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

ANDRÉ CABRERA SERRENHO^{a*}, BENJAMIN WARR^c, TÂNIA SOUSA^b, ROBERT U. AYRES^c, TIAGO DOMINGOS^b

^a *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom.*

^b *Maretec, Marine Environmental and Technology Center, Department of Mechanical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, 1, 1049-001 Lisboa, Portugal.*

^c *INSEAD, Boulevard de Constance, 77305 Fontainebleau, France.*

*Corresponding author, e-mail: ag806@cam.ac.uk

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 1920-1950 due to heating uses, soars between 1950-1980 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 its 1856 value, around 1MJ/2010€.

Keywords: energy; exergy; useful work; efficiency; energy intensity.

1. Introduction

Dramatic changes occurred in energy use patterns over the 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; Grubler 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) 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; Chen and Chen, 2007d; 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 (Figure 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; Warr et al., 2008; Williams et al., 2008).

Figure 1. Primary-to-useful energy and exergy flows. Transformation and conversion energy and exergy efficiencies are represented as η_1 , η_2 and ε_1 , ε_2 , respectively. Exergy destruction during conversion and transformation is represented as δ_1 and δ_2 , respectively.

Comprehensive useful work analyses have been made for the USA, United Kingdom, Japan and Austria (Ayres, 2008; Ayres et al., 2003; Ayres and Warr, 2005; Warr et al., 2010; Warr et al., 2008),

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 to 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%. However, different final uses for electricity can have very different efficiencies and so it is crucial to correctly account for these differences.

Previous useful work analyses (Ayres, 2008; Ayres et al., 2003; Ayres and Warr, 2005; Warr et al., 2010; Warr et al., 2008) considered an aggregate electricity final-to-useful efficiency equal to the average electricity final-to-useful efficiency of the USA, originally obtained in Ayres et al. (2005). Here we refine the useful work methodology considering separate final-to-useful efficiencies of the different electricity end-uses and sectors of the economy, since the sectoral structure of each country (other than USA) determines the useful work obtained from electricity.

The roadmap of this paper is as follows. We define useful work and describe the methodology in section 2. From historic energy records, we estimate final exergy figures and its breakdown in terms of energy vectors and useful work categories (section 3). In section 4, we estimate the final exergy-to-useful work conversion efficiencies for each category of use. We obtain and discuss the final exergy and useful work series for this country and period by types of use, as well as aggregate conversion efficiencies (section 5). Also, we compare the evolution of the useful work intensity in Portugal to intensity measures previously obtained for other countries (Warr et al., 2010). The differences of the Portuguese case, its meaning and consequences are discussed. We conclude by summarizing the main conclusions (section 6).

2. Methodology and data

Useful work accounting comprises a four-step methodology for each year and energy vector (Ayres et al., 2003):

1. Conversion of existing final energy data to final exergy values (section 2.1);
2. Allocation of the final exergy consumption of each final use sector to useful work categories (sections 2.2 and 3);
3. Estimation of second-law efficiencies for each final-to-useful transformation (sections 2.3 and 4);
4. Calculation of an overall useful work value by summing the total values obtained for each useful work category.

This methodology was applied to Portuguese energy data from 1856 to 2009. Energy data from 1960 to 2009 was collected from International Energy Agency (IEA) Energy Statistics and Energy Balances (IEA, 2011a, b). Historical estimates prior to 1960 were assembled from Henriques (2011).

2.1. Converting final energy to exergy data

Exergy is formally defined as the theoretical maximum amount of obtainable work when a thermodynamic system is brought to a reference state of thermodynamic equilibrium. Therefore, calculating exergy values from energy values, depend on the ability that different forms of energy have to deliver work. In most energy calculations, energy is displayed in one of the following forms: fuel, electricity, mechanical work, heat or non-energy products. For each form, the exergy content is different (Table 1). Mechanical (both kinetic and potential) and electric energy flows can be, in theory, completely converted to work, thus they have an exergy factor¹ of 1, while in the case of heat, the exergy factor is smaller than 1. Therefore, an electric energy flow can be completely converted to work and its exergy content equals its energy² (Table 1, row 2), while heat cannot be completely converted

¹ Exergy factor is commonly defined as the ratio of exergy to energy.

² In practice there are heat losses when converting for example kinetic energy to work, but they are unknown *a priori*, thus one decides to consider an efficiency of 1 which is the theoretical maximum given by the first law of thermodynamics, i.e. there is no

to work. In this case the maximum work extractable from a sub-system connected to a thermal reservoir at T_0 is the work obtained by an ideal Carnot engine (Table 1, row 4).

Table 1. Exergy content of different energy flows. Adapted from Ford et al. (1975); Moran and Shapiro (2004); Sciubba and Wall (2007); Szargut et al. (1988).

T_0 is the environment temperature and T is the temperature of the reservoir from which heat is added.

Energy flow (E)	Exergy content (B)	Observations
Fuel	$B = -\Delta G = \Delta H - T_0\Delta S \approx \Delta H $	The maximum work done by a fuel is the chemical work of its combustion. The term $T_0\Delta S$ is the heat rejected as a consequence of the entropy received.
Electricity	$B = E$	Electricity can be completely converted to work.
Work	$B = W$	Available work is exergy by definition.
Heat	$B = E \left(1 - \frac{T_0}{T}\right)$	The maximum work done by a heat flow is the work that would be done by a Carnot cycle working between T and T_0 .

Obtaining useful work statistics for a region/country implies the calculation of exergy from available energy datasets. We take into account exergy inputs that go beyond conventional energy accounting statistics: food for humans, feed for working animals and non-conventional sources, such as wind and water streams for mechanical drive uses in boats, mills and wells. This accounting involved the following groups of energy vectors:

- Coal and coal products;
- Oil and oil products;
- Natural gas;
- Combustible renewables;
- Electricity and CHP heat³;

theoretical thermodynamic result that sets a maximum conversion efficiency in this case. Therefore, we consider electricity as ‘pure work’.

³ Combining electricity and CHP heat in a single category may not be an adequate choice. However, IEA data assembles these two final energy uses in this group of energy vectors. Evidently, electricity and heat uses are handled differently in this paper, in terms of their distinct exergy contents and efficiencies.

- Food and feed;
- Other non-conventional.

Different data sources were used to compile this dataset. Final energy use regarding coal and coal products, oil and oil products, natural gas, combustible renewables⁴, and electricity and CHP heat were obtained from the IEA energy balances databases from 1960 to 2009 (IEA, 2011a). For the remaining period, final energy regarding these groups was estimated based on the primary energy dataset of Henriques (2011). Final energy use in the form of coal was obtained from primary coal subtracting the amount of coal used for electricity generation (DGSE, 1929-1984), which was estimated considering a time varying thermal power plants average efficiency also estimated by Henriques (2011). This is a reasonable procedure, because electricity generation is the only transformation process for coal since the early 20th century. For oil and oil products' final energy use, we used an analogous procedure, taking also into account crude oil used in refineries⁵ to produce oil products. Electricity figures prior to 1960 were estimated based on primary electricity values from Henriques (2011) plus electricity outputs from coal and oil (DGSE, 1929-1984; Henriques, 2011). CHP was not used before 1960.

