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ANALYSIS

Long term trends in resource exergy consumption and useful work supplies in the UK, 1900 to 2000

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ABSTRACT

Our aim is to explain historical economic growth in the UK economy by introducing an empirical measure for useful work derived from natural resource energy inputs into an augmented production function. To do this, we estimate the long-term (1900–2000) trends in resource exergy supply and conversion to useful work in the United Kingdom. The exergy resources considered included domestic consumption of coal, crude oil and petroleum products, natural gas, nuclear and renewable resources (including biomass). All flows of exergy were allocated to an end-use such as providing heat, light, transport, human and animal work and electrical power. For each end-use we estimated a time dependent efficiency of conversion from exergy to useful work. The 3-factor production function (of capital, labour and useful work) is able to reproduce the historic trajectory of economic growth without recourse to any exogenous assumptions of technological progress or total factor productivity. The results indicate that useful work derived from natural resource exergy is an important factor of production.

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1. Introduction

Economic growth theory was formulated in its current production function form by Robert Solow (Solow, 1956, 1957) and Trevor Swan (Swan, 1956). The theory assumes that production of goods and services (in monetary terms) can be expressed as a function of capital and labour. Incomes allocated to factor shares are assumed proportional to their relative productivities, as predicted by the theory of income allocation in a perfectly competitive market economy. However, such a model is able to explain only a small fraction of the observed growth. The major contribution to growth had to be attributed to 'technical progress' — an exogenous multiplier. The failures to integrate the physical components of economic growth, by excluding natural resource consumption from the model, and assumptions of 'abstract' exogenous technical progress have undesirable consequences for any forecasting of future economic growth. Firstly, because the driver of growth is unexplained, future economic growth is therefore assumed to continue at historical rates. Secondly, by ignoring the relationship between technology, natural resource consumption and economic growth, the direct impacts of alternative sustainability scenarios, for example with much lower energy intensity than in the past, cannot be explored.

Ayres (Ayres et al., 2003) suggested a thermodynamic approach to account for the productive inputs or 'useful

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work' provided by natural resources to the production processes. By doing so they reproduced historical trends of economic growth for the US, without recourse to any assumption of exogenous technical progress (Ayres and Warr, 2005), which permits investigation of economic growth trajectories under alternative energy intensity and efficiency scenarios Warr and Ayres (2006). They argue that the most important technical progress driving output growth in the past relates to improvements in the efficiency with which fuels (from natural resources) are converted into useful forms required to power economies. It is not the available work per se that powers economic activity but rather the useful work that it delivers to an end-use, such as heating or providing movement (Ayres and Warr, 2005; Warr and Ayres, 2006). The quantity of useful work that can be obtained from natural resources is determined by the efficiency of the technology used to convert them into useful work.

The energy efficiency characteristics of an economy change as it grows and with the exploitation of new or 'alternative' sources of energy, the introduction of new energy consuming technologies and new patterns of consumer driven demand. Technically, energy is a conserved quantity, which changes only in form as it is used. Exergy is actually what people mean when they refer to energy. Exergy refers to the maximum available work that an energy carrier can provide. While energy is conserved (as a consequence of the first law of thermodynamics), exergy is consumed in the process of conversion to useful work delivered to the point of use (as a consequence of the second law of thermodynamics). The fraction of natural resource exergy that is destroyed (and wasted) depends on the efficiency of the exergy conversion process. Therefore exergy analyses are invaluable to assess issues of 'energy' scarcity (or availability) and 'energy' efficiency.

Exergy accounting and resource-utilisation analysis is most commonly used to investigate the energy efficiency characteristics of engineering systems and processes. As the awareness of potential resource scarcity and the negative impacts of fossil fuel consumption have increased, exergy analysis has been used to investigate the exergy consumption patterns of socio-economic systems at various scales and levels of detail. At the macro-economic scale, providing estimates for a single year, studies have been realised for the US (Reistad, 1975), Sweden (Wall, 1987), Japan (Wall, 1990), Canada (Rosen, 1992), Italy (Wall et al., 1994), Turkey (Ertesvag and Mielnik, 2000), and the UK (Hammond and Stapleton, 2001). Fewer studies have examined the historical evolution of resource exergy supply and utilisation. Examples include studies for China covering the period 1980 to 2002 (Chen and Chen, 2007) and over a much longer period (1900–1998) for the entire US economy (Ayres et al., 2003).

The present work is a geographical extension of this work to the UK, to quantify the historical evolution and structural variation of natural resource exergy supplies, changes in the demand for energy services and efficiency improvements in service provision, namely the delivery of useful work to the point of use. By examining the long-run historical trends we provide an insight into the possible future developments of each dimension of the energy supply and demand structure, and the potential for efficiency improvements.

We also test the hypothesis put forward by Ayres and Warr (2005) for the UK economy over a historical period from 1990 to 2000. We compile a data set for natural resource exergy, allocate exergy inputs to categories of final use and arrive at a measure for useful work by applying conversion efficiencies. We use the time series of useful work we develop as an input to a three-factor production function (of capital, labour ad useful work) to model historical economic growth as measured by GDP.

2. Exergy, efficiency and useful work

The thermodynamic quantity known as exergy is formally defined as the maximum amount of work that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly (Szargut et al., 1988). Fossil fuels, hydropower (falling water), nuclear heat and products of photosynthesis (biomass, i.e. crops and timber) are the major sources of natural resource exergy input to the economy. Most other materials have little exergy in their original form, but gain exergy from fuels. The exergy embodied in a fuel can be equated approximately to the heat of combustion of that fuel. Combustion is a process where a substance reacts with oxygen (oxidizes) rapidly and generates combustion products that subsequently diffuse and thus equilibrate with the atmosphere. Combustion generates heat, which can do work via a Carnot cycle heat engine. Whatever increases the kinetic or potential energy of a subsystem can be called 'work' (it being understood that the subsystem is contained within a larger system in which energy is always conserved, by definition). The theoretical maximum of work that can be done by the heat is the chemical exergy of the fuel.

As a consequence of the second law of thermodynamics (the entropy law), available work (exergy) and actual work performed are not the same. Natural resource exergy is dissipated (used and destroyed) in all transformation processes. As exergy is transformed into less useful forms it is destroyed and is unavailable to perform useful work (entropy is the measure of this unavailability.) For each exergy consuming process it is theoretically possible to estimate a second law efficiency, whose value is determined on a unique scale (bounded by zero and one), defined relative to a minimum necessary exergy requirement to achieve a given task.

$$\xi = \frac{\text{available work of final outputs(useful work)}}{\text{available work of inputs(exergy)}}$$

The efficiency of the transformation depends on the end-use and the technology used to complete a given task (Carnahan and Ford, 1975). In addition to characterizing efficiency trends in individual technologies, it is also possible to combine efficiencies within and across activities to characterize their aggregate efficiency. The power of the exergy-based definition is that it provides a unified framework to combine efficiencies of many different technologies. For example, the aggregate exergy efficiency of a mix of technologies is simply the total work done divided by natural resource exergy input.

3. Analysis

The methodology comprises three distinct stages. The first is the compilation of apparent consumption of natural resource exergy into the domestic economy, the second is allocation of exergy to each category of useful work (final exergy consumption), and the third is the estimation of the useful work provided by each (see Fig. 1).

