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Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009

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ABSTRACT

Unlike conventional energy analyses, exergy analysis considers the quality of energy flows and efficiencies in their conversion. Additionally, conventional energy analyses focus on the primary and final stages of energy flows, and do not capture the last stage of energy transformations to useful end-uses. We further develop previous useful work accounting methodologies by considering the sectoral breakdown of electricity end-uses and efficiencies. Also, this paper is the first accounting for useful work covering a full agricultural-industrial-services economic transition, taking Portugal 1856–2009. Portuguese aggregate final-to-useful efficiency remains constant until 1920, slightly increases between 1920 and 1950 due to heating uses, soars between 1950 and 1980 due to electrification and industrialization, and stabilizes afterwards due to an increase in motorization and deindustrialization. Strikingly, along this period the ratio useful work/GDP varies by no more than 20% around its average and ends in 2009 at a value quite close to is 1856 value, around 1 MJ/2010€.

1. Introduction

Dramatic changes occurred in energy use patterns over recent centuries, with corresponding changes in the natural resources used to provide energy. In the 18th century industrializing countries shifted from wood-fired rural societies to coal-fired industries and later from coal to oil. More recently electricity was introduced as a new energy vector, and its increasing pervasiveness is linked to the transition from industrial to service economies. An exponential increase in the quantities of energy used, as well as drastic changes in energy quality took place and were linked to enormous wealth accumulation, population growth and an impressive improvement in the standard of living. These changes in terms of energy quantity, quality and the way in which energy sources are used are commonly known as energy transitions (Fouquet, 2008; Grübler and Nakićenović, 1996; Henriques, 2011; Krausmann et al., 2009; Schandl et al., 2009; Smil, 1991; Steinberger and Krausmann, 2011; Stern, 2004; Stern and Cleveland, 2004; Warr et al., 2010).

Studies on energy transitions can be focused on changes over time (1) in the use of natural resources (primary energy) and energy vectors (final energy) or (2)

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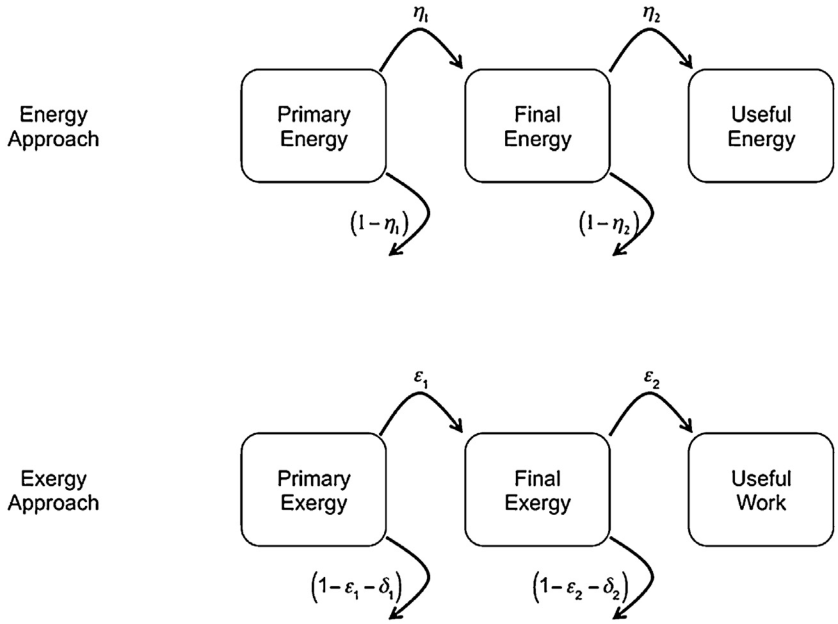

Fig. 1. Primary-to-useful energy and exergy flows. Transformation and conversion energy and exergy efficiencies are represented as $\boldsymbol{\eta}_1$, $\boldsymbol{\eta}_2$ and $\boldsymbol{\varepsilon}_1$, $\boldsymbol{\varepsilon}_2$, respectively. Exergy destruction during conversion and transformation is represented as $\boldsymbol{\delta}_1$ and $\boldsymbol{\delta}_2$, respectively.

in the energy uses (useful energy). A vast bibliography explores these issues, however, most studies focus on primary energy or final energy (Apergis and Payne, 2010; Chontanawat et al., 2008; Kümmel et al., 1985; Miketa and Mulder, 2005; Mulder and Groot, 2007; Stern, 1993). These approaches are useful to analyse transitions in energy supplies (where the energy comes from), but they do not capture how energy is used productively within the economic system, and consequently neglect the structure and the motivation for energy demand.

Exergy is a thermodynamic measure of energy quality, measuring the availability to perform work of a certain amount of energy, given reference environmental conditions. Exergy is extensively presented in the literature as a good variable for economic and sustainability assessments of energy, as it accounts for the quality in use and conversion of energy vectors and materials. Several exergy analyses (primary, final, and useful) have been done for different countries, such as single year studies for the USA (Reistad, 1975), Sweden (Wall, 1987), Japan (Wall, 1990), Italy (Milia and Sciubba, 2006; Wall et al., 1994), China (Dai et al., 2014), Turkey (Seckin et al., 2013), United Kingdom (Gasparatos et al., 2009b), and the Netherlands (Ptasinski et al., 2006), and historical analyses of patterns of exergy consumption for China (Chen and Chen, 2007a,b,c,d; Chen and Qi, 2007) and the United Kingdom (Gasparatos et al., 2009a,c). These works provide relevant economy-wide results, characterizing exergy flows, and exergy sources and consumers, but neither capture long-term trends and transitions nor explore the relations between exergy use and economic growth. We show here that useful work is a suitable energy measure to fulfil this task.

Useful work is the useful exergy of a given energy end use. It measures the result of an energy use rather than the amount of energy transferred to a final use. Formally, useful work can be defined as the minimum amount of work (or exergy) required to produce a given energy transfer. Useful work accounting implies an exergy analysis at the useful stage of energy flows (Fig. 1), and measures the actual amount of exergy (and not energy) delivered to a final function, e.g. the mechanical work actually used by a car from its fuel, the exergy of the heat actually provided to a blast furnace, or the light emitted by an electric lamp. Useful work accounting at a country-level enables the assessment of the quality of the energy used in an economy, providing better insights on the relation between economic growth and energy use (Ayres, 2008; Ayres et al., 2003; Ayres and Warr, 2005; Stern, 2010; Warr and Ayres, 2006,2010; Warr et al., 2010, 2008; Williams et al., 2008).

Comprehensive useful work analyses have been made for the USA, UK, Japan and Austria (Ayres, 2008; Ayres et al., 2003; Ayres and Warr, 2005; Warr et al., 2008, 2010), comprising the 20th century transitions and economic transformations, but none covers the full transition from a rural society through an industrial economy to a service economy. Here, we accomplish the analysis of a full transition, accounting for useful work in Portugal for a 154-year period (1856–2009).

One of the two main energy transitions usually considered is associated to the so-called second industrial revolution, with the introduction of electricity and oil as significant energy carriers. These two energy carriers, given their typical end-uses, have radically different final-to-useful 2nd law efficiencies, e.g., an electrical engine converts electricity to mechanical work at an efficiency greater than 70% and in some cases going up to more than 90% whilst a diesel or gasoline motor engine converts fuel to mechanical work at an efficiency in the range 10–13%.