Food for humans and feed for working animals have a quantitatively important role in the Portuguese economy, even though omitted in standard energy statistics. Food data prior to 1960 was obtained from Henriques (2011). From 1960 onwards, food intake data was obtained from the Food and Agriculture Organization of the United Nations database (FAO, 2011). Feed for working animals was estimated from the inventories of working animals in Henriques (2011).

Finally, energy data regarding other non-conventional vectors were obtained directly from Henriques (2011) for the entire timespan.

The consistency of the datasets used was verified for the transition or overlap years and differences of no more than 5% were found (DGSE, 1929-1984; FAO, 2011; Henriques, 2011; IEA, 2011a).

⁴ For combustible renewables, it was used the data from Henriques (2011) prior to 1990, and the IEA databases from 1990 onwards.

⁵ The first refinery operating in Portugal was installed in Lisbon in 1940. Before this year, all oil products were directly imported and the only exit of imported oil products to transformation processes was for electricity generation.

Exergy data was computed from final energy estimated figures based on different exergy factors for each group of energy vectors (Table 2).

Table 2. Exergy factor for energy vectors (Chen and Chen, 2006; Ertesvåg and Mielnik, 2000; Nakicenovic et al., 1996; Wall et al., 1994).

Energy carriers	Exergy factors
Coal and coal products	1.06
Oil and oil products	1.06
Natural gas	1.04
Combustible renewables	1.11
Electricity and CHP heat	1.00
Food and feed	1.00
Other non-conventional	1.00

2.2. Useful work categories

Useful work was classified within 5 different categories of use: heat, mechanical drive, light, other electric uses and muscle work. Non-energy uses are not considered⁶.

Heat includes all final energy uses where heat is used in a given process or device. Because of the strong influence of temperature on second-law efficiencies, the heat category is often subdivided in at least three different subcategories for different temperature ranges of the hot reservoir. The first is high temperature heat for reservoirs warmer than 500°C. These temperatures are used in some heat demanding industrial processes, mainly iron and steel industries, cement production, glass making and petroleum refining. A second group is medium temperature heat for reservoirs between 120°C and

⁶ Non-energy uses include all exergy uses whose goal is not an energy-related exploitation of a resource. The main examples are oil products such as plastics or lubricants that comprise exergy as they are a product of an energy resource, but its use is not as an energy flow but capital stock. To assess the overall exergy flow in a country, material flow analysis would be needed in order to account for the total (chemical) exergy of materials used, including metal-ore derived materials. The exergy embedded in material flows is out of the scope of the current analysis, as our main goal is the assessment of the services provided by energy vectors only. However, a full scale exergy accounting from resources to end-uses that takes into account materials embedded exergy could enable the assessment of both energy and non-energy uses, and an assessment of different material efficiency options in the consumption of exergy resources.

500°C (with the majority of cases below 200°C). This range of temperatures is widely used as process heat in the majority of industrial sectors. Finally, a low temperature heat class for temperatures below 120°C is defined for hot water, cooking and space heating uses (Ayres and Warr, 2010). This class of low temperature heat is further subdivided in several classes, because second-law efficiencies are much more sensitive to lower than higher temperatures. This enables a higher specification of second-law efficiencies for each different low temperature heat use. For all heating categories, different second-law efficiencies⁷ definitions are used depending on the type of energy source according to Table 3, eqs. (4) to (6), and taking into account the specific process temperatures.

⁷ For simplicity, when referring to second-law efficiencies, we mean final-to-useful second-law efficiencies.

Table 3. Second-law efficiencies (ϵ) of some frequent end-use devices. Adapted from Ford et al. (1975).

Note: $T_1 > T_2 > T_0 > T_3$. Definitions: W_{max} is the maximum amount of work that could be produced from the relevant energy input; W_{min} is the minimum amount of work required to produce the desired energy transfer; B stands for exergy; $|\Delta H|$ is the heat of combustion; and η and ϵ are the first- and second-law efficiencies, respectively.

End Use \ Source		Work W_{in}	Fuel Heat of combustion $ \Delta H $	Exergy B Heat Q_1 from hot reservoir at T_1
		$W_{max} = W_{in}$	$W_{max} = B$	$W_{max} = Q_1 \left(1 - \frac{T_0}{T_1}\right)$
Work W_{out}	$W_{min} = W_{out}$	$\epsilon = \eta = \frac{W_{out}}{W_{in}}$ (1)	$\epsilon = \frac{W_{out}}{B} \approx \eta$ (2)	$\epsilon = \frac{W_{out}}{Q_1 \left(1 - \frac{T_0}{T_1}\right)} = \frac{\eta}{1 - \frac{T_0}{T_1}}$ (3)
Heat Q_2 added to warm reservoir at T_2	$W_{min} = Q_2 \left(1 - \frac{T_0}{T_2}\right)$	$\epsilon = \frac{Q_2}{W_{in}} \left(1 - \frac{T_0}{T_2}\right) = \eta \left(1 - \frac{T_0}{T_2}\right)$ (4)	$\epsilon = \frac{Q_2}{B} \left(1 - \frac{T_0}{T_2}\right) \approx \eta \left(1 - \frac{T_0}{T_2}\right)$ (5)	$\epsilon = \frac{Q_2 \left(1 - \frac{T_0}{T_2}\right)}{Q_1 \left(1 - \frac{T_0}{T_1}\right)} = \eta \frac{1 - \frac{T_0}{T_2}}{1 - \frac{T_0}{T_1}}$ (6)
Heat Q_3 extracted from cool reservoir at T_3	$W_{min} = Q_3 \left(\frac{T_0}{T_3} - 1\right)$	$\epsilon = \frac{Q_3}{W_{in}} \left(\frac{T_0}{T_3} - 1\right) = \eta \left(\frac{T_0}{T_3} - 1\right)$ (7)	$\epsilon = \frac{Q_3}{B} \left(\frac{T_0}{T_3} - 1\right) \approx \eta \left(\frac{T_0}{T_3} - 1\right)$ (8)	$\epsilon = \frac{Q_3 \left(\frac{T_0}{T_3} - 1\right)}{Q_1 \left(1 - \frac{T_0}{T_1}\right)} = \eta \frac{\frac{T_0}{T_3} - 1}{1 - \frac{T_0}{T_1}}$ (9)

Mechanical drive includes all mechanical work end uses. It comprises all types of conversion to physical work, regardless the energy source. However, since different energy sources have different second-law efficiencies, source-specific subcategories of mechanical drive are considered, rather than a rough estimation of an aggregate efficiency for this category (eq. (2)). The most common uses in this category are internal combustion engines (depending on the source, natural gas, gasoline, diesel and aviation engines are distinguished), animal-drawn vehicles, and electric engines. The necessary disaggregation of data by final use sector and energy vector allows for the subdivision of this category in two main types of mechanical drive: transport (both freight and passenger) and stationary mechanical drive.