We consider five forms of useful work, heat, light, mechanical drive, muscle work and electricity. Electricity can be regarded as 'pure' useful work, because it can perform either mechanical or chemical work with very high efficiency, i.e. with very small frictional losses. The two steps from natural resource exergy to useful work supply involve transformation and conversion losses. Transformation losses depend on the efficiency of the energy transformation sector (e.g. the transformation of fossil fuels to electricity or crude oil to products from crude oil). Conversion losses refer to the efficiency of energy use equipment such as furnaces, boilers, internal combustion engines to mention only a few.

4. Apparent consumption of natural resource exergy

We compiled a database of resource inputs including coal, crude oil and petroleum products, natural gas, and renewable resources (including biomass). Our main sources for data were the British Historical Statistics compiled by Mitchell (1988), John Nef's comprehensive work on coal (1932) and the Statistical Abstract for the United Kingdom, in later years Annual Abstracts of Statistics (1870ff) as well as earlier work on the UK social metabolism (Schandl and Schulz, 2002; Krausmann and Schandl, 2006; Schandl and Krausmann, 2007). We calculated the exergy for all resources as a multiplier of heat content (Szargut et al., 1988). For fossil fuels the exergy input is equivalent to the domestic energy supply in exergy units. We do not account for exergy losses incurred abroad, for example in converting crude oil into imported petroleum products, but do consider exergy losses in the domestic refinery process. To arrive at a full picture for energy inputs we added primary electricity inputs from hydroelectric and nuclear. For hydroelectric power generation, the exergy input is an estimate of the available work of water flowing through the turbines. For nuclear power it equals the heat generated and subsequently available for conversion into electricity. In each case an estimate of the exergy input relies on estimates of the efficiency of conversion of available work into electricity (described in more detail later). The estimate of biomass exergy inputs includes fuel wood/charcoal and biomass inputs that went to feed the working human and animal population. We used a simple model to back-calculate the food and feed biomass exergy inputs consumed from estimates of daily energy intake and the efficiency of the food and feed processing systems (Wirsenius, 2000).

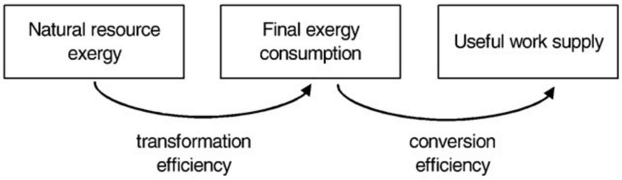

Fig. 1 – The conversion from natural resource exergy to useful work.

Fig. 2a and b show the total exergy inputs (by source) and the share of the total exergy provided by each source. At the start of the 20th century coal provided 91% (7685 PJ) of the total exergy input (8425 PJ), other fossil fuels less than 1% (37 PJ), the remainder being provided by biomass inputs (703 PJ). The United Kingdom was among the first nations to experience industrialisation during the 1800s and a concomitant shift from reliance on biomass to fossil fuel exergy sources, principally coal.[1] Coal was the dominant source of energy throughout the 19th century. Over the course of the 20th century the reliance on coal declined as other energy carriers, first petroleum products and more recently gas then renewable and nuclear exergy sources, were more widely used.

In the post WWII economy (circa 1950) oil exergy inputs increased to 8% (721 PJ), of an increasing total (9206 PJ), substituting for coal (81%, 7437 PJ) in the fuel mix. The most rapid changes in the exergy supply structure occurred in the latter half of the century, with a marked diversification in the fuel supply mix. From 1950 to the early 70s reliance on coal declined as the use of petroleum products increased. The oil crisis of 1973 slowed this substitution trend. At the same time the importance of natural gas exergy inputs grew with the discovery and exploitation of domestic supplies, also nuclear energy supplies increased.

By the end of the century coal accounted for 15% (1775 PJ) of the total exergy input (12,155 PJ). While the total biomass exergy inputs had increased, they still represented approximately the same fraction of the total as they did in 1900 (14%, 1789 PJ). In contrast, oil and gas and renewables (including nuclear) increased their shares to 26% (3179 PJ), 33% (4068 PJ) and 11% (1344 PJ) of the total exergy input respectively.

4.1. *Allocation of primary resource exergy flows to useful work categories*

The second stage of the methodology involves the allocation of flows of natural resource exergy to different categories of 'useful work'. For purposes of empirical estimation, it is helpful to distinguish between five types of useful work which are further subdivided. The first category is electricity which we consider as pure work that can be used for all other purposes. The second category is fuel used to drive prime movers, including all kinds of internal and external combustion engines, from stationary steam turbines to jet engines. The third category is fuel used to generate heat. This grouping is further subdivided according to the temperature of the heat requirement. Direct high-temperature (HT) heat (>600 °C) drives endothermic processes such as carbo-thermic metal smelting, also some endothermic chemical processes like

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[1] Coal was known and used in the UK before 1800, however, the contribution of coal to total energy supply became only relevant around 1850 (see Sieferle et al., 2006; Krausmann et al., 2008).

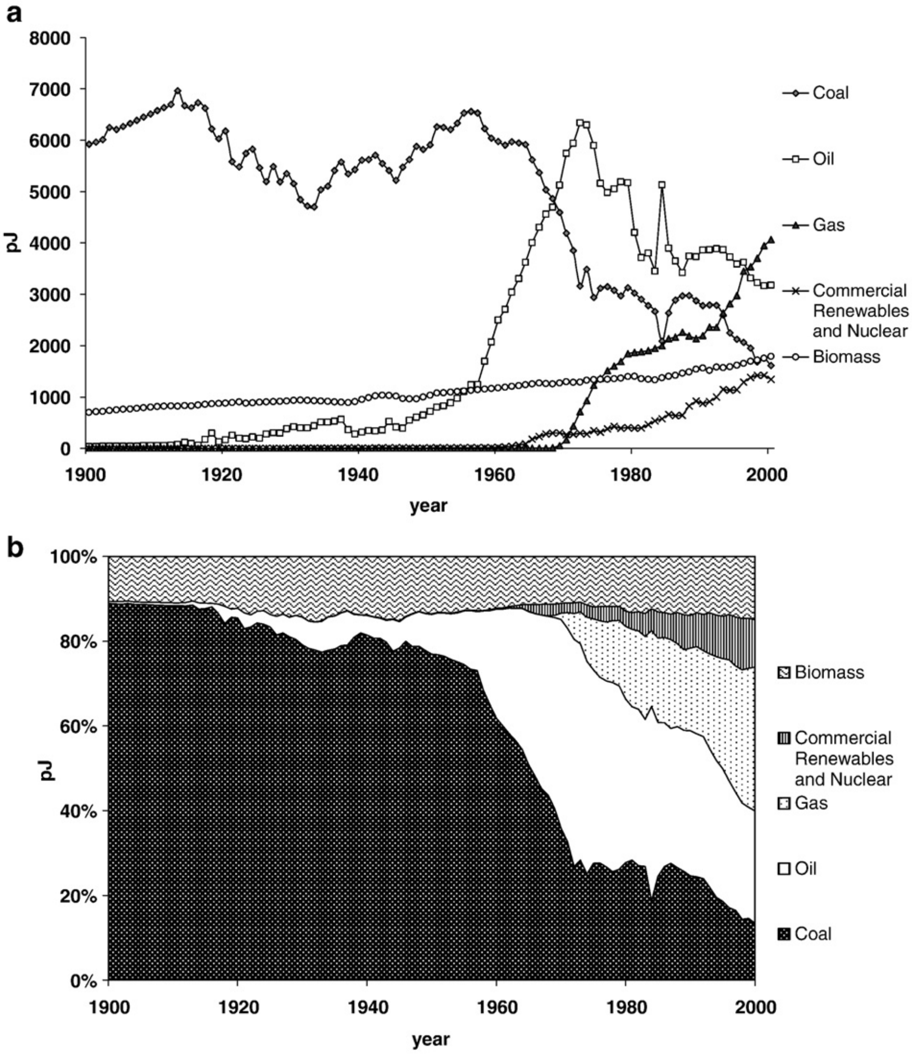

Fig. 2 – a. Natural resource exergy inputs by energy carrier, 1900–2000. b. Natural resource exergy inputs share by energy carrier, 1900–2000.

