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# Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009

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ABSTRACT

Energy intensity measures, defined as the ratio of energy use to gross domestic product of a country, are widely used to study the productivity of energy use in an economy. Unlike conventional primary and/or final energy intensities, useful work intensity (useful work/gross domestic product) addresses the problem of aggregating in a single measure the different energy forms used, and allows for a clear distinction between thermodynamic efficiencies and structural changes in the demand for energy end-uses. Here, our aim is twofold: (1) Disclose the factors that control the useful work intensities across the EU-15 countries over the deindustrialization process, performing a decomposition of the useful work intensities from 1960 to 2009. (2) Describe a methodology for the automatization of useful work accounting, based on a general mapping of energy end-uses from IEA (International Energy Agency) energy balances. We show that, in contrast to the other conventional energy intensity measures, useful work intensity depends only on the intensity of high temperature heat uses and the relative size of residential energy needs. Aggregate thermodynamic efficiencies slightly increased as a consequence of technological improvements, but were negatively affected by deindustrialization, as a consequence of a transition to less efficient and productive energy uses.



## 1. Introduction

Energy intensity is commonly defined as the ratio of energy use to GDP (Gross Domestic Product) of a country. There are different types of energy intensity indicators, depending on the energy use measure. Different stages in the energy flow of a country can be defined, from energy resources to end-uses. The most frequent stages are (1) primary energy that refers to the enthalpy or internal energy of the fuels as they are provided by Nature, and (2) final energy that stands for the enthalpy or internal energy of the energy forms as they are used by producers or consumers.

For each time period $t$ (usually one year) the usual energy intensity measures are defined by:

$$\text{Primary Energy Intensity}_t = \frac{\text{Primary Energy Use}_t}{\text{GDP}_t}, \quad (1)$$

$$\text{Final Energy Intensity}_t = \frac{\text{Final Energy Use}_t}{\text{GDP}_t}. \quad (2)$$

These intensities, widely used as indicators of energy-economic performance or even as a measure of the productivity of energy uses, are very often employed in many kinds of sustainability analysis [1–9]. However, the usefulness and significance of these intensity measures at the aggregate country-level have been subject to controversy, at least for two reasons. On the one hand, the use of a high level of aggregation of both the numerator and denominator of primary/final energy intensities does not capture the structural changes in energy consumption and their economic impact [10,11]. On the other hand, the use of (primary/final) energy intensities to carry out comparisons across countries at different levels of economic development becomes problematic due to the differences in the quality of the energy forms used.

Addressing these concerns, recent energy intensity analyses have been carried out at the disaggregate sectoral level to assess changes in energy efficiency, and relation among energy uses, economic activity, and human development over the last few decades

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[12–15]. However, these assessments rely on primary or final energy intensity measures that can lead to erroneous and incomplete conclusions. These intensities depend on the transformation and end-use thermodynamic efficiencies, which depend on technological options, energy conversion processes and patterns of energy end-uses. This makes it impossible to relate such intensity measures with the economic productivity of energy services. As an example, a decreasing trend in primary energy intensity that results from improvements in the transformation efficiencies of the energy sector is compatible with an increasing trend in the demand for energy services per unit of output, due to a transition in technological choices and end-use patterns. In this context, Percebois [16] acknowledges the importance of considering useful energy intensities (eq. (3)), stating that they are the only capable of providing an assessment of the overall resource to end-use efficiency of a system, in contrast to an analysis focused on primary energy intensities.

$$\text{Useful Energy Intensity}_t = \frac{\text{Useful Energy Delivered}_t}{\text{GDP}_t} \quad (3)$$

Decomposition techniques have been applied to numerous primary/final energy intensity analyses with different approaches and goals, such as: measuring the environmental relief resulting from the transition to a service economy [4,17]; assessing the convergence in energy intensities across countries [18,19]; assessing the effects of urbanization and industrialization in energy intensities [20]; or even quantifying the contributions of structural changes and efficiency improvements as determinants of energy intensities [15,21–24]. Divisia index techniques have also been used to disaggregate energy intensities, addressing the problem of energy quality [14,25]. However, these analyses do not focus on the useful stage of the energy flow and consequently do not take into account the full range of energy transformations from resources to end-uses, disregarding the different contributions of efficiency improvements and changes in the structure of energy end-uses.

In this paper, we perform the decomposition of an energy intensity variable that is situated at the useful stage of the energy flow, using an exergy approach: useful work intensity (eq. (4)). By situating the energy accounting at the level of satisfied energy needs, useful work quantifies the actual amount of exergy delivered to end-uses, after all transformation processes subject to conversion efficiencies. This allows for a clear distinction between the thermodynamic efficiencies and the structural changes in the demand for energy end-uses, and their independent contributions to intensity. Additionally, accounting for useful work (instead of useful energy) addresses the problem of the quality of the different energy forms used, quantifying only the effect of an energy use, independently of the energy form or end-use.

$$\text{Useful Work Intensity}_t = \frac{\text{Useful Work Delivered}_t}{\text{GDP}_t} \quad (4)$$

We carry out the decomposition of useful work intensity in the members of the European Union prior to the 2004-enlargement (EU-15) from 1960 to 2009. This time frame comprises the deindustrialization and industrial offshoring process in these countries and their transition to a service economy. Standard energy intensities and useful work intensities changed differently during this time frame, and the decomposition performed here allows us to unveil the structural changes in the economy that promoted those changes in useful work intensities.

Performing this task requires the calculation of useful work time series for each country. Previous useful work analyses have been done for single countries and longer time series [26]. Here we calculate useful work time series systematically for each EU-15 country from the IEA (International Energy Agency) energy balances [27] for the commercial energy carriers and the FAO of the United Nations (Food and Agriculture Organization) database [28] for food and feed, using a general mapping of energy uses and efficiencies. This method, described in Section 2, provides a useful work time series for each EU-15 country obtained automatically from the IEA energy balances. All the useful work results, aggregate efficiencies and intensities are presented in Section 3. The decomposition analysis and statistical analysis of the useful work intensities are described in Section 4. Finally, a summary and discussion are presented in Section 5.

**Table 1**
Disaggregation of end-use categories and data sources.

| Disaggregated end-use categories | Aggregated end-use categories | Data sources |
|---|---|---|
| Fuel – high temp. heat (500 °C) | Heat | [27] |
| Fuel – medium temp. heat (150 °C) | | |
| Fuel – low temp. heat (120 °C) | | |
| Fuel – low temp. heat (90 °C) | | |
| Fuel – low temp. heat (50 °C) | | |
| CHP – medium temp. heat (150 °C) | | |
| CHP – low temp. heat (120 °C) | | |
| CHP – low temp. heat (90 °C) | | |
| CHP – low temp. heat (50 °C) | | |
| Steam locomotives | Mechanical drive | |
| Diesel vehicles | | |
| Gasoline/LPG vehicles | | |
| Aviation | | |
| Navigation | | |
| Natural gas vehicles | | |
| Diesel-electric | | |
| Oil – stationary mech. drive | | |
| Coal – stationary mech. drive | | |
| Coal/oil light | Light | |
| Electricity – industry | Electricity | |
| Electricity – transports | (treated separately) | |
| Electricity – other sectors | | |
| Food for humans | Muscle Work | [28] |
| Feed for working animals | | |

## 2. General mapping of energy end-uses and efficiencies

Useful work ($U$) is calculated for each year ($t$) and combination of energy carrier $i$—economic sector $j$—energy end-use category $k$. This process requires a mapping for energy end-uses, the estimation of thermodynamic second-law efficiencies for each enduse – category ($\varepsilon_{t,k}$), and the definition of an exergy factor[1] for each energy carrier ($\phi_i$) (eq. (5)).

$$U_{t,ijk} = \varepsilon_{t,k}\phi_i E_{t,ijk} \quad (5)$$

The mapping depends on the level of disaggregation of the energy database that provides final energy consumption data ($E_{t,ijk}$). There is a wide choice of energy databases, but the International Energy Agency [27] exhibits the significant advantage of having a systematic framework for all countries and years, avoiding the methodological diversity of energy accounting and sectoral disaggregation of national statistics.