Light includes the total lighting end uses whatever the energy source. Nowadays lighting comes almost all from electricity, although in the beginning of the 20th century most lighting was produced from oil products, fat or “town gas” made from coal. Light efficiency calculations differ from other categories in their methodology. Light efficiency does not measure the share of exergy used that is transformed in a useful work output, because it is measured in lumens per Watt⁸. The use of a different methodology in this case may raise a question of consistency. However this lighting efficiency methodology is widely used in lighting literature and efficiency studies (Ayres et al., 2005; Fouquet and Pearson, 2006; Nordhaus, 1998).

Other electric uses include all electricity final uses that do not provide heat, mechanical drive or light. The main examples are electronic equipment and electrochemical uses of electricity. Their estimation was based on previous historical studies (Ayres et al., 2005; Rosen and Bulucea, 2009).

The muscle work category comprises useful work from feed and food energy uses, i.e. the useful share of human intake of food exergy. It takes into account the food consumption of the country. Efficiency calculations in this category consider the human and animal efficiency of converting exergy from food or feed to muscle work. This muscle work category aims to quantify the mechanical work produced by humans and animals, without measuring the exergy embodied in human labour as in the Extended Exergy Accounting method suggested by Rocco et al. (2014).

2.3. Measuring efficiencies

In thermodynamics one often considers two different efficiency definitions: energy efficiency, or first-law efficiency, and exergy efficiency, or second-law efficiency (Cullen and Allwood, 2010; Ford et al., 1975; Hammond and Stapleton, 2001).

Energy efficiency expresses the fraction of energy of desired kind that is transferred in a process. It is defined as (Ford et al., 1975)

⁸ Lumen is a unit of luminous flux, which is a measure of the share of visible light emitted by a luminous source. It achieves a maximum for a source emitting green light with a wavelength of 555 nm – the colour to which the human eye is most sensitive. Lumen per watt is therefore a measure of the luminous efficacy of a given source, for which an ideal 555 nm source has 683 lm/W, or 100% efficiency.

$$\eta = \frac{\text{desired energy transfer}}{\text{relevant energy input}} . \quad (10)$$

For example, when assessing a power cycle the first-law efficiency is the quotient of the net work done by the cycle and the heat input to the cycle. As a consequence of the 1st and the 2nd laws of thermodynamics, we get $0 \leq \eta < 1$ in this case. However, energy efficiency does not behave this way for all energy uses and devices. Heat pumps exhibit first-law efficiencies greater than 1, because the relevant energy input does not include the heat input from the environment (the cold reservoir).

Since the domain of η is any positive real number, this example demonstrates that the first-law efficiency does not provide a comparable figure of merit across energy uses (Ford et al., 1975).

The second-law efficiency is defined as the ratio of end use/source in exergy terms (Cullen and Allwood, 2010; Moran and Shapiro, 2004):

$$\epsilon = \frac{\text{desired exergy output}}{\text{relevant exergy input}} . \quad (11)$$

This second-law efficiency is widely accepted and used as a figure of merit for energy use. It measures for each process the distance from the theoretical ideal process, as it compares the actual amount of work output with the theoretical maximum.

As a consequence of the second law of thermodynamics, exergy efficiency is bounded by $0 \leq \epsilon \leq 1$, and therefore the 2nd law efficiency expresses a figure of the quality and closeness to an ideal process for a given energy use.

To obtain 2nd law efficiency values in this work we will use the following definition, obtained directly from eq. (11) applying the definition of exergy:

$$\epsilon = \frac{\begin{array}{c} \text{minimum amount of work} \\ \text{required to produce the desired energy output} \\ \text{maximum amount of work} \end{array}}{\text{that could be produced from the relevant energy input}} . \quad (12)$$

This definition is useful in the context of this paper because we want to measure and study the performance of energy uses throughout a country or an economy. Table 3 presents the second-law

efficiency for several sources and end-uses of energy. The use of eq. (12) allows for a clear intuition on Table 3: each row (end use) has the same expression for the minimum amount of work and each column (source) has the same expression for the maximum. For example, eq. (7) is the ratio $\frac{W_{min}}{W_{max}}$ with $W_{min} = Q_3 \left(\frac{T_0}{T_3} - 1 \right)$, because in a Carnot refrigeration cycle (the ideal situation) $Q_3 \left(\frac{T_0}{T_3} - 1 \right)$ is the amount of work required to extract Q_3 from a cold reservoir at T_3 . Also $W_{max} = W_{in}$ because the source is work itself.

2.4. Useful work for each year

Useful work values for each year (U) can be obtained after the estimation of second law final-to-useful efficiencies, as

$$U = \sum_i \epsilon_i B_i ,$$

where B_i stands for the final exergy of the useful work category i and ϵ_i is the second-law final-to-useful efficiency for the useful work category i .

3. Allocation of final exergy to useful work categories

A straightforward allocation of final energy to useful work categories can be made regarding food and feed – for muscle work – and the other non-conventional vectors – for mechanical drive. However, the allocation procedure becomes more complex regarding the remaining energy vectors.

Regarding coal and oil products, natural gas and combustible renewables, the allocation of final energy uses to useful work categories was made for the period 1960 to 2009 from IEA energy balances, based on the sectoral disaggregation provided by this database (Appendix A). However, for former years the allocation process is less intuitive. This allocation was based on existing records of national and international official entities for trade and customs and previous works on the history of energy use in Portugal (Appendix B). Regarding electricity, the allocation was based in detailed information that characterizes the electricity end-uses. A brief description of this allocation and of the idiosyncrasies of the use of each energy vector in Portugal is presented herein for each energy vector.

3.1. Coal

Coal started to be used in Portugal by the end of the 18th century when the first Portuguese coal mines started to be explored. First coal replaced firewood and served thermal uses in households, providing low temperature heat and space heating. Later, it was introduced in industries for the same uses (Henriques, 2006, 2011). The use of coal for mechanical drive was made possible by the huge railway investments in the late 19th century. Another noteworthy coal consumer are boats, but their consumption figures are very difficult to track (Henriques, 2011). Therefore we assumed the growth rate in the length of Portuguese railways as a proxy for the use of coal for mechanical drive⁹.

During the First World War coal consumption dramatically fell due to European instability and disturbance in coal imports. Portuguese domestic coal production was small and of low quality, which caused a temporary substitution of firewood for coal in thermal uses. After World War I some instability in coal imports remained and the use of coal declined. With the industrial promotion plans of the mid-1950's, a decreasing coal use became confined to some of the industrial medium and high temperature heat uses.

Since 1985, when the Sines thermoelectric power station started its activity, almost all uses of coal have been primarily assigned to electricity generation instead of heat. Also since 1985, coal consumption in the cement production industry has dominated coal direct final uses. Mechanical drive from coal took place mainly in steam locomotives that were replaced by the 1970's.

3.2. Oil

In Portugal all crude oil has to be imported. The country started in 1861 importing oil products such as kerosene and later butane and oil lubricants that were used in private and public lighting. The imports of gasoline, diesel and fuel-oil started in the first decades of the 20th century. These combustibles were used for the first motor vehicles, but also for electricity and heat generation (DGSE, 1929-1984; Henriques, 2011; INE, 1875-2009).

