USEFUL WORK AS A REFINED ENERGY MEASURE. TRANSITIONS IN PORTUGAL FROM 1856 TO 2009.

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Overview

Dramatic changes occurred in the energy use patterns over the recent centuries. There were evident changes in the natural resources used to provide energy. In the 18th century industrializing countries shifted from wood to coal and later from coal to oil. More recently electricity was introduced as a new energy carrier playing its own role in the energy system. An exponential increase in 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 standards 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 (Henriques 2011; Krausmann *et al.* 2009; Schandl *et al.* 2009; Stern 2004; Stern *et al.* 2004; Warr *et al.* 2010b).

A vast bibliography explores the changes in the paradigms' patterns of energy use. However most studies focus either on primary energy or final energy variables (e.g. Apergis *et al.* 2010; Chontanawat *et al.* 2008; Kümmel *et al.* 1985; Miketa *et al.* 2005; Mulder *et al.* 2007; Stern 1993). These approaches tend to focus on energy supplies (where the energy comes from), and do not consider how energy is used productively within the economic system.

Methods

In this work we start by reviewing the theoretical basis of exergy-related concepts as well as the useful work variable, present the link between useful work and conversion efficiencies and the detailed methodology followed to obtain historical data on useful work for a given country.

Finally this methodology is applied to the Portuguese data of energy use from 1856 to 2009. We obtain exergy and useful work series. Historical data is presented and we describe the exergy breakdown in terms of natural resources, types and categories of use, and the evolution of exergy to useful work conversion efficiencies. We conclude discussing the useful work results in the context of other European countries, the observed characteristics of the energy transition, and the intensity measures.

Results

Portuguese final exergy consumption and useful work dramatically increased since mid-19th century. However in this period structural changes in the mix of exergy final consumption took place. The transitions from combustible renewables, namely firewood, to coal and later to oil and electricity are apparent. Also, the share of food in the societal exergy inputs dramatically decreased with the massive use of high-density energy carriers. Food and feed products evolved from essential to irrelevant in the Portuguese energetic context.

Allocating exergy inputs to useful work categories enabled the assessment on the evolution of exergy uses instead of sources. In global terms is visible the transition from poor to nobler uses, such as medium and high temperature heat, mechanical drive and other electric uses instead of low temperature heat and food & feed. This allocation was done

for each energy product and final consumption sector individually. However, grouping data in groups of energy carriers enabled more detailed information on the evolution of exergy inputs.
Types of energy use have also changed. In this context it is more adequate to analyze the evolution of the share of each useful work category than analyze the share of exergy by type of use. Useful work shares by useful work categories are much more stables and influenced by structural changes in the demand for energy services. The structure of useful work categories changed in the analyzed period in Portugal. Such changes show a transformation of useful work needs. The economy evolved to a much greater dependency on mechanical drive services than in the past. Also, other electric uses and higher temperature heat uses gained importance. These changes take effect as a consequence of the industrialization of the country and mobility needs that drove to increases in the transport sector energy uses. Notwithstanding, these changes occur slowly and in very well defined historical periods.

Conclusions

When compared with final exergy intensity, useful work intensity is almost constant since 1856 with a variation of about 20% below and above the 154-year average value. This result seems to confirm the assumption that useful work allows for an analysis closer to final uses, centered in types of exergy use and energy service provided rather than a quantitative description of the amount of energy resources used to the same result.
The constancy of useful work intensity enables further research concerning future GDP growth trends. The consistency of such result must be confirmed by running the presented methodology for other countries. If so, the consistency of previous results relating the strong relation between useful work and economic growth (Warr *et al.* 2010a) may be confirmed and new insights on growth theory may be obtained.

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