IEA energy balances [27] provide systematic energy statistics for each EU-15 country from 1960 to 2009. This consistent framework with a reasonable level of sectoral disaggregation enables a general mapping, allocating each economic sector to one

[1] The exergy factor is defined as the ratio of exergy to energy (enthalpy, internal energy or others).

**Table 2**
Considered exergy factors [29–31].

| Energy carriers | Exergy factors |
|---|---|
| Coal products | 1.06 |
| Oil products | 1.06 |
| Coke | 1.05 |
| Natural gas | 1.04 |
| Combustible renewables | 1.11 |
| Electricity | 1.00 |
| Food and feed | 1.00 |
| CHP and geothermal heat | 0.40 |
| Solar thermal heat | 0.25 |

end-use category. As the second-law efficiency of each end-use depends also on the energy carrier used in each case, it is essential to split the usual end-use categories (heat, mechanical drive, light, muscle work and other electric uses) into a more disaggregated level.

Electricity can be used either for heating, lighting, mechanical drive, or other electric uses. This multiplicity of purposes of electrical uses does not allow for a simple allocation of electricity consumption to just one end-use category, which led us to treat electricity uses separately. It is important to split electricity consumption into industrial, transportation and other sectors, in order to provide different end-uses' allocations for each of these three sectors.

Muscle work results depend on data for food for humans and feed for working animals, which are absent from standard energy databases, as the IEA balances. This implied the use of FAO database [28] only for this end-use category.

In Table 1 describes the disaggregation of end-use categories, as well as the databases used for each one.

The energy databases used here [27,28] provide final energy consumption data disaggregated in 63 different energy carriers, that could be grouped in 9 sets with common exergy factors (Table 2).

In the next subsections, the mapping and the estimation of efficiencies are described separately, whenever different methodologies are used.

### 2.1. Coal, oil, natural gas, combustible renewables and heat

This subsection refers to all energy carriers whose final energy values are obtainable from the IEA energy balances, except electricity (which is described later). The mapping of the pair energy carriers — economic sectors into disaggregated end-use categories is presented in the Supporting Information File – Section A. This mapping allows us to easily obtain energy data by end-uses directly from the energy databases, such as the IEA highly disaggregated energy balances. This methodology has been used by previous useful work analyses.

**Table 3**
Temperatures and first-law efficiencies by heating category [33,35].

| Heating category | Service temperature ($T_s$) | First-law efficiency (1960–2009) |
|---|---|---|
| Fuel – high temp. heat (500 °C) | 500 °C | 58%–71% |
| Fuel – medium temp. heat (150 °C) | 150 °C | |
| Fuel – low temp. heat (120 °C) | 120 °C | |
| Fuel – low temp. heat (90 °C) | 90 °C | |
| Fuel – low temp. heat (50 °C) | 50 °C | 49%–57% |
| CHP – medium temp. heat (150 °C) | 150 °C | 58%–71% |
| CHP – low temp. heat (120 °C) | 120 °C | |
| CHP – low temp. heat (90 °C) | 90 °C | |
| CHP – low temp. heat (50 °C) | 50 °C | 49%–57% |

**Table 4**
Annual average and winter average temperatures by country (1960–2009) [34].

| Country | Annual average temperature (°C) | Winter average temperature (°C) |
|---|---|---|
| Austria | 9.4 | −0.3 |
| Belgium | 10.7 | 4.0 |
| Denmark | 8.8 | 1.6 |
| Finland | 5.7 | −4.0 |
| France | 13.3 | 6.0 |
| Germany | 9.4 | 0.8 |
| Greece | 17.7 | 9.9 |
| Ireland | 9.6 | 5.0 |
| Italy | 14.9 | 6.0 |
| Luxembourg | 8.9 | 1.1 |
| Netherlands | 9.9 | 3.3 |
| Portugal | 16.1 | 11.1 |
| Spain | 15.9 | 10.0 |
| Sweden | 7.5 | −0.8 |
| United Kingdom | 8.5 | 4.3 |

Second-law efficiencies (Supporting Information File – Section B) are defined for each disaggregated end-use category (as in Table 1) and year. These categories correspond to heating, mechanical drive and lighting uses, all of them described below.

#### 2.1.1. Heat

Heating from fuel second law efficiencies ($\varepsilon$) is a function of a technological first-law efficiency ($\eta$) and of environment and service temperatures, $T_0$ and $T_s$ respectively [32]:

$$\varepsilon = \eta\left(1 - \frac{T_0}{T_s}\right). \tag{6}$$

For each heating category, an adequate first-law efficiency was defined, according to technological evolution [33]. Table 3 shows the range of first-law efficiencies considered for each heating category, as well as the service temperatures defined. Typically, the lowest temperature heat categories refer to domestic heating, where the use of less efficient open chimney heaters is higher than in other heating categories. The environment temperatures were set differently for each country, making heating second-law efficiencies also different for each country. An annual average temperature ($T_0$) was considered for each country. Assuming that space heating uses occur just during the winter months, the second-law efficiency for *Low Temperature Heat (50 °C)* was considered as the average between low temperature heat uses (with an environment temperature equal to the annual average temperature) and space heating uses (with an environment temperature equal to the annual average temperature of the winter months – December, January and February) [34] – Table 4.