petroleum refining. Intermediate-temperature (MT) heat (100–600 °C), is used for example to increase the solubility of solids in liquids; liquefaction of viscous solids or liquids delivered to the point of use by steam. Low-temperature (LT) heat (<100 °C), is required primarily for hot water or space heat. The fourth category is energy use for light. The final category includes muscle work provided by draught animals and human workers.[2]

Where available, we have used the breakdown of energy consumption statistics to identify the magnitude of flows to each type of final exergy consumption. Often it is possible to associate a particular product with a final exergy type, for example to allocate aviation fuel to the transport group, or town gas for public lighting. Where information was lacking we have been forced to make certain assumptions based on a sectoral breakdown of energy use. There is very little published data allocating industrial heat requirements (as opposed to primary energy consumption) by temperature. A detailed study for the US grouped half of all US industrial process heat into high-temperature (>600 °C) uses and the other half into the intermediate category (Lovins, 1977). Based on this study, we assume that half of all flows of coal and gas and furnace oil to the industrial sector are used for high-temperature processes, the remainder for medium-temperature processes. We assume that flows to the residential and commercial sector are mainly used to provide low-temperature (space) heat. Of course these are simplifications as some of the flows to industry are clearly used for other purposes such as space heating, mechanical drive or electricity generation. However, we assume that these flows are minor relative to the dominant use in each sector.

Fig. 3a shows the final exergy consumption by useful work type and Fig. 3b the breakdown of final exergy flows to each type of useful work. The dominant trends found include the constant decline of exergy consumption for industrial uses (high and medium temperature heat) as a fraction of the total

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[2] All methodological issues around the allocation of resource exergy use to useful work categories and the application of efficiencies to estimate useful work supply are described in greater detail in Ayres et al. (2003).

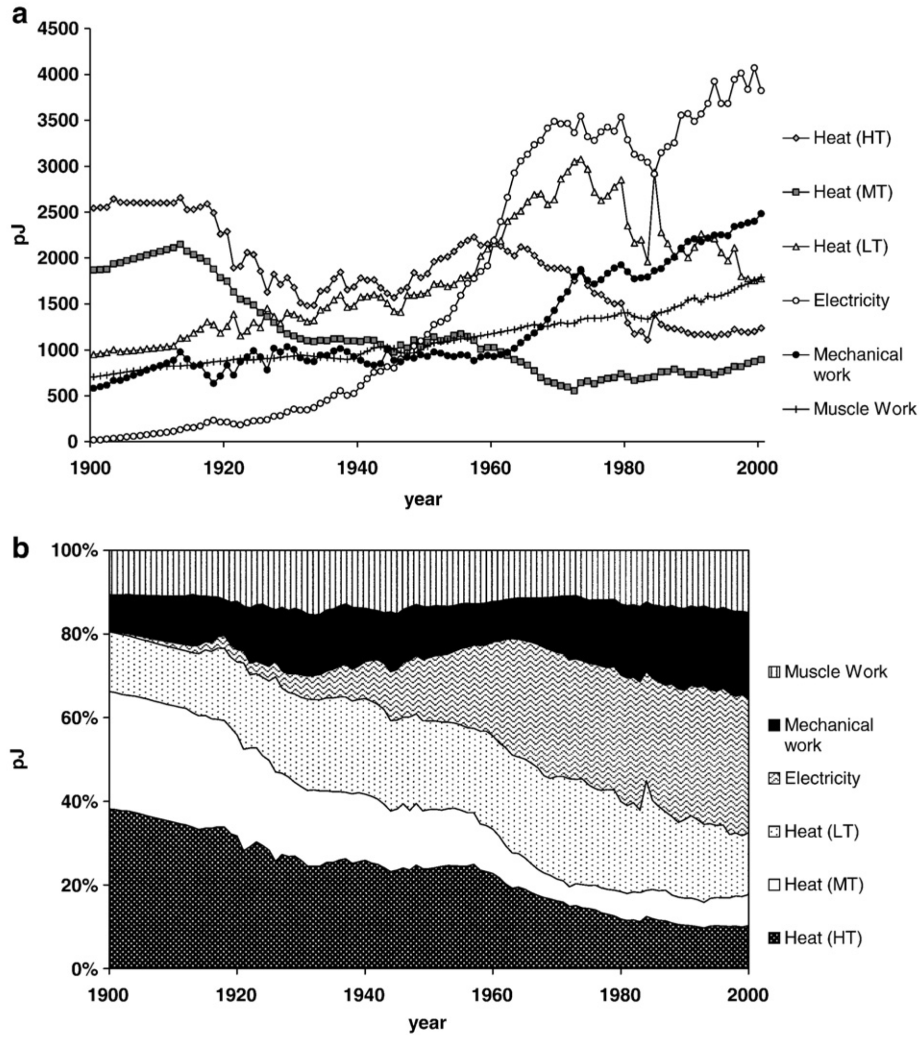

Fig. 3 – a. Final exergy consumption by useful work type, UK 1900–2000. b. Final exergy consumption share by useful work type, UK 1900–2000.

exergy consumed, the result of shifting industry structure to less energy intensive activities, more efficient use of final exergy inputs by industry, and increased use of electricity substituting for coal and oil powered processes. In 2000, exergy flows to electricity generation were 195 times (3852 PJ) the amount consumed in 1900. Similarly non-fuel uses of petroleum feedstock increased a hundredfold with the development of the domestic petrochemical industry. The total non-fuel exergy demand, which includes consumption of petroleum products such as lubricating oils, bitumen and waxes, increased 30 fold. Biomass inputs increased in proportion to the working population.

The aggregate trends hide considerable variability in the structural patterns of resource use for individual fuels. Fig. 4a–c show the quantity and the share fraction of the final exergy flow to each useful work category for coal, oil and gas resource exergy inputs. There has been considerable substitution between fuels for certain types of work, most notably the shift from coal powered steam locomotives to petrol and diesel powered internal combustion engines and electric rail. Similarly, first oil then increasingly gas (and electricity) have largely replaced coal as a source of exergy for space heating and many industrial processes. By the end of the century seventy percent of coal was used to generate electricity, the remainder was used to provide heat for industrial purposes; over 65% of all petroleum products were used to provide mobility; gas was used for space heating (33%), electricity generation (29%), and industrial heat processes (37%).