⁹ Rail traffic, rather than the length of railways, has a direct relation with exergy consumption. The lack of data on passenger-kilometres or tonnes-kilometres over such a long timeframe led us to assume traffic growth rate proportional to the length of railways' growth rate. However, since energy use in trains is extremely modest (less than 1% of the total final exergy consumption) for the overall results assessed in this paper, this proxy for rail energy use is considered to be satisfactory.

Since 1941, Portuguese National Statistics started the assessment of energy uses in the industrial sector. Based on these figures, one can estimate the shares of mechanical drive and thermal uses from oil products (INE, 1941-1960).

During the last decades heating oil uses are shrinking, the use of oil to generate electricity has almost vanished and nearly 70% of final direct use of oil products occurs in the transport sector.

3.3. Natural gas

Natural gas was introduced in Portugal in 1997 after the construction of a gas pipeline that enabled natural gas imports from Algeria. The introduction of natural gas substitutes some energy services provided by coal, combustible renewables and mainly by oil products. Its most important uses occur in the heavy industry sector, mainly for medium and high temperature heat. Domestic sector shares of use for space and water heating and cooking almost stabilized since 2000. Electricity generation from natural gas is also a very important secondary use.

3.4. Combustible renewables

Combustible renewables were used mainly for low temperature heat and space heating uses. Henriques (2011) provides data on firewood energy final uses by households, industries and transport sector. It is reasonable to think that all domestic use of firewood is for cooking, space and water heating, falling within the category of low temperature heat uses. Also, firewood uses by the transport sector provide mechanical drive as a substitute for coal in years of coal scarcity.

Industrial uses of firewood are more difficult to assess. Different uses can be made, however it is reasonable to think that all of them are thermal energy uses. Different industrial activities, even in the 19th century, required high or medium temperatures in their processes, e.g. foundries and ceramics and glass processing. Therefore we assumed a 50% split for medium temperature uses and 50% for low temperature heat uses of firewood in industry.

More recently other combustible renewables' products started being used, such as biofuels for mechanical drive. These uses occur significantly only after 1990, years for which we have detailed data available in the IEA energy balances (IEA, 2011a).

3.5. Electricity

Since 1960 the IEA energy balances provide data on electricity consumption for each sector of the economy, although no detail on the electricity end-uses is known. For the pre-1960 period the lack of information is even more striking, since there is no available data on detailed sectoral electricity uses. To take advantage from existing detail for each period (before and after 1960) two methodologies were followed to estimate the shares of electricity uses by each useful work category.

Since 1960 it is possible to distinguish between industrial and non-industrial (domestic + services) electricity uses. Therefore we consider these two groups of electricity consumers in this period, for which we estimate shares of electricity uses by each useful work category. Portugal lacks consistent statistics on electricity uses. For the domestic sector INE only provides data on comfort indicators of households as well as on electricity uses and electric equipment owned by families since 1987 (DGGE, 2004; INE, 1987-1997, 2010). For the industrial sector in 1960, electricity uses are provided by Industrial Statistics (INE, 1941-1960). These datasets combined with information from the Energy Information Administration (EIA, 2006) for US industries provide an insight on the shares of electricity uses across sectors in Portugal since 1960.

For the period before 1960, to overcome the absence of convenient data, we used available information for Portugal of the shares of electricity uses by useful work category, and extrapolated the evolution of these shares for the entire time span, using the estimations on the evolution of the shares of different electricity uses in the USA (Ayres et al., 2005). Convenient adaptations were made in order to match the electricity end-uses in Ayres et al. (2005) and the useful work categories defined in section 2.2. Estimated shares of electricity end-use for each year are presented in the supplementary data file attached to this paper.

3.6. Other non-conventional

Exergy inputs from non-conventional energy vectors comprise wind kinetic energy flows for sailing ships and fishery boats, as well as wind and water streams for cereal mills and industrial mills. These values are obtained from Henriques (2011) and accounted as pure mechanical drive uses.

4. Second law final-to-useful efficiencies

Useful work values can only be obtained after the estimation of second law final-to-useful efficiencies. In section 3, final exergy figures were obtained and allocated to useful work categories. This classification helps to identify specific patterns of energy use and consequently different aggregated final-to-useful efficiencies for each useful work category.

4.1. Heat

Heating final-to-useful efficiencies are obtained from eq. (4), (5) or (6), whenever heat is provided from electricity, a fuel combustion process, or a CHP facility, respectively. In any case, heat efficiencies depend on the first-law efficiency (η), the environment reference temperature (T_0) and the temperature at which heat delivery occurs (T_2). Heating uses from CHP heat depend also on the temperature of the steam provided (T_1).

Estimating heating final-to-useful efficiencies implies assessing the evolution of first-law efficiencies (η) that capture the state of the art of heat end use devices. Technological changes in heat exchangers, boilers, furnaces, and radiators imply changes in first-law efficiencies of these devices. Heat exergy uses occur mainly in industry as process heat. Technological change in industry heat uses is not very well documented in the literature, except for ammonia and polyethylene industries, sectors where process heat plays a crucial role (Joyce, 1991; Smil, 2001). These studies provide data on energy productivity of ammonia and polyethylene industries that are adequate representatives for heat uses¹⁰. We can therefore estimate aggregate first- and second-law efficiencies for most of the 20th century (Figure 2).

¹⁰ Polyethylene and ammonia industries comprise the most relevant chemical industries in Portugal since 1960.

Figure 2. Second-law efficiencies of heat production from 1856 to 2009.

We have distinguished two different environment temperatures (T_0) for each year to compute the heating second-law efficiencies: (i) the average temperature for the winter months in Lisbon¹¹ for space heating uses; (ii) the yearly average air temperature for Lisbon for the remaining heat uses (IGIL, 1856-2007).

The temperature at which heat transfer occurs (T_2) is chosen differently for each heating use category: high, medium or low temperature heat. As second-law efficiencies are much more sensitive to lower than higher temperatures, we subdivided low temperature heat in several subcategories, considering T_2 values from 23°C for space heating to 120°C for some industrial uses.

¹¹ Lisbon is located near Portugal centroid's latitude and is the biggest city, comprising a significant share of Portuguese industries. Also, thermal amplitudes within the Portuguese territory are not that significant. Therefore, it is reasonable to consider Lisbon temperatures as reference temperatures.

4.2. Mechanical drive

Gasoline engines (those that perform Otto thermodynamic cycles) have a second-law efficiency given by (Ford et al., 1975; Heywood, 1988; Ross, 1997):

$$\epsilon \approx \eta_{theoretical\ maximum} \prod_{i=1}^6 \alpha_i, \quad (13)$$

where $0 \leq \alpha_i \leq 1, \forall i$ are coefficients that stand for the bias from real to ideal use settings and $\eta_{theoretical\ maximum}$ depends on the compression ratio and the specific heat ratio ($\gamma = \frac{c_p}{c_v} \approx 1.4$):

$$\eta_{theoretical\ maximum} = 1 - \left(\frac{1}{r}\right)^{\gamma-1}.$$

Table 4 shows the values for each coefficient α_i and Figure 3 shows the evolution for compression ratios.