**Table 5**
Description of the methodology used to estimate final-to-useful second law efficiencies for each mechanical drive category.

| Mechanical drive category | Observations and references |
|---|---|
| Steam locomotives | Efficiency estimations adapted from Fouquet [33] and Smil [36] and extrapolated in order to match estimation for recent years from Nakicenovic, Gilli [37]. |
| Navigation | Ayres and Warr [38]. |
| Aviation | |
| Oil – stationary mech. drive | |
| Coal – stationary mech. drive | |
| Diesel-electric | Nakicenovic, Gilli [37], Ayres, Ayres [39]. |
| Diesel vehicles | *Vide* Eqs. (8) and (9), and Table 6. |
| Gasoline/LPG vehicles | |
| Natural gas vehicles | |

**Table 6**
Considered $\alpha_i$ coefficients. Based on Ford, Rochlin [32], Heywood [40], Ross [41].

| 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. | 0.85–0.90 | Friction losses have decreased during the 20th century. We assumed an evolution from 0.85 to 0.90 between 1960 and 2009. |
| 4 | Partial load. | 0.40–0.45 | 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 vehicles worked closer to full power. We assumed an evolution from 0.45 to 0.40 between 1960 and 2009. |
| 5 | Accessories losses (includes air conditioning). | 0.90 | |
| 6 | Transmission losses. | 0.75 (autom.); 0.90 (manual) | In Europe the vast majority of vehicles have had manual transmission. |

A similar method was applied for CHP (combined heat and power) heating second law efficiencies, according to eq. (7) [32], and considering that CHP heat is delivered at 180 °C ($T_1$).

$$\varepsilon = \eta \frac{1-\frac{T_0}{T_2}}{1-\frac{T_0}{T_1}} \tag{7}$$

### 2.1.2. Mechanical drive

Second-law efficiencies of mechanical drive categories were obtained using the methods and references shown in Table 5. Given somewhat equal access to technologies across the EU-15 countries over the last 50 years, it is reasonable to assume equal second-law efficiencies for all countries, according to the benchmark technologies and references below.

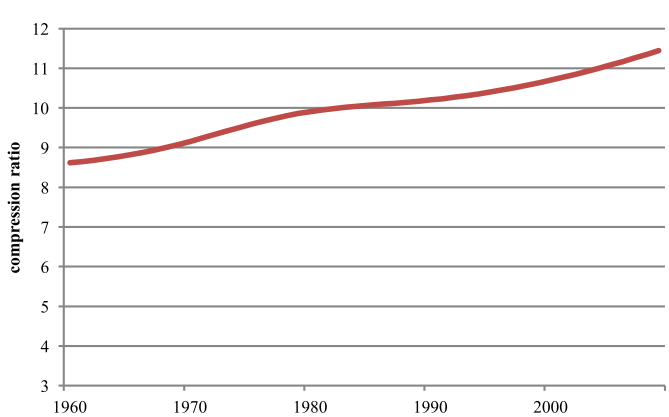


**Fig. 1.** Compression ratio of standard gasoline engines from 1856 to 2009.

Gasoline engines (those that perform Otto thermodynamic cycles) have a second-law efficiency given by Refs. [32,40,41]:

$$\varepsilon \approx \eta_{\text{theoretical maximum}} \prod_{i=1}^{6} \alpha_i, \tag{8}$$

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

$$\eta_{\text{theoretical maximum}} = 1 - \left(\frac{1}{r}\right)^{\gamma-1}. \tag{9}$$

Table 6 shows the values for each coefficient $\alpha_i$ and Fig. 1 shows the evolution for compression ratios.

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 [32].

### 2.1.3. Light

Coal/oil light uses stand for the usual lighting uses from oil and coal products, namely kerosene and town gas. These energy end-uses were sparsely used along this time frame in Western Europe, as they mainly occurred before electrification.

All lighting efficiencies (coal/oil and electric) are obtained through an indirect procedure, taking as reference the maximum luminous efficacy of a light emitting at the wavelength for which the human eye is most sensitive. Consequently, the lighting efficiency of each light source is defined only by its luminous efficacy, according to eq. (10) [39,42,43],

$$\varepsilon = \frac{\eta}{683\text{ln}/W}, \tag{10}$$

where $\eta$ stands for the luminous efficacy of a given light source.

Fouquet [33] provides annual estimations of average luminous efficacy for the United Kingdom, which are considered the same for all countries (Fig. 2).

### 2.1.4. Electricity

Useful work from electricity requires a different approach, taking into account the different electricity end-uses. We assume here a standard approach, equally applied to all countries, that considers different shares of electricity end-uses for industries, transports and remaining sectors. Final exergy consumption from electricity is directly obtained from the IEA energy balances, disaggregated by sectors. For each sector, Table 7 details the assumptions on shares of end-uses and its references. The series of shares of electricity end-uses by sector are shown in the Supporting Information File – Section C.

Table 8 shows the methods and references used to estimate the second-law efficiencies for each electricity end-uses. Section D of the Supporting Information File shows the estimated electricity efficiencies over this time span.

### 2.1.5. Food and feed

Muscle work calculations are based on supply statistics of food for humans and feed for working animals [28]. The methodology followed is described below.

*2.1.5.1. Food.* Muscle work from humans ($U_{MW_h}$) in year $y$ relies on country-level data for daily metabolizable energy content of supplied food *per capita* ($e_m$), according to eq. (11):

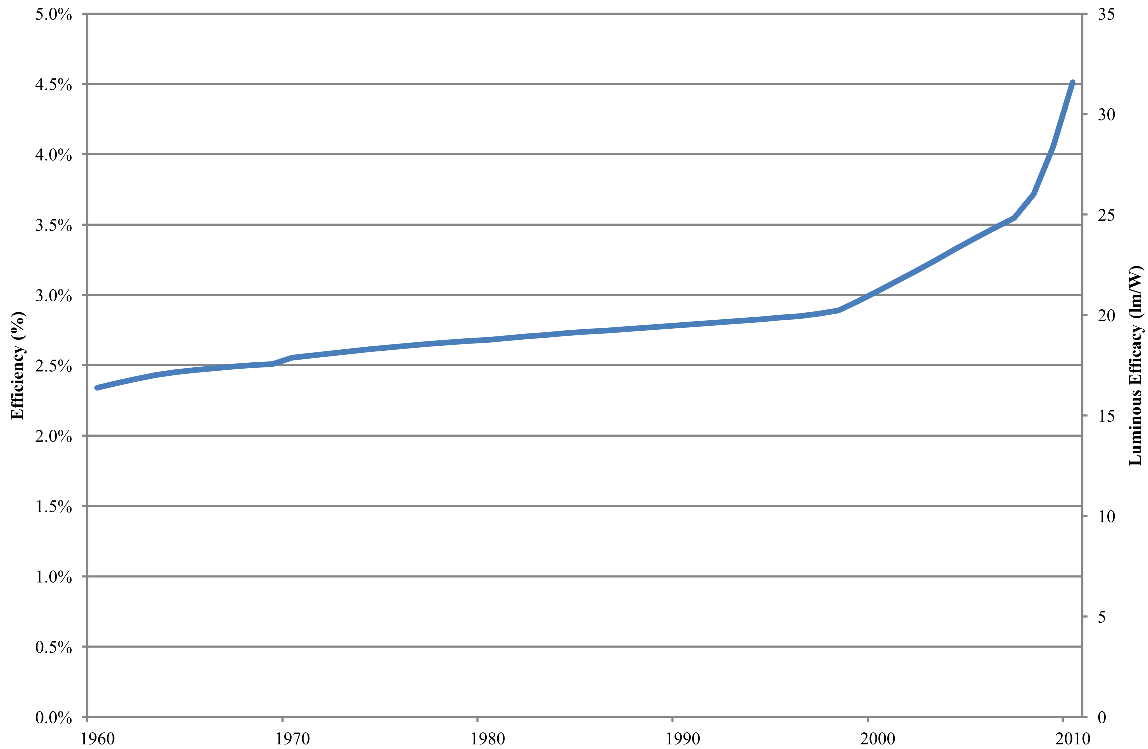


**Fig. 2.** Evolution of the average lighting efficiency and luminous efficacy [33].

$$U_{\mathrm{MW_h},y} = 365 e_{\mathrm{m},y} p_y t \alpha_y \varepsilon, \tag{11}$$

where $p_y$ stands for the population in the year $y$; $t$ the working fraction of the day; $\alpha_y$ the intake to end-use ratio; and $\varepsilon$ the efficiency. Table 9 details these parameters.