5. Conversion energy estimates

To arrive at an efficiency estimate for electricity generation (i.e. for prime movers) we estimate the aggregate efficiency of electricity generation by fossil fuels as the ratio of net electricity output at a facility to the exergy content of input 'fuels' provided by statistics (Mitchell, 1988). The exergy inputs used to generate electricity from renewable and nuclear resources are not reported and therefore had to be estimated. The exergy input for hydro and nuclear power supplies was calculated as the electricity output times the inverse of the estimated efficiency of the facility. For hydro-power, the

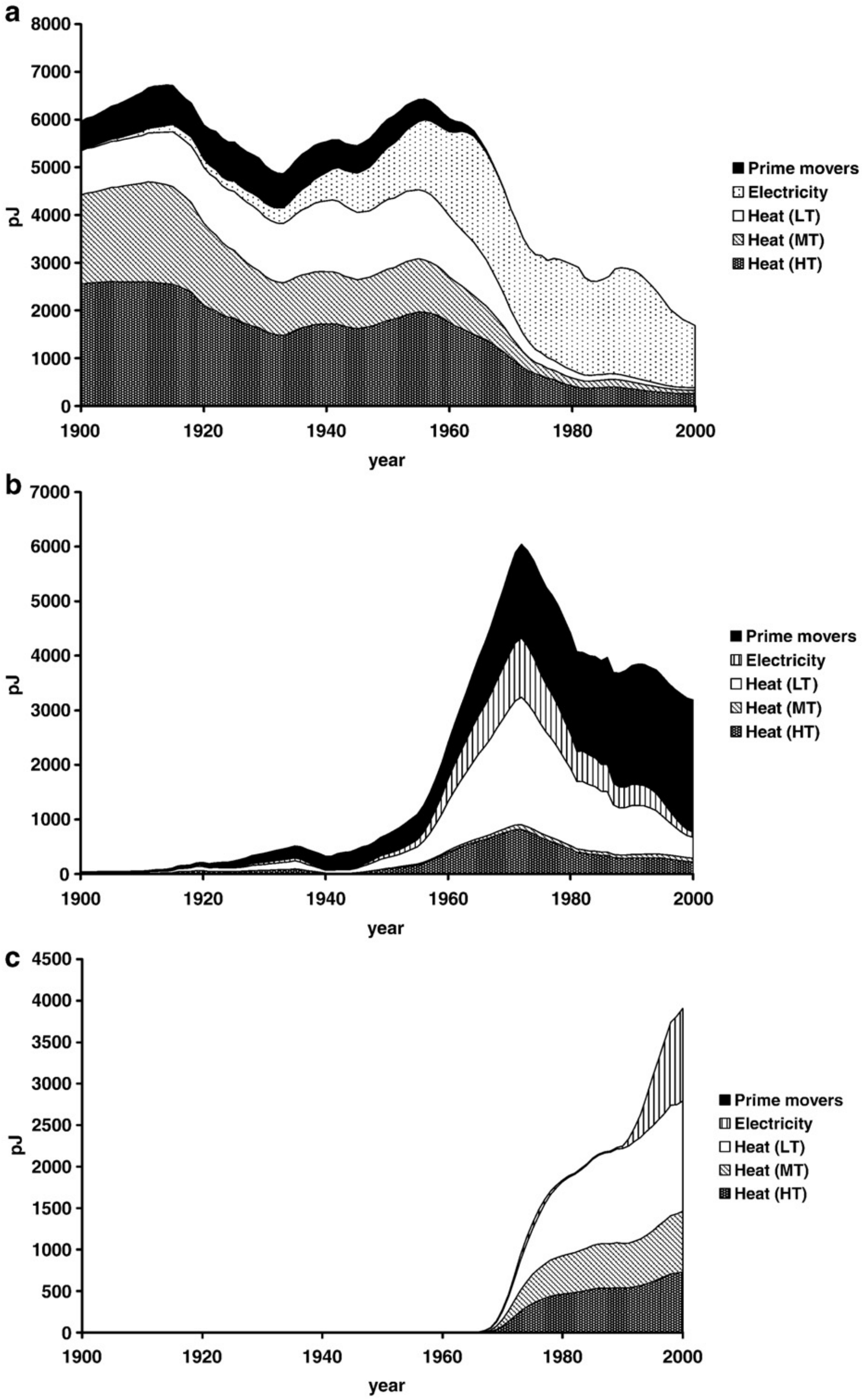

Fig. 4 – a. Coal, final exergy consumption by useful work type, UK 1900–2000. b. Petroleum, final exergy consumption by useful work type, UK 1900–2000. c. Natural Gas, final exergy consumption by useful work type, UK 1900–2000.

electricity output is available from statistics and the input "fuel" is the potential energy change associated with water falling through the turbine. Lacking UK specific data, information on dam characteristics (efficiency) are taken from a document listing technical data for Japanese hydroelectric dams built in the last century. The efficiency estimates increase linearly from 70% in 1900 to 90% in 2000, for natural flow hydroelectricity and a constant 30% for pumped storage facilities. For nuclear power, we assumed that the thermal efficiency of nuclear reactors is on average 33% (Fig. 5).

To provide a coherent aggregate measure of exergy to useful work, accounting for the substitution of electricity for direct fuel use an estimate of the efficiency of electricity use is required. The detailed data required to do this for the entire century is not available, so we use an estimate of the electricity end-use efficiency generated for the US by one of

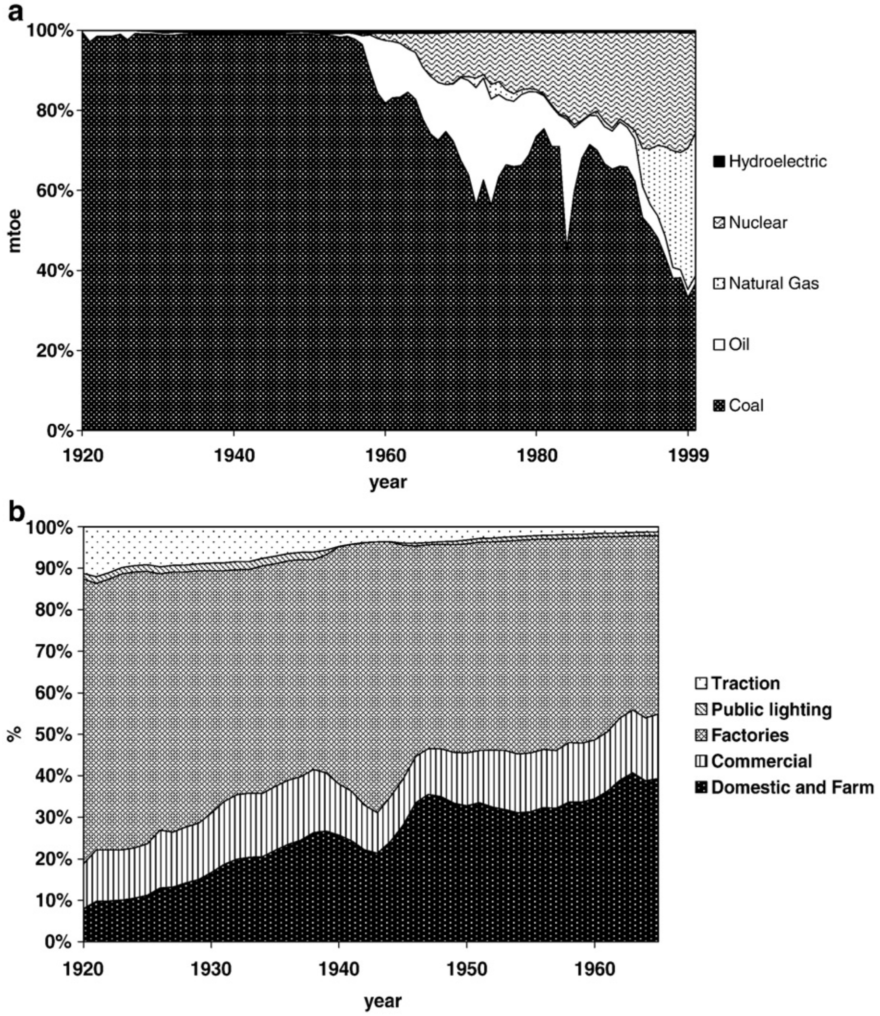

Fig. 5 – a. Fuel inputs to electricity generation, UK 1920–2000. b. Breakdown of electricity use, UK 1920–1965.

the authors, assuming, that the US and UK have similar electricity end consumption patterns (Ayres et al., 2005).

