%
Fuel-air Otto-cycle, stoichiometric	0.75	40%
Burning and cylinder wall losses	0.8	32%
Frictional losses	0.8	26%
Partial load factor	0.75	19%
Accessories	0.55	11%
Transmission	0.75	8%
Net output to rear wheels (efficiency)		8%

A.2.3. Air

For aircraft up to 1945, most engines were piston-type spark ignition IC engines and fuel was high octane (100 plus) gasoline. Engine efficiencies were comparable to those achieved by high compression engines (12:1) under constant load, or approximately 33% before corrections for internal losses (0.8) and variable load penalty (0.75), giving an estimated overall efficiency of 20%. Post WWII gas turbines replaced piston engines. One of the major disadvantages of the gas turbine was its lower efficiency (hence higher fuel usage) when compared to other IC engines. Since the 1950s the thermal efficiency improved (18% for the 1939 Neuchatel gas turbine) to present levels of about 40% for simple cycle operation, and about 55% for combined cycle operation. Assuming a thermal efficiency of 18% in 1940 and 50% in 2000, we apply an internal loss factor of 0.8 and a variable load penalty factor of 0.75, to provide net efficiency estimates of gas turbines as 11% in 1940 and 30% in 2000.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolecon.2010.03.021.

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