Table 4. Considered α_i coefficients. Based on Ford et al. (1975); Heywood (1988); Ross (1997).

Coefficient i	Meaning	Approximate value	Notes
1	Reduction due to stoichiometry deviations.	0.75	Deviations from stoichiometric conditions occur just momentarily.
2	Combustion and cylinder wall's losses.	0.75	
3	Friction losses.	0.75 – 0.90	Friction losses have decreased during the 20th century. We assumed an evolution from 0.75 to 0.90 between 1900 and 2000.
4	Partial load.	0.40 – 0.50	In average terms, vehicles partial load is very low. Rare situations occur where full power is used, except in heavy transport vehicles that work close to the maximum. This coefficient has been evolving during the 20th century. By the beginning of the century vehicle worked closer to full power. We assumed an evolution from 0.50 to 0.40 between 1900 and 2000.
5	Accessories losses (includes air conditioning).	0.90	
6	Transmission losses.	0.75 (autom.); 0.90 (manual)	In Portugal and generally in Europe the vast majority of vehicles have had manual transmission.

Figure 3. Compression ratio of standard gasoline engines from 1856 to 2009.

Regarding Diesel vehicles, it is reasonable to assume that their second-law efficiency is 25% higher than gasoline vehicles, because a well designed Diesel engine exhibits a greater compression ratio and a better fuel-burning efficiency (Ford et al., 1975).

Mechanical drive uses also comprise other equipment such as steam locomotives, Diesel-electric locomotives, aviation engines, boat engines and electric motors. For these five different mechanical drive equipment, second-law efficiencies may be estimated based on previous studies. Since most of this equipment is imported, it is reasonable to think that it follows the efficiency evolution paths of other countries, namely central European countries and the USA (Ayres et al., 2003).

Figure 4 summarizes estimated second-law efficiencies for mechanical drive uses in Portugal.

Figure 4. Mechanical drive equipment second-law efficiency from 1856 to 2009.

4.3. Light

Light end use efficiencies are well documented in the literature (Ayres et al., 2005; Fouquet and Pearson, 2006; Nordhaus, 1998). Lighting available technologies in Portugal did not differ in time significantly from other developed countries. It seems reasonable to apply US estimated efficiencies estimated by Ayres et al. (2005) to the Portuguese case.

4.4. Other electric uses

Ayres et al. (2005) subdivide other electric uses in two classes: (i) use in communication, electronic and electric devices; (ii) electrochemical uses. Using US second-law efficiencies from Ayres et al. (2005) and knowing the share of these two types of electricity (section 3.5) use we estimated second-law efficiencies for this useful work category. Other electric uses only gains relevance since the 1950's in Portugal, as a consequence of the huge industrial development that drove a significant increase in electricity uses. In this period the pattern of electricity use changed in Portugal, shifting from lighting uses to electrochemical and mechanical driving uses, mainly in industries. Since the 1970's the

pervasive use of electric equipment, namely radios, TV sets, and more recently appliances, personal computers, and electronic devices, changed the electricity uses in households (Table 5). Such electronic devices comprise a significant diversity of end-uses and include heating, ventilation and air conditioning (HVAC), refrigeration and household appliances. Thus, this group exhibits an average second-law efficiency lower than electrochemical uses, causing an overall decrease in other electric uses' efficiency since the 1970's in Portugal.

Table 5. Dissemination of electric equipment in Portuguese homes in percentage (INE, 1970, 1976, 1983, 1987-1997, 1992, 1997, 2002, 2008, 2010).

%	1960	1970	1980	1990	2000	2005
Fridge	75.6	81.1	86.8	91.9	97.1	99.0
Electric heater	18.8	27.1	35.1	40.8	52.0	53.3
TV	71.3	78.1	85.1	91.3	97.9	98.9
Computer	0.0	0.0	0.0	5.0	22.0	43.9

Figure 5 shows estimated second-law efficiencies of light and other electric uses in Portugal.

Figure 5. Light and other electric uses second-law efficiencies in Portugal from 1895 to 2009.

4.5. Muscle work

Muscle work is the sum of useful work provided by working animals and humans.

Used datasets provide data on food intake per capita as metabolizable energy (FAO, 2011; Henriques, 2011), which is the amount of energy in the consumed food that could be used by the organism.

However, final exergy calculated must refer to food supply gross exergy data. These figures are obtained multiplying metabolizable data by a gross/metabolizable ratio which is estimated to be 1.23 for Western European countries, according to Wirsenius (2000).

However not all supplied food is eaten and a useful work calculation must take this into account. The supplied/eaten ratio has evolved from 95% in the second-half of the 19th century to only 63% nowadays (Wirsenius, 2000).

Feed intake by working animals was provided by the statistics of Henriques (2011). Similarly to muscle work from food calculations, a gross/metabolizable ratio was estimated to be 1.54 and a supplied/eaten ratio of 64% was considered (Wirsenius, 2000).

Muscle work figures are obtained considering a food/feed-to-useful work efficiency of 13% for humans and working animals (Smil, 1994).

5. Results and discussion

Overall, we see that Portuguese final exergy consumption dramatically increased from nearly 100 PJ in 1856 to 903 PJ in 2009, accompanying most developed countries (Figure 6). Final exergy and useful work results for each year are presented in the supplementary data file attached to this paper.

Figure 6. Portuguese final exergy inputs by vector.

The transition from feed, food and biomass to fossil fuels is visible during the analysed period. In 1856, biomass (including food and feed) accounted for nearly 95% of the total final exergy consumption in Portugal. In that year the first railway in Portugal between Lisbon and Carregado (a small town about 30 km north of Lisbon) was inaugurated. The first industrialization era had started in Portugal and fossil fuels started to gain relevance in the energy panorama. Thereafter the share of food and feed in societal exergy inputs dramatically decreased with the massive use of high-density energy vectors. Food and feed products evolved from quantitatively essential to irrelevant in the Portuguese energetic context.

Figure 6 shows that in this 154-year evolution there was a change in the final exergy mix input to the economy. Coal was the first class of fossil fuels introduced in Portugal. It gained relevance in the final exergy mix achieving nearly 20% by 1913. However, a huge retraction of coal imports from European countries during the First World War ended the growing share of coal. In the post-WWI decades oil products started being used for mechanical drive and heating. Also since the mid-1940s decade electricity started gaining relevance. In quantitative terms the absolute figures of final exergy consumption rose significantly from the 1960s decade onwards as a consequence of vast industrialization programs known as the second industrialization era in Portugal. In the end of the 20th

century the energy transition from biomass products to fossil fuels and electricity has stabilized with an overall change from 95% to 20% of the share of biomass in total exergy inputs.

Portuguese useful work also increased substantially, from 6.6 PJ in 1856 to more than 175 PJ in 2009 (Figure 7). It is worth mentioning a more than 26-fold increase in useful work, a 9-fold increase in final exergy and an almost 3-fold increase in population over this timespan, showing different behaviours of these quantities due to efficiency improvements and transformations in intensities.

Figure 7. Portuguese useful work by category.