Mechanical work for transport and static shaft power refers to all uses of exergy to provide mechanical drive for vehicles 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 (Dewulf and Van Langenhove, 2003). 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 and Van Langenhove (2003), while elegant is not feasible. The reason is that 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. Reistad (1975) estimated the efficiency of transport modes for the US, but these are for a single year and are not suitable for historical estimates. 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. The useful work delivered is estimated as the efficiency times the total exergy input to each mode, provided by national statistics. 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. Of course such a definition is a limited representation of the actual service delivered, but it does permit 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. As Fig. 6a shows, we distinguish three modes of transport, road (diesel and gasoline), rail (steam and diesel-electric), and air transport and attempt to estimate time series of exergy efficiency for each.

Our simple model for road transport takes as its starting point the theoretical ideal gas air-cycle Otto engine, the single

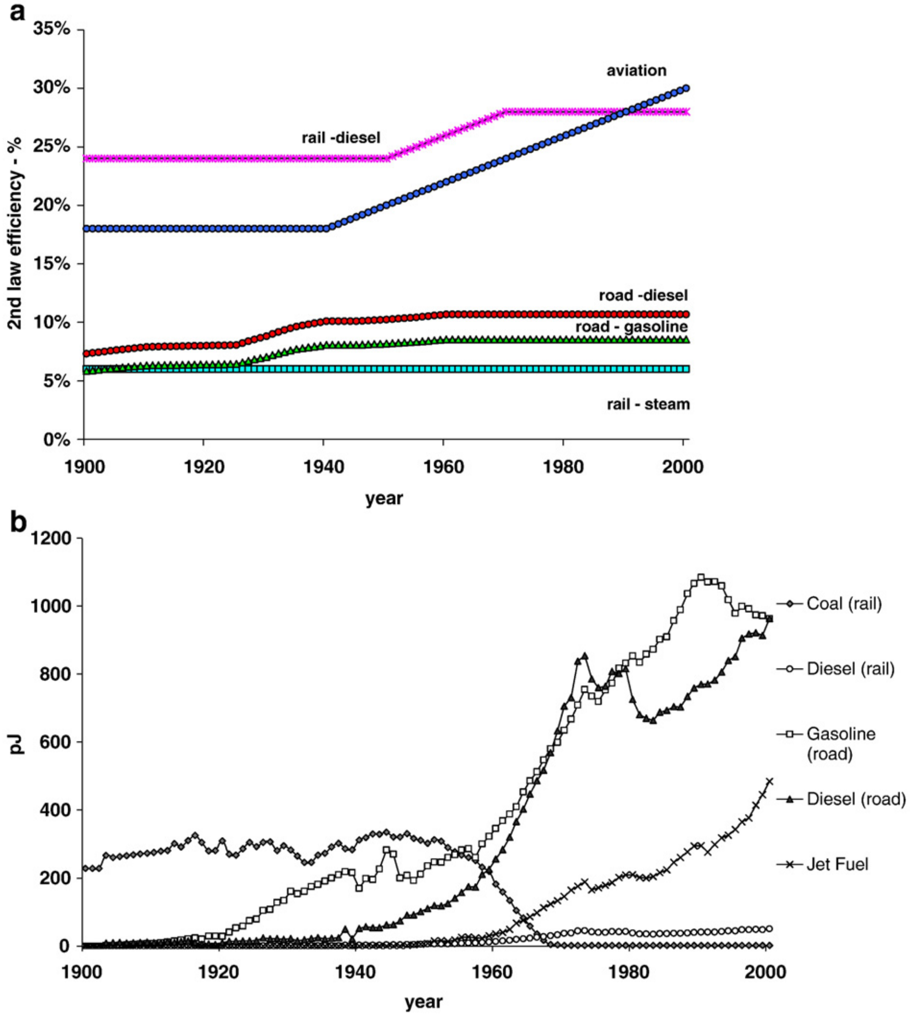

Fig. 6 – a. Estimated efficiencies of transport machines. b. Natural resource exergy inputs to transport, UK 1900–2000.

largest energy user in the transportation sector. Energy losses within the engine decline as the compression ratio *r* increases, according to the formula,

$$\eta_{\text{road}} = 1 - \left(\frac{1}{r}\right)^{y-1} \qquad (1)$$

where γ is the adiabatic compressibility ($\gamma = 1.4$) (Carnahan and Ford, 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. 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 percent greater than that of a comparable Otto-cycle engine (NAS, 1973). Other efficiency losses were estimated as constant and were accounted for to obtain the net output to the rear wheels (Kummer, 1974).

The past century saw the rapid growth of steam-powered locomotion and subsequently its substitution for diesel-electric and electric drive. The thermal efficiency of steam locomotives remained relatively constant being estimated at 8% in 1950 (Ayres and Scarlott, 1952), whereas diesel-electric locomotives reached 30% (Summers, 1971). 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).

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.

As a next step, we were looking at direct heat and quasi-work. Process improvements that exploit improvements in heat transfer and utilization may be classed as thermodynamic efficiency gains. 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'.

There is little published data describing the breakdown of heat requirements. Energy statistics tend only to distinguish total industrial use from residential/commercial uses. 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, lime calcination, glass-making, ammonia synthesis and petroleum refining, and mid-temperature uses (100–600 °C), such as 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.

We consider high-temperature heat first. There are very many high-temperature industrial uses of exergy. 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_3-3Fe+3/2 CO_2, plus the amount of heat input to bring the ore to its melting point (1813 K). The total of these two steps is 8.6 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 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:

$$\text{Efficiency of steel} - \text{making} = (1.3\ \text{EAF share} + 8.3(1 - \text{EAF share}))$$

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.

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 (e.g. 0^C) to the inside (e.g. 20^C). The basic equation for a Carnot cycle is

$$W/Q = (1 - T_c/T_h) \tag{2}$$

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 (Eq. (2)) directly gives the 2nd law efficiency of space heating. This varies according to the indoor and outdoor temperatures, posing a challenge for estimation of 2nd law efficiency of space heating. In practice it is difficult to know the actual operating conditions for heating systems. The answer depends on both climate and the operating practices in residences, which 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 to dealing with this complexity: we assume average, time-independent values of T_c=7 °C and T_h=20 °C. These values are those required for the European EN 255 Standard to calculate the Coefficient of Performance (COP) for heat pumps, and presumably reflect the understanding of industry of typical operating conditions. For direct combustion-based heating (such as a natural gas furnace), the exergy efficiency is

$$\begin{aligned}&\text{Exergy efficiency (combustion heater)}\\&\quad = \text{first law efficiency}^*(1 - T_c/T_h)\end{aligned}$$

where the first law efficiency is the share of heat of combustion actually entering the room. Coal fires with chimneys, which were common until the 1970s, have a first law efficiency of about 70%. For a heat pump, the base exergy efficiency is simply its COP divided by that of an ideal Carnot engine operating between the same operating temperatures. However, since heat pumps are driven by electricity, the total efficiency is given by multiplying this base efficiency time by the net value for electricity generation. In Table 1 we list 1st and 2nd law efficiencies for different heating technologies. The

Table 1 – 1st and 2nd law efficiencies of space heating technologies (Th=20C, Tc=7C)

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[a]	100%	4.4% (1.8%)
Heat pump[b]	300%	14.2% (5.7%)

[a] 40% electricity generation efficiency.