*2.1.5.2. Feed.* Muscle work from working animals ($U_{\mathrm{MW_{wa}}}$) is almost negligible in Western Europe over this time span. These values rely on country-level data of heads of asses, mules and horses, according to eq. (12):

$$U_{\mathrm{MW_{wa}},y} = 365 h_{i,y} e_i \varepsilon, \tag{12}$$

**Table 7**
Shares of electricity end-uses by sector.

| Sectors | End-use categories | Observations and references |
|---|---|---|
| Transports | Mechanical drive | It is considered that all electricity uses in the transport sector are mechanical drive uses, using electric engines. |
| Industries | Mechanical drive<br>Heat<br>Other electric uses | The same shares considered in Serrenho, Warr [44].[a] |
| | Light | The same share of lighting considered by Fouquet and Pearson [43]. |
| Other sectors | Mechanical drive<br>Heat<br>Other electric uses | The same shares considered in Serrenho, Warr [44].[a] |
| | Light | The same share of lighting considered by Fouquet and Pearson [43]. |

[a] It includes HVAC (heating, ventilation and air conditioning), and refrigeration.

**Table 8**
Electricity end-use efficiencies.

| End-use categories | Sectors | Observations and references |
|---|---|---|
| Mechanical drive | Transports<br>Industries<br>Other sectors | [39]. |
| Heat | Industries | Low temperature heat (120 °C). It was used the same calculation method of Section 2.1.1 with a first-law efficiency of 100%.[a] |
| | Other sectors | Low temperature heat (50 °C). It was used the same calculation method of Section 2.1.1, with a first-law efficiency of 100%. |
| Light | Industries<br>Other sectors | *Vide* Section 2.1.3. |
| Other electric uses | Industries<br>Other sectors | Weighted average of second-law efficiencies for communication/electronics and electrochemical end-uses by Ayres, Ayres [39]. |

[a] In spite of some high temperature heat electric uses, mainly in iron and steel and chemical industries, they exhibit very low shares of use and are neglected here.

where $h_{i,y}$ stands for the heads of the animal $i$ in the year $y$; $e_i$ the daily metabolizable energy content of eaten feed per head of animal $i$; and $\varepsilon$ the efficiency. Table 10 details these parameters.

**Table 9**
Parameters for muscle work from humans.

| Parameters | Observations and references |
|---|---|
| $e_{\mathrm{m},y}$ | Country level – data of daily metabolizable energy supply from food *per capita* – [28]. |
| $p_y$ | Yearly population of each country from the country indicators provided by IEA [27]. |
| $t$ | 8/24, assuming an average 8 h of muscle work activity per day. |
| $\alpha_y$ | [45]. |
| $\varepsilon$ | 13% [36]. |

**Table 10**
Parameters for muscle work from working animals.

| Parameters | Observations and references |
|---|---|
| $h_{i,y}$ | Country-level data of heads of animals $i = \{\text{asses, horses, mules}\}$ [28]. |
| $e_i$ | $e_{\text{asses}} = 12,198\text{kcal/d}$ [2]. $e_{\text{horses}} = 18,742\text{kcal/d}$ [2]. $e_{\text{mules}} = 15,832\text{kcal/d}$ [2]. |
| $\varepsilon$ | 13% [36]. |

## 3. Useful work, GDP, and second-law efficiencies

Total final exergy consumption in the EU-15 grew from about 21 EJ to 45 EJ, a more than 2-fold increase between 1960 and 2009 (Fig. 3). Meanwhile, over this time span these countries had a 25% population increase, an almost 3-fold increase in useful work (Fig. 4) and a 4-fold increase in the total GDP, with a corresponding narrow increase in aggregate second-law efficiencies from 16.5% in 1960 to about 20% in 2009 (Fig. 5). The useful work increase was mainly due to a higher demand for mechanical work, namely transports. Fig. 6 shows the variability across the EU-15 countries,