Over this timespan the structure of useful work categories changed in Portugal (Figure 8). The economy evolved to a higher dependency on mechanical drive services than in the past. Also, as referred, other electric uses and higher temperature heat uses gained importance. These changes happened as a consequence of the industrialization of the country and mobility needs that led to increases in transport sector energy uses.

Figure 8. Useful work by category in percentage.

Relevant increases in the final-to-useful efficiency are visible, starting in the beginning of the 20th century but in a more pronounced way since World War II (Figure 9). This shows technological progress at the energy use level, but is also a consequence of changes in the type of energy uses and energy vectors to a more efficient setup. Technological changes implied more efficient devices and enabled more efficient and valuable uses of energy. We can identify four different periods of efficiency improvements:

- Until 1920 – There are not significant changes. During this period exergy inputs are used for muscle work and low temperature heat, resulting in an aggregate efficiency between 6% and 7%. Until 1920 there was a slight substitution from fuelwood to coal, keeping the exergy uses unchanged, and therefore with no significant impact on efficiencies.
- From 1920 to 1950 – There is a slight improvement in aggregate efficiency, mainly motivated by low, medium and high temperature heat uses and their efficiencies, as a consequence of a phase of primordial industrialization in Portugal.
- From 1950 to 1980 – This was the period with fastest efficiency improvements, mainly motivated by the electrification process that occurred firstly in industries, providing electric stationary work. This led to the pervasive use of electric mechanical drive (second-law efficiencies of about 70–80%). Another factor was the increasing high temperature heat uses

(second-law efficiencies of about 34–44%), caused by the second industrialization era in Portugal.

- From 1980 onwards –The aggregate efficiency stabilized between 18% and 20% after 1980, due to a significant increase in automobile uses that have offset the continuing but slowing down electrification process.

Figure 9. Aggregated final-to-useful second-law efficiency in Portugal from 1856 to 2009.

Additional insight can be obtained by considering final exergy and useful work intensities, i.e., final exergy/GDP and useful work/GDP ratios, respectively. This approach implicitly assumes, like all energy intensity studies, that all energy uses are associated to economic activity. This assumption is empirically sensible as long as the ratio of economic to non-economic uses is approximately constant and conceptually sensible as long as we consider that all energy uses are indirectly supporting economic activities, even if not being directly used in them.

For this analysis, a real GDP time series is necessary. Here we use the historical GDP series recognized by the Bank of Portugal (Banco de Portugal) and published in Lains (2003) and in Maddison (2001). For the period before the mid-twentieth century, the real GDP time series is estimated using production indices based on physical quantities (with aggregation based on the relative shares of each sub-sector at a reference year), so no price index is required (real values are directly calculated, so there is no need

to convert from nominal to real values). It is the rate of change of the production indices that is used, which has the advantage of removing the effect of different accounting conventions in different time periods.

Henriques (2011), based on the analysis of primary energy intensity for Portugal, found three main periods: 1856 – 1920, with a constant primary energy intensity; 1920 – 1973, with a decrease to one third of primary energy intensity; 1973-present, with a comparative constancy of primary energy intensity. Interestingly, in the period 1920 – 1973, modern energy intensity (i.e., coal, oil and primary electricity) had no great changes, i.e., “*modern energy intensity recovered its 1913 values in the mid 1970s*” (Henriques, 2011, p.111). The intensity of traditional energy decreases essentially because it is growing slower than GDP. Henriques (2011) finds no Kuznets curve in energy intensity, either with total energy or with modern energy. Henriques (2011) considers as a very relevant explanatory factor the fact that during a long period household energy dominated the energy system (71% of primary energy in 1880; still 60% in the 1950s).

Figure 10 plots final exergy and useful work intensities in Portugal from 1856 to 2009. We can identify different periods with distinct behaviours in intensity measures:

- Until 1920 – Both curves have a somewhat decreasing trend, because efficiency remained almost constant over this period.
- From 1920 to 1950 – A slight improvement in aggregate efficiencies, together with an accelerated decrease in final exergy intensity and a stable trend in useful work intensity, shows a reduction in the demand for exergy resources to each unit of GDP.
- From 1950 to 1980 – The period of fast electrification and efficiency improvements promoted a sharp reduction in the exergy intensity. This decreasing path was interrupted in the 1960's as a consequence of the most significant industrialization period in Portugal¹². Useful work intensity also slightly decreases until 1970, but dramatically increases during the 1970's, mainly motivated by two factors: (i) a very fast demographic transformation, with the resident population increasing from 8.6 millions in 1974 to 9.7 millions in 1980, as a consequence of

¹² Over the 1960's, known as the second industrialization era in Portugal, industrial value-added increased from 38% to 51% of the GDP (Lains, 2003).

the democratic revolution and the decolonization process; (ii) a significant increase in the use of electricity-powered goods (Table 5) as well as the popularization of individual cars, intensifying the domestic (recreational and non-productive) energy uses. These two factors, motivated an increase in non-productive energy uses and a consequent increase in the useful work consumed that outstripped a modest GDP growth, are demonstrated by: (i) a higher average annual growth rate in residential exergy consumption (8.4%) compared to the total final exergy consumption (5.2%); (ii) an increase in the share of gasoline in total road transport consumption (from 39% to 59%) over the period from 1974 to 1980, with a corresponding increase in useful work intensity of 0.05 MJ/€.

- From 1980 onwards – Final exergy and useful work intensities stayed almost constant, whereas the aggregate efficiency increased only slightly.

Figure 10. Exergy intensity and useful work intensity in Portugal from 1856 to 2009.

So, the main difference regarding energy transitions that our final and useful exergy analysis brings, compared to primary energy, is regarding the period 1920 – 1973, which we can split in two: (i) 1920 – 1950, when there is an a reduction of primary and final energy intensities as a consequence of an improvement in final-to-useful efficiencies, and (ii) 1950 – 1973, when there is a change in the structure of energy uses.

In Figure 11¹³ and Figure 12 the primary exergy¹⁴ and useful work intensities of Portugal are compared with previous country-level useful work analyses (Warr et al., 2010). Exergy intensities show a quite common decreasing trend. However, useful work intensities (Figure 12) tell a different story.

Figure 11. Primary exergy intensity across Portugal, UK, USA, Austria and Japan.

¹³ In this figure we show primary exergy instead of final exergy to allow a direct comparison to primary exergy estimation in previous useful work analyses.

¹⁴ Primary/final exergy and energy intensities exhibit a similar path, because they only differ in an aggregate coefficient, the exergy factor, which is close to 1.

Figure 12. Useful work intensity across Portugal, UK, USA, Austria and Japan.

Table 6 shows the primary exergy and useful work intensities' trends of these countries, using the Prais-Winsten estimation method. Judged by the coefficients of determination and the tests of significance, there is a *ceteris paribus* evidence of a decreasing time trend of primary exergy intensities across the 5 countries, while for the useful work intensities the hypothesis of absence of a time trend cannot be rejected for any country at the level of significance of 5%. On the one hand, this result confirms a decreasing demand for energy (or exergy) resources per unit of GDP, simultaneously with important efficiency gains. On the other hand, the useful work intensities capture changes in patterns of energy use, since useful work accounts for satisfied energy needs, contrarily to primary exergy that accounts for resource inputs.