[b] COP=3.2; 40% electric efficiency.

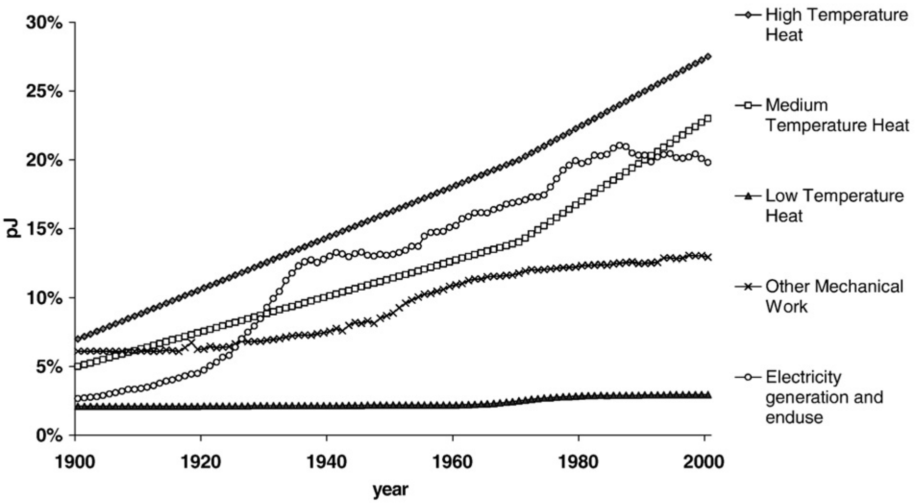

Fig. 7 – Efficiencies of natural resource exergy to useful work, UK 1900–2000.

available statistics list only the coal, oil and gas consumed in the residential and commercial sectors. Lacking information describing the mix of heating technologies and the exergy used for each over the entire century we assumed that coal was used in coal fires, gas and petroleum in furnaces. The aggregate efficiency ranges from 1.5% in 1900 to 3% in 2000 (Fig. 7).

Table 2 – Details of the method of estimation of biomass exergy and muscle work

Flows	Efficiencies [a]	Definition	Notes
Human appropriated phytomass	Feed and Feedstock utilisation efficiency *Values:* US: 0.64 JP: 0.65 EU: 0.62	Feed intake (for animal commodities) and feedstock use (for processed vegetable/fruit commodities) per corresponding phytomass appropriation.	Factors having the largest impact include the harvest index, pasture utilisation, and extent of use of by-products and residues as feed. Also reflects phytomass internal uses, losses in distribution and storage and feed processing losses. See Wirsenius (2000) pp. 114–116.
Products	Product generation efficiency US: 0.16 JP: 0.20 EU: 0.24	Product generated per feed intake	Reflects efficiency of the conversion to commodity. For animal food systems equivalent to the *feed-equivalent* conversion efficiency.
Commodities	Commodity utilisation efficiency US: 0.55 JP: 0.77 EU: 0.58	Food eaten per food products generated	Takes account of losses in distribution and storage, losses in the food utilisation process (i.e. non-eaten). Application of this efficiency to 'food end-use per capita' provides 'food intake per capita' (see below).
Food end-use per capita	Wirsenius (2000) p.61 Table 3.3	Digestible energy — gaseous, urine losses = metabolizable energy.	Estimates from wholesale supply (end-use supplied from FAO Food Balance Sheets). Note this is not the actual food intake.
Food intake per capita	Wirsenius (2000) p.62 Table 3.4 US:9.3 J JP: 9.0 EU: 9.3		Estimated using daily food energy requirements instead of data on true food intake. The driving variable in the FPD model (Wirsenius, 2000) is end-use. End-use — intake = non-eaten food. The amount of faeces and urine is estimated as the difference between GE and ME for each eaten flow. We have used data from 2000 (Wirsenius) and estimates of 1900 daily intake to fit a logistic curve, providing a time series of daily intake estimates.
Workers food intake		Employed * Work to rest ratio	Time series of per capita intake reconstructed from 10 year averages using a logistic function of time with start and end values: 2500 kcal per capita per day in 1900, 2900 kcal per capita per day in 2000. Hours worked from Mitchell (1988).
Muscle work (workers)	Food to work efficiency (human (0.2)	Workers food intake * Food to work efficiency	Approximation from Smil (1998), pp. 91–92.

[a] Trade neutral values.

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 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. It is impossible for a summary paper such as this.

In fact, most of the improvements in heating/cooling efficiency on recent decades arise from a combination of non-technical factors, primarily urbanization, increasing residential density and improved building standards. It is fairly obvious that an apartment building is inherently more efficient from a heating perspective than a single family house. The reason is that neighbouring apartments with common walls, offer less exposure to the outside air. The same is true when the ceiling of one apartment adjoins the floor of another. Whereas a single family home has (at least) four walls and a roof through which heat can be lost, an apartment in a multi-family structure may have only one or at most two outside walls. Windows are actually the most important channels for heat loss. The trend toward replacing old-style wood-frame windows fabricated on-site by prefabricated windows with double (or even triple) panes of glass has sharply reduced this source of heat loss.

For estimating the efficiency of muscle work we start with food intake per capita per day. From this point the calculation goes in two directions; (1) to estimate the biomass inputs in the form of food (cereals, vegetables and fruit) and feedstock (requirements for animal products (such as milk and meat); (2) to estimate the useful muscle work supply from the food and feed energy intake. Details of the steps in the calculation are provided in Table 2.

In the first exercise, the coefficients of the efficiency of successive transformations from phytomass to product (0.62) and then food commodity (0.24) are provided by Wirsenius (Wirsenius, 2000). The ratio of food intake to food supplied (food end-use) indicates the wastage factor (0.58), suggesting that almost half of all food supplies are not eaten. We estimate the useful muscle work supply from the energy intake at 20%