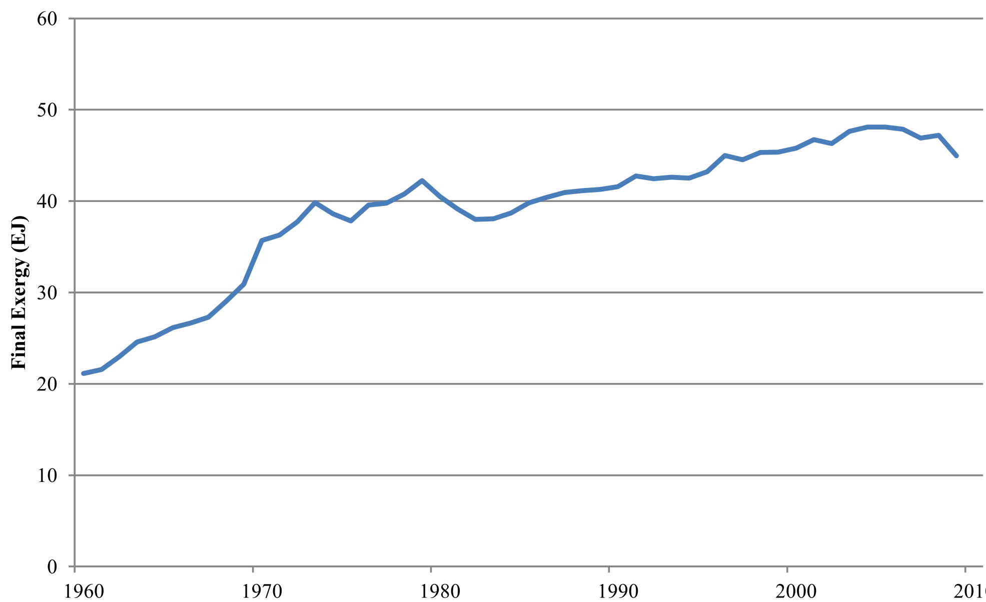


**Fig. 3.** Total final exergy consumption in the EU-15 countries from 1960 to 2009.

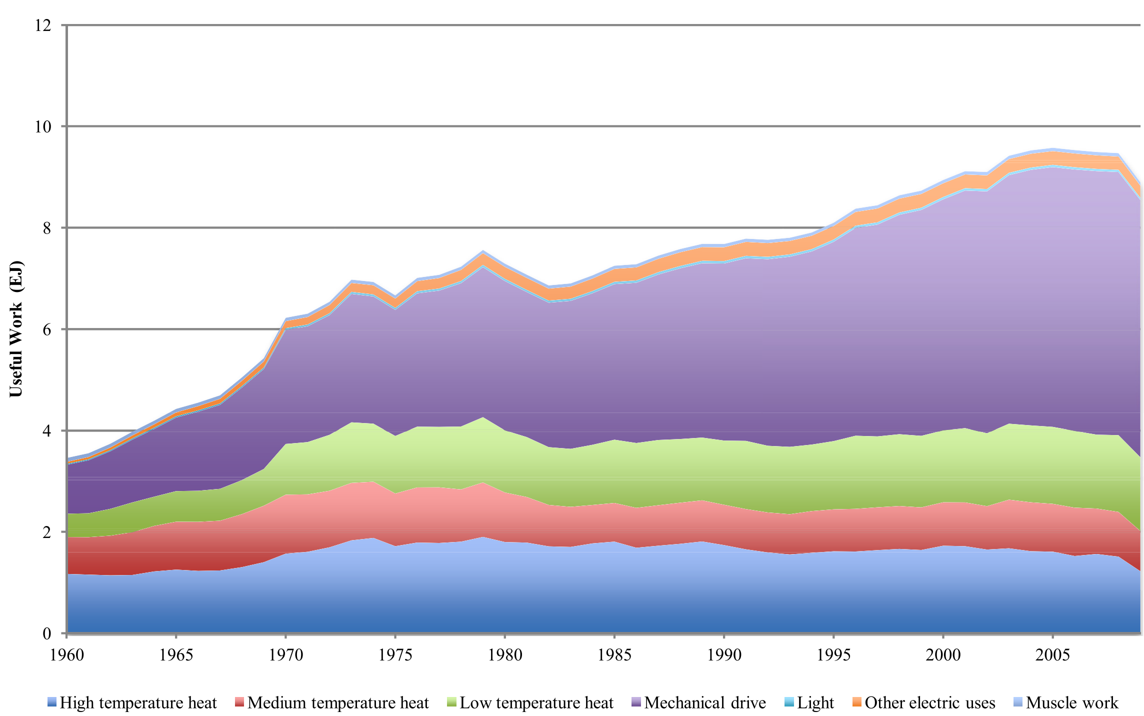


**Fig. 4.** Total useful work delivered to the EU-15 countries from 1960 to 2009.

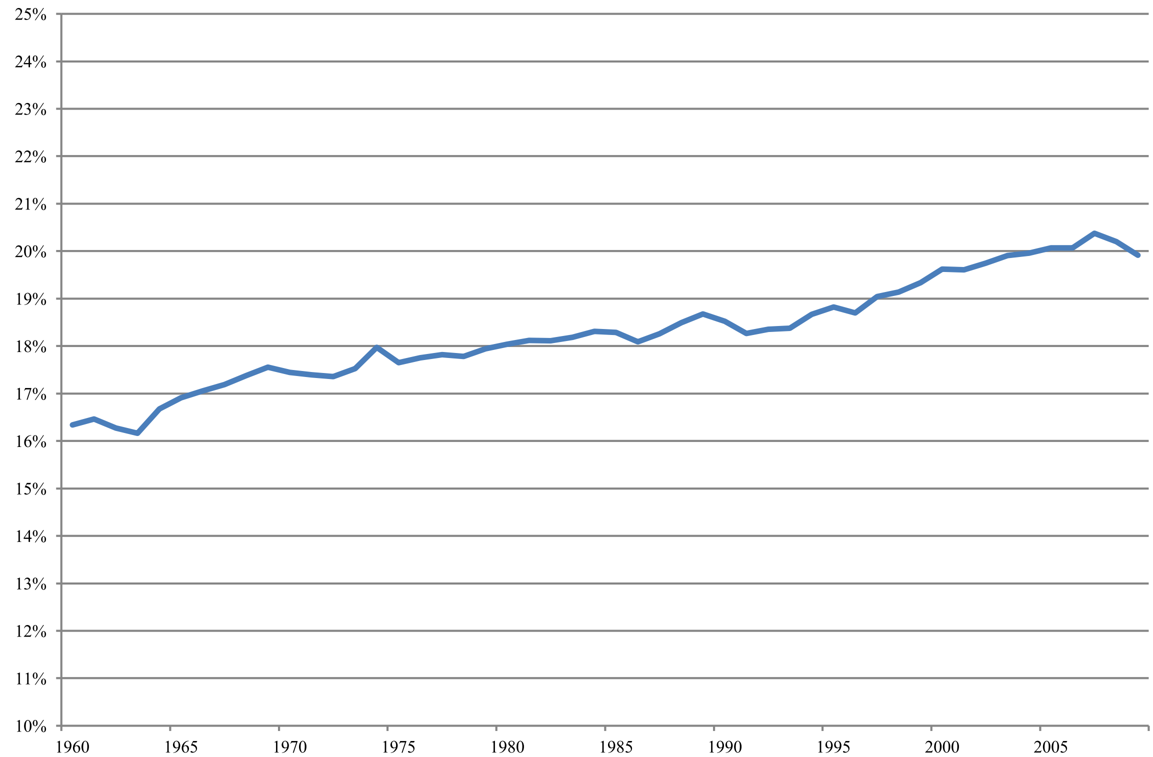


**Fig. 5.** Final-to-useful aggregate second-law efficiency of the EU-15 countries from 1960 to 2009.

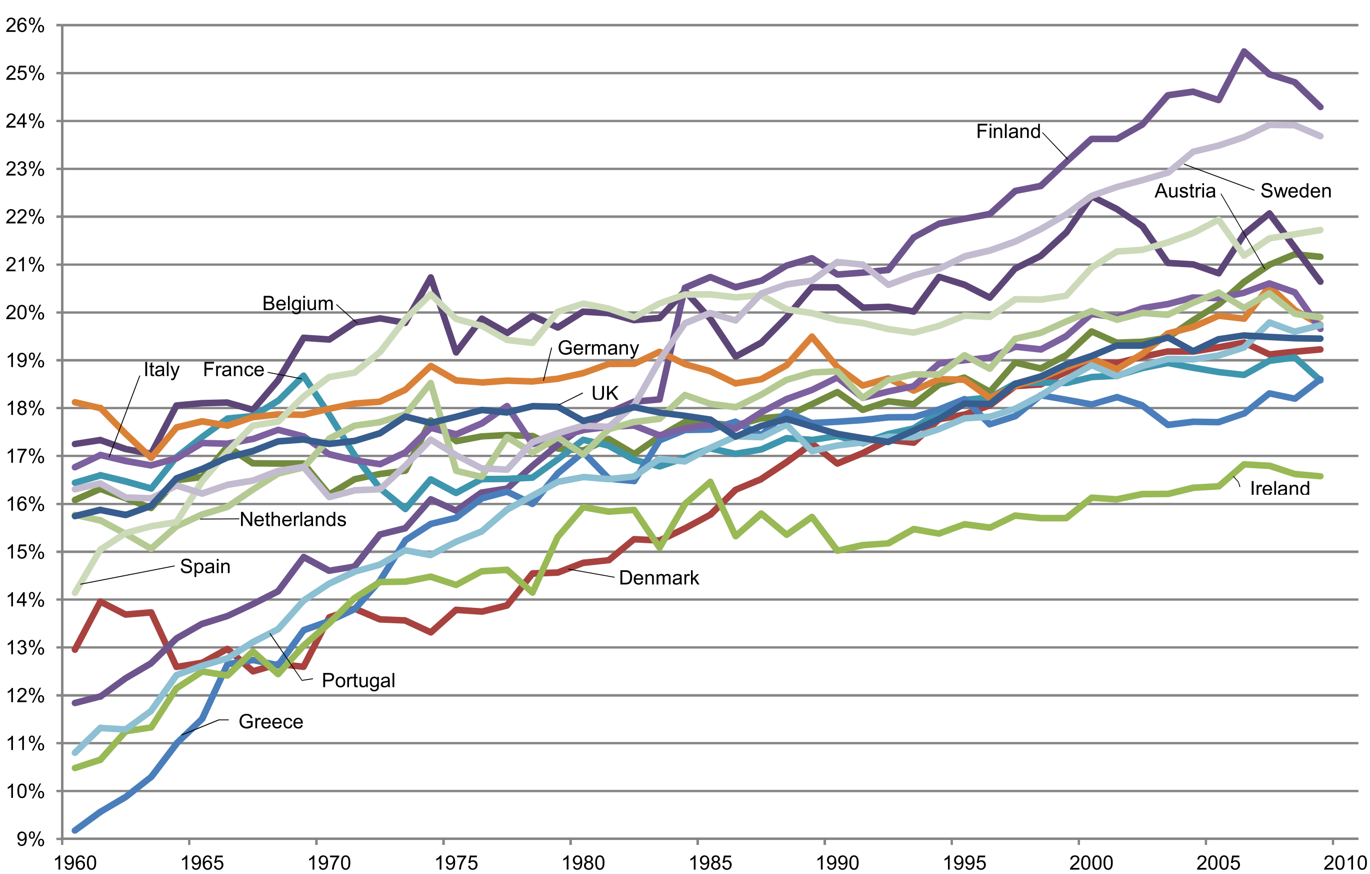


**Fig. 6.** Final-to-useful aggregate second-law efficiency for each EU-15 country from 1960 to 2009.

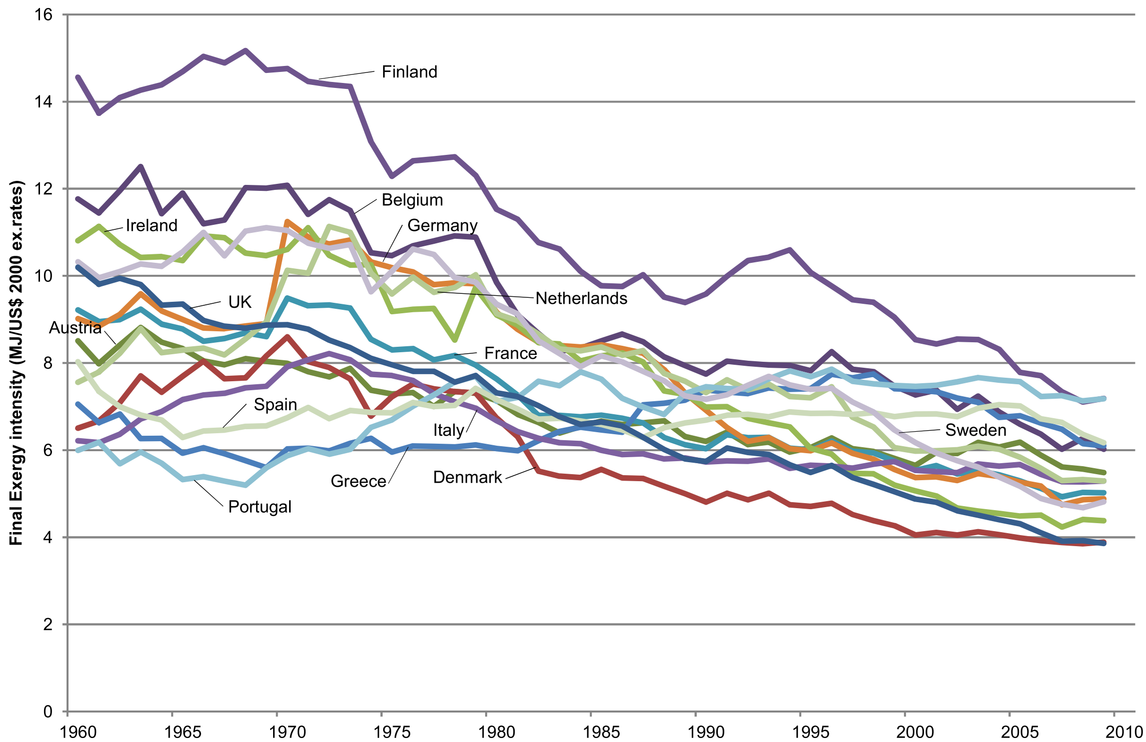


**Fig. 7.** Final exergy intensities for each EU-15 country from 1960 to 2009.

regarding the 2nd law efficiencies. GDP time series were taken from IEA databases in constant prices, using exchange rates [27].

The different paces of final exergy, useful work and GDP growth, imply different behaviors regarding their intensities. Final exergy intensities (Fig. 7) exhibit a decreasing trend across the EU-15 countries, more evident in countries with higher intensity values. There is a convergence from highly scattered intensities, ranging between 6 and 14.5 MJ/US$ in 1960 and 4 and 7.5 MJ/US$ in 2009. Intensities are higher in the northern countries and lower in the southern countries. Regarding useful work intensities (Fig. 8), an