Table 6. Estimated relationships of intensity measures in countries, using the Prais-Winsten method. The explanatory variable is the time (t), and the dependent variable is either the primary exergy intensity (PBI_t) or the useful work intensity (UWI_t); R^2 is the coefficient of determination; Standard error of the estimate is given in parentheses.

*** Parameter is significant at the level of 1%.

** Parameter is significant at the level of 5%.

* Parameter is significant at the level of 10%.

Country	Primary exergy intensity		Useful work intensity	
	Estimated relationships	Goodness of fit	Estimated relationships	Goodness of fit
Portugal (1856-2009)	$PBI_t = 272.9^{***} - 0.131^{***}t + \varepsilon_t$ (39.8) (0.0206)	R^2 adj. = 0.46	$UWI_t = 5.30^* - 0.0019t + \varepsilon_t$ (3.00) (0.0016)	R^2 adj. = 0.33
Austria (1950-2000)	$PBI_t = 420.4^{***} - 0.205^{***}t + \varepsilon_t$ (41.2) (0.0208)	R^2 adj. = 0.91	$UWI_t = 1.31 + 0.0002t + \varepsilon_t$ (6.74) (0.0034)	R^2 adj. = 0.63
Japan (1900-2000)	$PBI_t = 188.9^{***} - 0.090^{***}t + \varepsilon_t$ (34.6) (0.0177)	R^2 adj. = 0.66	$UWI_t = -15.7 + 0.0086^*t + \varepsilon_t$ (9.81) (0.0050)	R^2 adj. = 0.04
USA (1900-2000)	$PBI_t = 669.3^{***} - 0.327^{***}t + \varepsilon_t$ (55.0) (0.0282)	R^2 adj. = 0.70	$UWI_t = -2.23 + 0.0021t + \varepsilon_t$ (7.59) (0.0039)	R^2 adj. = 0.13
UK (1900-2000)	$PBI_t = 397.3^{***} - 0.194^{***}t + \varepsilon_t$ (45.7) (0.0235)	R^2 adj. = 0.69	$UWI_t = -9.00 + 0.0053t + \varepsilon_t$ (7.17) (0.0037)	R^2 adj. = 0.07

Excluding Portugal, useful work intensities grew significantly after the II World War, peaking almost synchronously and exhibit a turning point around 1970 (Warr et al., 2010), mostly due to a significant increase in electricity-powered goods and the popularization of individual cars and consequently a sharp increase in passenger transport. This process took place in Portugal later. On the one hand, Portugal industrialized and opened its economy later, during the 1960's; these are the two main factors that explain the accelerated economic growth in this decade (Lains and Ferreira da Silva, 2005). On the other hand, Portuguese colonial war (1961 – 1974) led to a decrease in the useful work intensity, similar to what had occurred in the UK and USA during the II World War, due to a war economy that promoted a cutback of all non-productive energy uses.

The deindustrialization process that started in Portugal by the 1980's, and by the 1970's in the other countries, promoted significant changes in the uses of energy: less useful work for high temperature heat (from 18.5%/16 PJ in 1980 to 7.8%/13.7 PJ in 2009) and stationary power uses, and an increasing share of transport and other electric uses. This transition to a service economy led to a decrease in useful work intensities and a stagnation in second-law efficiencies, more pronounced in the most

industrialized countries, as a consequence of replacing very efficient high temperature heat uses (about 47%) for individual cars (about 13%) and lower temperature heat uses (about 9–26%).

6. Conclusions

Useful work is an exergy assessment that situates the analysis at the level of satisfied needs, after all processes of energy transformation and conversion. In this paper, we present a useful work accounting methodology that considers final-to-useful efficiencies for all energy uses, enabling a better characterization of the energy end-uses. This required refining the methodology used in previous analyses regarding the treatment of electricity. Previous works considered an aggregate electricity end-use efficiency (for the USA), neglecting differences in final-to-useful electrical conversions. We consider separately final-to-useful efficiencies of electricity end-uses in the relevant useful work categories: heat (low, medium, and high temperature), mechanical drive (electric motors), light, and other electric uses. This distinction turns out to be extremely relevant, since sectoral structure in Portugal is very different from the USA along most of the period considered (e.g., the share of industry in economic activity) and since the efficiencies in the several useful work categories are quite different.

The long-term analysis of energy uses presented in this paper implied the use of historical energy data and the estimation of missing data and efficiencies for several technical components of the energy system. However, rigorous data for estimating conversion efficiencies and energy end-use allocation are not available from the IEA energy balances or any other major energy datasets. Besides, neither the IEA nor other major energy dataset publishers provide any uncertainty analysis. This makes it impossible to do any formal accuracy assessment, a problem that has also been acknowledged by other energy analyses (e.g. Cullen and Allwood, 2010). Notwithstanding, these are currently the best available energy data that can be used to provide a picture of the historical trends.

The interpretation of the structure and dynamics of the Portuguese useful work in the very-long term allowed for a better understanding of the importance of useful work accounting and its sensitivity to structural changes in the way energy is used and how it is related with the economic growth process. This paper presents a useful work accounting for Portugal from 1856 to 2009, assessing the energy transitions in terms of energy vectors and types of uses, and the interpretation of the relation between energy use and economic growth across the entire transition from a rural society to a service economy,

exploring the corresponding sectoral and structural transitions. In Portugal, the final exergy mix has significantly changed since 1856. A transition from biomass products to fossil fuels and electricity took place. Also, the useful work by types of use has changed from 1856 to 2009, accompanying the major structural changes in the demand for energy services. Such structural changes were promoted by the introduction of new energy vectors and the consequent changes in the final exergy mix. Such transition and technological progress fostered the improvements in final-to-useful conversion efficiencies.

In Portugal, the aggregate final-to-useful efficiency remained essentially unchanged until the end of the agricultural economy, in spite of important changes in energy vectors (mainly an important substitution of firewood for coal until WWI). The main efficiency improvements occurred due to electrification and industrialization, from 1950 to 1980. A recent transition to a service economy, resulting from the offshoring of heavy industries and consequent deindustrialization, has contributed to a stagnation of aggregate efficiencies. For Portugal from a pre- to a post-industrial economy and in contrast to conventional intensity measures, the useful work intensity (useful work / GDP) does not exhibit a significant time trend. The same result was obtained for other five countries (Table 6). A more detailed analysis can be found in Serrenho et al. (2014).

Recent decoupling literature (UNEP, 2011) acknowledges the need for reducing the level of resource utilization per unit of GDP, which, regarding energy, represents a reduction of the primary energy (or exergy) intensity. Such economic intensity may be achieved by increasing primary-to-final efficiency, final-to-useful efficiency and/or by decreasing useful work intensity, as expressed by eq. (14).

$$\frac{\text{Primary exergy}}{\text{GDP}} = \frac{\text{Primary exergy}}{\text{Final exergy}} \frac{\text{Final exergy}}{\text{Useful work}} \frac{\text{Useful work}}{\text{GDP}} \quad (14)$$

The results obtained, namely (1) the inexistence of a time trend concerning useful work intensity and (2) the recent stagnation of the aggregate thermodynamic efficiency, suggest that further reductions in primary energy (or exergy) intensity may only be achieved:

- by increasing primary-to-final efficiency, subject to thermodynamic limits. However, recent efficiency stagnation suggests that future useful work increases, associated with higher demand for energy services, may only be provided with higher consumption of final exergy and energy resources, rather than efficiency improvements.