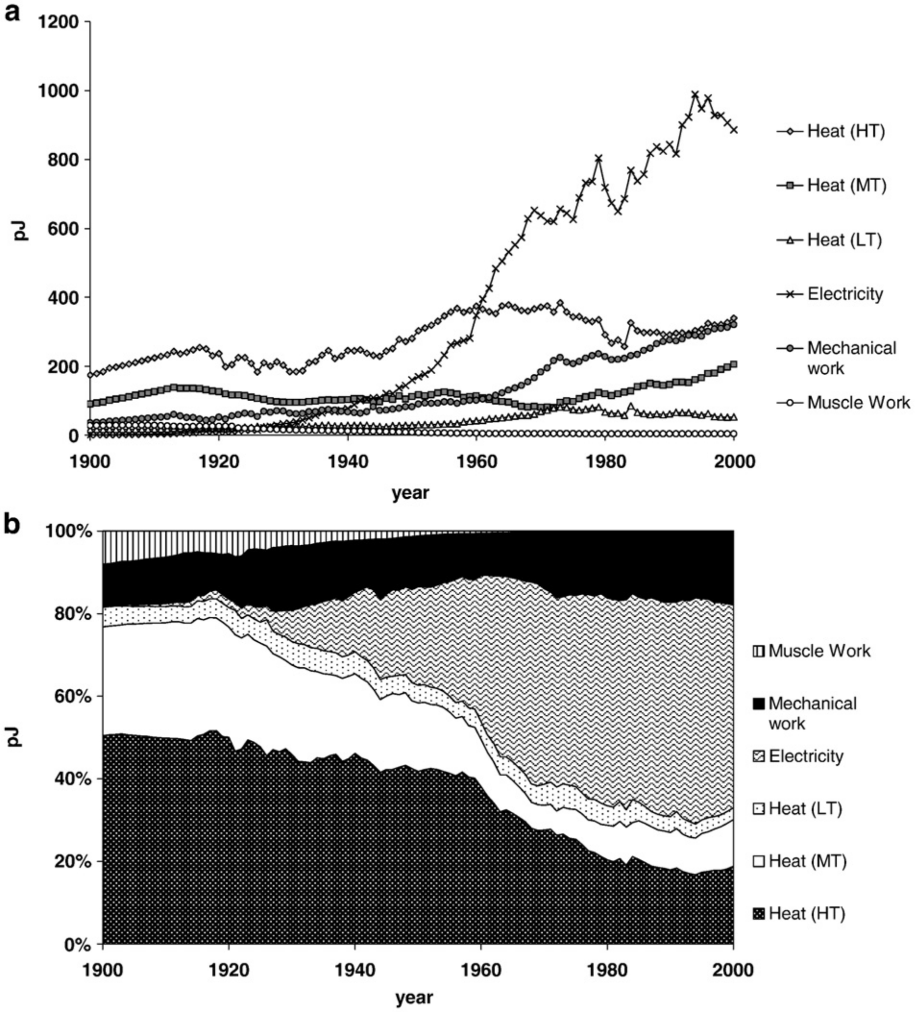

Fig. 8 – a. Useful work supply by type, UK 1900–2000. b. Useful work share by type, UK 1900–2000.

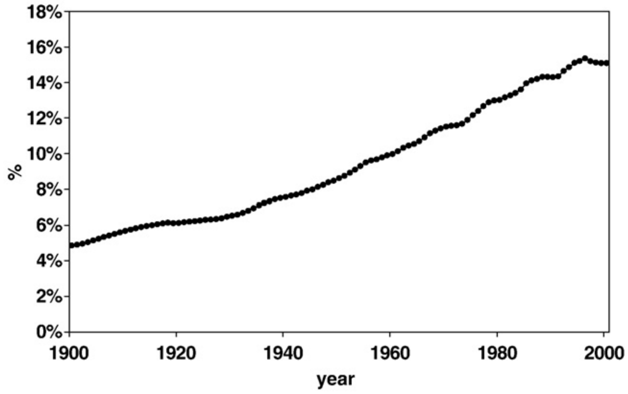

Fig. 9 – Aggregate efficiency of fuel exergy conversion to useful work, UK 1900–2000.

(Smil, 1998). We then estimate the ratio of hours worked to those at rest from estimates of the number of hours worked per month and adjust the total useful work supply accordingly.

6. Total useful work and aggregate efficiency

Fig. 7 presents the aggregate economy-wide efficiencies of conversion for each type of useful work. The most marked improvements are for high and medium temperature heat for industrial processes. Similarly the efficiency of electricity generation and distribution and utilisation has improved greatly, although no marked improvement is evident post 1980. The exergy efficiency of transportation (other mechanical work) has doubled over the century, but has not improved significantly since 1970, when gasoline engines operated at higher compression ratios. In contrast the exergy efficiency of intrinsically less efficient low temperature heat processes have not developed at a similar pace.

Using these efficiencies we estimate the total useful work provided by final exergy inputs. These results are shown in Fig. 8a and b. It is useful to compare these graphs with those for exergy inputs (Fig. 2a and b). In 2000 electrical devices consumed 36% of exergy inputs but supplied 45% of the useful work. Exergy inputs to high and mid-temperature uses have declined, yet the amount of useful work they are able to deliver has increased, by virtue of efficiency improvements in industrial processes. In 1900 almost half of the total exergy was used for these industrial purposes, delivering 60% of the useful work supplies. By 2000 they consumed only 20% of the exergy inputs and delivered 30% of the useful work. In contrast low-temperature heat uses required 17% of the total exergy inputs and provided only 3% of the useful work. Also transportation (mechanical drive) accounts for 21% of consumed exergy, but a smaller fraction 15% of the useful work. Biomass exergy inputs, almost 10% of the useful work in 1900 account for only a small fraction of the useful work by the end of the century. Commercial exergy supplies have now substituted for almost all draught animal and human muscle work.

From an estimate of the total exergy input and the useful work output we estimate the aggregate exergy efficiency as shown in Fig. 9. From 1900 to 1940 it increased at an average rate of 1.1% per annum, post-war to the present day at the slightly faster rate of 1.14% per annum. In more recent years there is some indication of a slow down, possibly the result of a combination of factors, a) rapidly growing exergy use for the less efficient space heating and transport uses, b) the substitution of less efficient electrical devices for direct use of exergy and c) technological barriers to progress in improving thermodynamic efficiencies, in particular in electricity generation.

Plots of the ratio of exergy and useful work to GDP reveal their 'economic' efficiency. Fig. 10 shows that the natural resource exergy intensity of GDP declines at an average rate of 2.4% per annum. This is a whole percentage point faster than the rate of decline estimated for the US (Warr and Ayres, 2006). In contrast the useful work/GDP ratio is on average increasing until the 1920s when it declines, coinciding with rapid improvements in the efficiency of electricity generation and its more widespread utilisation in the economy. The lowest value of the useful work/GDP ratio (1.5 TJ per million $) coincides with WWII, a period when all fuels were rationed

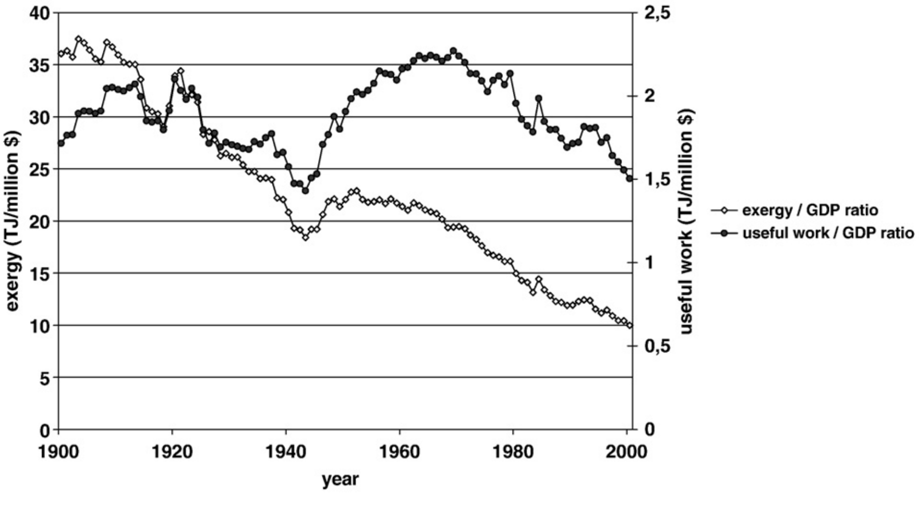

Fig. 10 – Natural resource exergy and useful work supply intensity of GDP, UK 1900–2000.

