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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

Benjamin Warr [a,*], Robert Ayres [b], Nina Eisenmenger [c], Fridolin Krausmann [c], Heinz Schandl [d]

[a] INSEAD, Boulevard de Constance, 77305 Fontainebleau, France
[b] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria and Chalmers Institute, Gothenburg, Sweden
[c] Institute of Social Ecology, Klagenfurt University, Schottenfeldgasse 29, 1070 Vienna, Austria
[d] CSIRO Sustainable Ecosystems, GPO Box 284, Canberra ACT 2601, Australia

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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.

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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

* Corresponding author. Tel.: +33 1 60 72 4000.
E-mail address: benjamin.warr@insead.edu (B. Warr).

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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.

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