- by structural changes that reduce the useful work intensity. However, the inexistence of a significant time trend concerning the useful work intensity supports the need to focus the debate on the scale of growth, rather than the reliance on relative decoupling to achieve sustainability (e.g. Jackson, 2009).

Acknowledgments

We acknowledge the support of FCT through PhD grant SFRH/BD/46794/2008 to André Cabrera Serrenho and through project PETE (PTDC/AMB/64762/2006). We also acknowledge the support of AdI through project *Energy Wars* (QREN7929).

The majority of the work by André Cabrera Serrenho was done whilst at IN+, Centre for Innovation, Technology and Policy Research, Department of Mechanical Engineering, Instituto Superior Técnico, Universidade de Lisboa.

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Appendices

A. Allocation of useful work categories with IEA energy balances (1960-2009)

Sector		Energy carrier		Useful work category
Energy sector own uses	Coal mines	Coal products		Medium temperature heat
		Oil products	Gas/diesel oil	Mechanical drive
	Oil and gas extraction	Oil products	Gas/diesel oil	Mechanical drive
			LPG	Mechanical drive
	Oil refineries	Oil products		Medium temperature heat
		Natural gas		Medium temperature heat
	Gas works	Coal products		High temperature heat
		Natural gas		High temperature heat
	Coke ovens	Coal products		High temperature heat
		Natural gas		High temperature heat
Industry	Patent fuel plants	Coal products		Medium temperature heat
		Oil products	Bitumen	Low temperature heat
	Other non-specified		Gas/diesel oil	Mechanical drive
		Coal products		High temperature heat
	Iron and steel	Oil products	Gas/diesel oil	Mechanical drive
			Fuel oil	High temperature heat
			LPG	High temperature heat
		Natural gas		High temperature heat
		Coal products		50% High temperature heat
				50% Medium temperature heat
		Oil products	Gas/diesel oil	Mechanical drive
			Fuel oil	50% High temperature heat
			LPG	50% Medium temperature heat
			Non-specified	
	Chemical and petrochemical	Natural gas		50% High temperature heat
				50% Medium temperature heat
		Combustible renewables	Industrial waste	High temperature heat
			Solid biofuels	Low temperature heat
	Non-ferrous metals	Coal products		50% High temperature heat
				50% Medium temperature heat
		Oil products	Gas/diesel oil	Mechanical drive
			Fuel oil	50% High temperature heat
			LPG	50% Medium temperature heat
		Natural gas		50% High temperature heat
				50% Medium temperature heat
		Combustible renewables	Solid biofuels	Low temperature heat
	Non-metallic minerals	Coal products		High temperature heat
		Oil products	Gas/diesel oil	Mechanical drive
			Fuel oil	50% High temperature heat
			LPG	50% Medium temperature heat
			Petroleum coke	
		Natural gas		50% High temperature heat
				50% Medium temperature heat
		Combustible renewables	Industrial waste	High temperature heat
			Solid biofuels	Low temperature heat
	Transport equipment	Coal products		50% High temperature heat
				50% Medium temperature heat
		Oil products	Gas/diesel oil	Mechanical drive
			Fuel oil	50% High temperature heat
			LPG	50% Medium temperature heat
		Natural gas		50% High temperature heat
				50% Medium temperature heat
	Machinery	Coal products		50% High temperature heat
				50% Medium temperature heat
		Oil products	Gas/diesel oil	Mechanical drive
			Motor gasoline	
			Fuel oil	50% High temperature heat
			LPG	50% Medium temperature heat
		Natural gas		50% High temperature heat
				50% Medium temperature heat
		Combustible renewables	Solid biofuels	Low temperature heat
	Mining and quarrying	Oil products	Gas/diesel oil	Mechanical drive

Sector		Energy carrier		Useful work category
Food and tobacco	Coal products	Motor gasoline		50% High temperature heat
		Fuel oil		50% Medium temperature heat
		LPG		50% High temperature heat
		Natural gas		50% Medium temperature heat
		Oil products		Low temperature heat
	Oil products	Gas/diesel oil		Mechanical drive
		Motor gasoline		Mechanical drive
		Kerosene		Low temperature heat
		Fuel oil		Low temperature heat
		LPG		Low temperature heat
Paper, pulp and print	Coal products	Natural gas		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Gas/diesel oil		Mechanical drive
		Fuel oil		Low temperature heat
	Oil products	LPG		Low temperature heat
		Natural gas		Low temperature heat
		Combustible renewables		Low temperature heat
		Solid biofuels		Low temperature heat
		Oil products		Low temperature heat
Wood and wood products	Coal products	Gas/diesel oil		Mechanical drive
		Fuel oil		Low temperature heat
		LPG		Low temperature heat
		Natural gas		Low temperature heat
		Combustible renewables		Low temperature heat
	Oil products	Solid biofuels		Low temperature heat
		Gas/diesel oil		Mechanical drive
		LPG		Mechanical drive
		Motor gasoline		Mechanical drive
		Fuel oil		Low temperature heat
Construction	Coal products	Natural gas		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Gas/diesel oil		Mechanical drive
		LPG		Mechanical drive
	Oil products	Motor gasoline		Mechanical drive
		Fuel oil		Low temperature heat
		Natural gas		Low temperature heat
		Combustible renewables		Low temperature heat
		Solid biofuels		Low temperature heat
Textile and leather	Coal products	Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Solid biofuels		Low temperature heat
	Oil products	Coal products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Solid biofuels		Low temperature heat
Other non-specified	Coal products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
	Oil products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
Transport	Coal products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
	Oil products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
Other	Coal products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
	Oil products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
Agriculture/forestry	Coal products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
	Oil products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
Fishing	Coal products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
	Oil products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
Other non-specified	Coal products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
	Oil products	Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat
		Oil products		Low temperature heat
		Combustible renewables		Low temperature heat

B. Allocation of useful work categories for the period 1856-1959

Energy vector	Useful work category	Data sources
Coal and coal products Oil and oil products	High Temp. Heat	INE (1941-1960) DGSE (1929-1984) Henriques (2011)
	Medium Temp. Heat	
	Low Temp. Heat	
	Mechanical drive	Henriques (2011) Fouquet and Pearson (2006)
	Light	
Combustible renewables	Medium Temp. Heat	Henriques (2011)
	Low Temp. Heat	
	Mechanical drive	
Electricity	High Temp. Heat	Ayres et al. (2005) INE (1941-1960) Fouquet and Pearson (2006)
	Low Temp. Heat	
	Light	
	Other electric uses	
	Mechanical drive	
Food for humans	Muscle work	Henriques (2011)
Feed for working animals		
Other non-conventional	Mechanical drive	