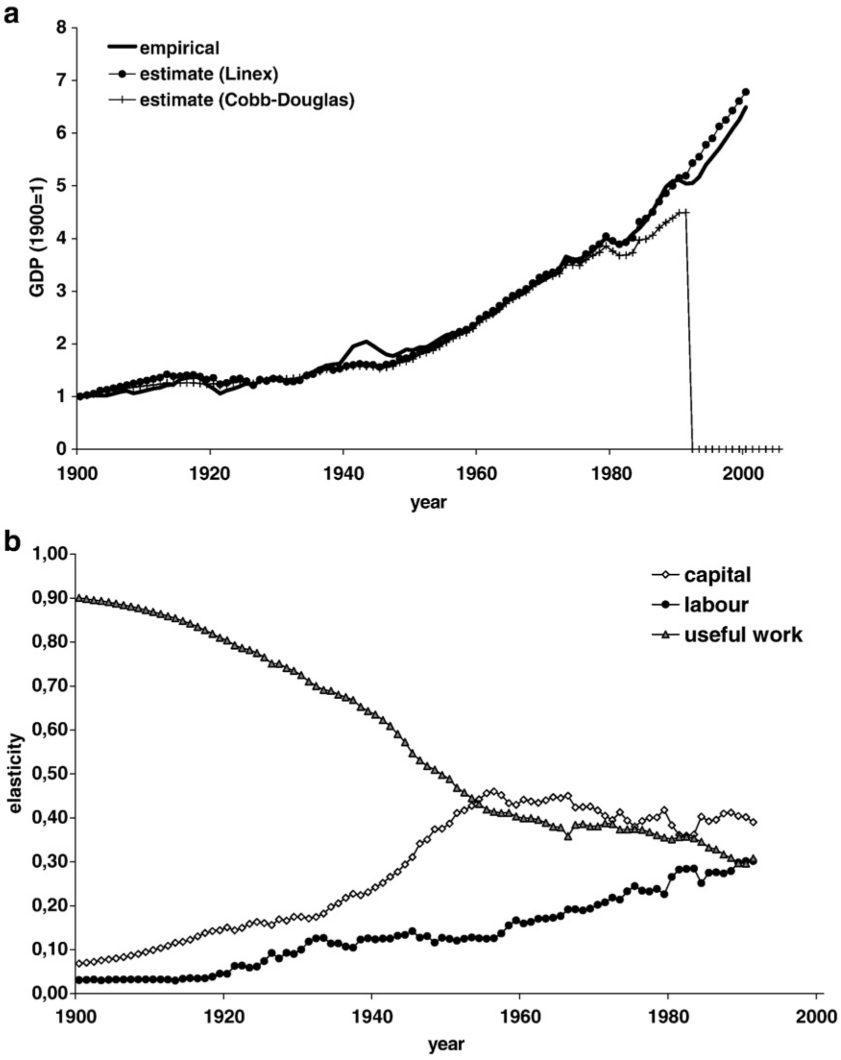

Fig. 11 – a. Empirical and estimated GDP, UK 1900–2000. b. Linex production function time dependent marginal productivities, UK 1900–2000.

and used with considerable attention to utilisation efficiency. The declining trend reversed over the period 1945 to 1971. The exergy intensity of GDP increased for the only time during the century as heavy industries and cities were rebuilt following the war time destruction.

By the early 1950s these investments paid off. What follows was a period of unprecedented growth of private car ownership and construction of new houses. The growth phenomenon also coincided with the rapid growth of the importance of electrical energy use, and the proliferation of new appliances and 'parasitic' energy uses (for example watching TV), consumption uses of fuels that do not necessarily contribute as much to economic output as other uses. Nevertheless, the improvements in exergy conversion meant that the exergy intensity of GDP declined, while the useful work intensity increased. By 1970 the useful work intensity of GDP was at its highest over the century, reaching 2.6 TJ per million $.

The first oil crisis and subsequent energy price hike stimulated a sharp reversal in this trend. Over the period 1970 to 2000 the useful work/GDP ratio declined at an average rate of 1.4% per annum. The reasons include the continued efficiency improvements of the efficiency of heat uses in industry, more importantly restructuring of the economy, a process of deindustrialisation and a global transfer of heavy, exergy-intensive industries to less affluent nations, and the increasing importance of less-energy intensive service and financial sectors of the economy.

7. Modelling historic economic growth with useful work as a factor of production

We model output growth as a function of capital stock (monetary value), labour (hours worked) and useful work inputs (Joules).[3] For comparison we used two models, an

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[3] For a detailed discussion on all conceptual and methodological issues related to the alternative production function augmented by useful work inputs see Ayres et al. (2003) and Ayres and Warr (2005).

energy-augmented Cobb–Douglas production function without exogenous technical progress,

$$y = k^{\alpha} l^{\beta} u^{1-\alpha-\beta}$$

and an alternative model, the LINEX function which avoids the unrealistic neoclassical equilibrium assumption of constant elasticity of production and cost shares, but retains properties of constant returns to scale and satisfies the requirement of non-negative marginal productivities (Kümmel et al., 1985; Kümmel, 1989, 2002).

$$y = u \, \exp\left[a\left(2 - \left(\frac{l-u}{k}\right)\right)\right] + ab\left(\frac{l}{u} - 1\right)$$

The estimates, presented in Fig. 11 show that it is possible to reproduce the historical trend in output growth for the entire century without recourse to any assumption of exogenous and undefined technical progress of total factor productivity. Based on these results we argue that the improved exergy conversion to useful work efficiency acts as a proxy in the model for technical progress.

The results for the LINEX model are more precise than those provided by the C-D model, by virtue of its time dependent marginal productivities which reflect the dynamic substitution of factors under technological change. As Fig. 11b shows, the time trends of factor productivities reveal that useful work has been an important factor driving economic growth over the past century. The value of the estimated exponent for useful work in the C-D model confirms this finding, being notably higher (0.34) than the factor cost share of energy in the national accounts.

8. Conclusions

Estimation of the economy-wide trends in exergy supply, consumption and use efficiency over such a long period is not without its difficulties. Clearly it is not possible to reflect the complex reality of all the processes and transformations that occur. The principal sources of uncertainty stem from the estimation of the exergy flows to each type of useful work and the efficiencies of conversion. Also there have been efficiency improvements that we have not been able to account for, but whose effects might be significant. For example, we do not estimate improvements in transport efficiency resulting from vehicle weight changes, or driving patterns. Similarly we do not estimate the improvements in space heating efficiency resulting from improved insulation. The latter would reduce the overall efficiency but increase its improvement rate.

The efficiency conversion from fuel exergy to useful work has more than doubled over the past century. We suggest that this measure serves as a useful proxy reflecting the most significant technological advances that have occurred. As a consequence, by including useful work as a factor of production we are able to reproduce observed economic growth without recourse to assumptions of exogenous 'technical progress'. These results provide compelling evidence to suggest that the useful work supplied by natural resource exergy is the correct factor of production, rather than exergy per se, and that improvements in the efficiency with which fuel exergy is converted into useful work is a significant driver of growth. Improvements in energy conversion efficiency are in fact recursively related to improvements in the terms of trade with which the economy is able to access natural resource exergy. Exergy efficiency and economic growth – capital accumulation and investments in technical progress – recursively drive each other.

It appears that sustained economic growth in our current economic system depends on high inputs of fossil fuels despite considerable efficiency gains. It needs further investigation to better understand whether a reduced reliance on fossil fuels and a reduction in carbon emissions might be achieved without considerable reductions in gross domestic product.

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