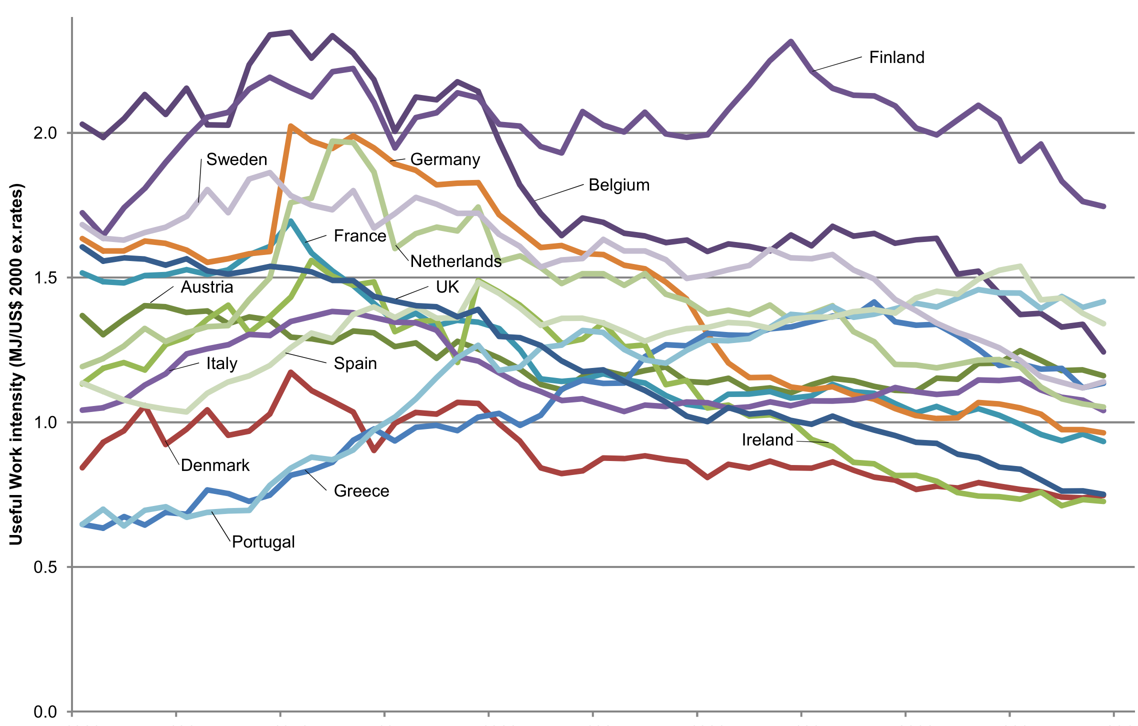


**Fig. 8.** Useful work intensities for each EU-15 country from 1960 to 2009.

**Table 11**
Stepwise regressions of useful work intensity by economic sector. Robust standard errors are in brackets.

| $X_j$ | #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|
| Energy ind. uses | 0.2435 (0.0113) | 0.2479 (0.0112) | 0.2436 (0.0128) | 0.3145 (0.0377) | |
| Iron & steel | 0.4142 (0.0056) | 0.4155 (0.0060) | 0.4150 (0.0061) | 0.4356 (0.0083) | 0.4158 (0.0120) |
| Chemical ind. | 0.3429 (0.0162) | 0.3373 (0.0164) | 0.3501 (0.0178) | | |
| Non-ferrous ind. | 0.3431 (0.0423) | 0.3514 (0.0420) | 0.3917 (0.0442) | | |
| Non-metallic ind. | 0.2928 (0.0202) | 0.2849 (0.0210) | 0.2889 (0.0243) | 0.3401 (0.0350) | |
| Transp. ind. | 0.4087 (0.1503) | 0.4261 (0.1480) | | | |
| Machinery ind. | 0.2818 (0.0594) | 0.2773 (0.0595) | 0.4116 (0.0672) | | |
| Mining ind. | 0.2864 (0.1013) | 0.2729 (0.1010) | | | |
| Food & tobacco | 0.1355 (0.0304) | 0.1399 (0.0294) | 0.1955 (0.0291) | | |
| Paper ind. | 0.2538 (0.0184) | 0.2606 (0.0171) | 0.2776 (0.0187) | | |
| Wood ind. | 0.1326 (0.0511) | 0.1232 (0.0505) | | | |
| Construction ind. | 0.1570 (0.0697) | | | | |
| Textile ind. | 0.1865 (0.0737) | 0.2339 (0.0814) | | | |
| Other industries | 0.2763 (0.0092) | 0.2765 (0.0092) | 0.2719 (0.0096) | 0.1557 (0.0173) | |
| Aviation | 0.1643 (0.0324) | 0.1640 (0.0328) | 0.2033 (0.0344) | | |
| Road transp. | 0.1453 (0.0094) | 0.1434 (0.0097) | 0.1374 (0.0101) | 0.1919 (0.0279) | |
| Navigation | 0.3821 (0.0248) | 0.3794 (0.0266) | 0.3804 (0.0282) | 0.3226 (0.0432) | |
| Rail transp. | 0.0326 (0.0387) | | | | |
| Pipeline transp. | 0.7956 (0.2248) | 0.7898 (0.2399) | | | |
| Other transport | 0.3441 (0.1363) | 0.3479 (0.1372) | | | |
| Residential | 0.0835 (0.0045) | 0.0841 (0.0045) | 0.0900 (0.0048) | 0.1027 (0.0098) | 0.1273 (0.0162) |
| Services | 0.0829 (0.0115) | 0.0843 (0.0115) | 0.1156 (0.0168) | | |
| Agriculture | 0.1601 (0.0251) | 0.1557 (0.0326) | | | |
| Fishing | 0.0975 (0.0670) | | | | |
| Others | 0.0952 (0.0108) | 0.0939 (0.0107) | 0.0874 (0.0100) | | |
| Intercept | 0.0061 (0.0006) | 0.0060 (0.0006) | 0.0059 (0.0006) | 0.0040 (0.0011) | 0.0018 (0.0018) |
| $R^2$ | 0.9734 | 0.9726 | 0.9662 | 0.8481 | 0.7091 |
| *F*-statistic | 592.19 | 620.26 | 676.15 | 512.68 | 628.03 |

increasing or decreasing trend is not clearly visible. Different countries exhibit distinct trends over this time span, overall leading to higher intensities for the northern countries and lower for southern countries.[2]

Country decomposition of useful work by type of end-use, as well as time series of final exergy, useful work and second-law efficiencies are presented in the Supporting Information File – Section E. In the next section we analyze the useful work intensities to find the factors that explain their changes.

## 4. Modeling useful work intensities

The methodology followed in this paper to calculate useful work intensities allows the use of two different decomposition analyses. One by sectors of economy, with the level of disaggregation of the energy datasets; and the other by energy end-uses, with the disaggregated end-uses defined in Table 1. The panel dataset assembled for the EU-15 over this time span enables the following model framework that may be applied to the current dataset and time span:

$$\left(\frac{U}{\mathrm{GDP}}\right)_{i,t} = \alpha + \sum_{j=1}^{n} \beta_j \left(\frac{X_j}{\mathrm{GDP}}\right)_{i,t} + u_{i,t}, \tag{13}$$

where $U$/GDP stands for the useful work intensity of the country $i$ in the year $t$, which is decomposed in a constant ($\alpha$) and in the intensity of $n$ factors $X_j$.

Eq. (13) is obtained from eq. (5), considering: (1) each factor $X_j$ as the final exergy consumption of either each $n$-sector of the economy, or each $n$-energy end-use, stemming two dimensions for decomposition; (2) each coefficient $\beta_j$ as an average final-to-useful second-law efficiency; (3) and adding a constant ($\alpha$) to obtain an unrestricted linear model, and an error term ($u$).

We performed the Wooldridge test for autocorrelation in panel data, because the dataset is a macro panel with a long time series [46,47]. This test shows that for each independent variable described above it is impossible to reject the null hypothesis of inexistence of first-order autocorrelation at the level of 10%. The presence of autocorrelation is solved with the use of first differences in the independent and dependent variables [46,47]. In this case, the general model (13) becomes.

$$\Delta\left(\frac{U}{\mathrm{GDP}}\right)_{i,t} = \delta + \sum_{j=1}^{n} \beta_j \Delta\left(\frac{X_j}{\mathrm{GDP}}\right)_{i,t} + \Delta u_{i,t}. \tag{14}$$

For all regressions we applied the Breusch–Pagan/Cook–Weisberg and the White tests for heteroskedasticity. Results reject the null hypothesis of homoskedasticity at the level of significance of 10%. Robust standard errors were used to overcome heteroskedasticity.

A stepwise regression methodology was employed to disclose the relevant independent variables [48], running two different analyses for each dimension of the decomposition described above. Tables 11 and 12 show some steps of these stepwise regressions, using ordinary least squares with robust standard errors, based on the setting (14).

Results show that without substantial loss of the joint significance of the explanatory variables, the (industrial) high temperature heat and residential uses explain most of the variation in useful work intensities (model #5 in Tables 11 and 12). High temperature heat uses are used in the industrial sector and especially in the iron and steel industries, explaining the similar partial effect of both iron and steel and high temperature heat exergy consumption. As expected, the estimated coefficient of about 0.41 is approximately equal to the average second-law efficiency for high temperature heat uses over this time span.

[2] German intensities exhibit a significant increase from 1969 to 1970. This fact is a result of a change in the geographical coverage of the used databases, which include the new federal states (from the former German Democratic Republic) from 1970 onwards.

**Table 12**
Stepwise regressions of useful work intensity by energy end-use. Robust standard errors are in brackets.

| $X_j$ | #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|
| High temp. heat | 0.3928 (0.0036) | 0.3929 (0.0036) | 0.3910 (0.0046) | 0.4057 (0.0108) | 0.4067 (0.0120) |
| Medium temp. heat | 0.1878 (0.0062) | 0.1881 (0.0062) | 0.1863 (0.0070) | 0.1795 (0.0212) | |
| Low temp. heat | 0.0825 (0.0050) | 0.0832 (0.0048) | 0.0891 (0.0050) | | |
| Steam locomotives | 0.0236 (0.0258) | | | | |
| Diesel vehicles | 0.1393 (0.0064) | 0.1394 (0.0064) | | | |
| Gasoline/LPG vehicles | 0.0961 (0.0097) | 0.0925 (0.0093) | 0.1136 (0.0144) | | |
| Aviation | 0.2253 (0.0252) | 0.2263 (0.0263) | 0.1827 (0.0310) | | |
| Navigation | 0.3468 (0.0093) | 0.3460 (0.0100) | 0.3330 (0.0162) | 0.3777 (0.0238) | |
| Natural gas vehicles | −0.2297 (0.3920) | | | | |
| Diesel-electric | 0.7781 (0.2349) | 0.7565 (0.2239) | | | |
| Stationary mech. drive | 0.3375 (0.0097) | 0.3348 (0.0093) | 0.3307 (0.0128) | 0.4323 (0.0364) | |
| Coal/oil light | 0.0271 (0.0205) | | | | |
| Electricity – industry | 0.5116 (0.0274) | 0.5092 (0.0267) | 0.4902 (0.0321) | | |
| Electricity – transports | 1.0274 (0.1171) | 1.0264 (0.1118) | | | |
| Electricity – other sectors | 0.2828 (0.0209) | 0.2803 (0.0204) | 0.3084 (0.0281) | | |
| Food for humans | 0.0610 (0.0181) | 0.0830 (0.0138) | | | |
| Feed for working animals | 0.0199 (0.0166) | | | | |
| Intercept | 0.0048 (0.0004) | 0.0047 (0.0004) | 0.0054 (0.0005) | 0.0062 (0.0012) | 0.0011 (0.0017) |
| $R^2$ | 0.9871 | 0.9870 | 0.9785 | 0.8699 | 0.7288 |
| *F*-statistic | 2575.87 | 3289.06 | 2446.63 | 470.28 | 1152.23 |

**Table 13**
Regressions of useful work intensity. Robust standard errors are in brackets. *** Parameter is significant at the level of 1%. ** Parameter is significant at the level of 5%. * Parameter is significant at the level of 10%.

| $X_j$ | #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|
| Intensity of high temperature heat exergy consumption | 0.4054*** (0.0090) | 0.4067*** (0.0105) | | 0.4028*** (0.0092) | |
| Intensity of residential exergy consumption | 0.1317*** (0.0121) | | 0.1367*** (0.0281) | 0.1294*** (0.0122) | |
| Intercept | 0.00335 (0.00242) | 0.00105 (0.00336) | −0.0074 (0.00426) | | −0.0098** (0.00489) |
| $R^2$ | 0.7875 | 0.7288 | 0.0633 | 0.7888 | 0.0000 |

In spite of having a quite low partial effect, the intensity of residential exergy consumption plays also an important role and has the second higher explanatory power after high temperature heat uses. It stands for the relative size of residential energy demand. The multiple residential end-uses do not allow a clear identification in Table 12. Its joint significance with high temperature heat uses is tested in Table 13, employing an ordinary least squares model with panel-corrected standard errors, as it is recommended for panel datasets with a small cross-sectional dimension compared to the time dimension of the panel [49]. Different models were tested to evaluate the explanatory power of independent variables.

In Table 13, the coefficient of determination of models #2 and #3 provide evidence of the different explanatory power of high temperature heat and residential consumption. The intensity of high temperature heat uses exhibits a very high explanatory power, compared with the intensity of residential exergy consumption. The multiple regression models #1 and #4 exhibit a higher explanatory power than any of the models in Table 11 or Table 12, showing the convenience of high temperature heat and residential intensities to explain the useful work intensity.

It is also noteworthy that the intercept is not statistically significant at the level of 10%, suggesting that useful work intensity is constant, unless high temperature heat uses or domestic energy demand change. Based on previous results we suggest the following description for useful work intensity:

$$\Delta\left(\frac{U}{\mathrm{GDP}}\right)_{i,t} = \underset{(0.0092)}{0.4028}\,\Delta\left(\frac{B_{\text{high temp. heat}}}{\mathrm{GDP}}\right)_{i,t} + \underset{(0.0122)}{0.1294}\,\Delta\left(\frac{B_{\text{residential}}}{\mathrm{GDP}}\right)_{i,t}. \tag{15}$$

Given the results above, it is relevant to test whether conventional energy intensity measures exhibit the same behavior. We used final exergy intensities as a proxy for conventional measures and we employed the same methodology (Table 14) to test the explanatory power of these factors on final exergy intensities. We show that high temperature heat and domestic energy uses are not enough to explain the variation in the final exergy intensity. Model #1 exhibits a moderate explanatory power, but a negative intercept is statistically significant at the level of 1%, suggesting an external decreasing trend, probably as a consequence of efficiency improvements.

## 5. Discussion and conclusions

An economy-wide energy end-use analysis was carried out for the EU-15 countries from 1960 to 2009, encompassing a broader set

**Table 14**
Regressions of final exergy intensity. Robust standard errors are in brackets. *** Parameter is significant at the level of 1%.

| $X_j$ | #1 | #2 | #3 | #4 |
|---|---|---|---|---|
| Intensity of high temperature heat exergy consumption $\left(\frac{B_{\text{high temp. heat}}}{\mathrm{GDP}}\right)_{i,t}$ | 0.9705*** (0.0566) | 0.9823*** (0.0754) | | |
| Intensity of residential exergy consumption $\left(\frac{B_{\text{residential}}}{\mathrm{GDP}}\right)_{i,t}$ | 1.235*** (0.0668) | | 1.2473*** (0.0887) | |
| Intercept | −0.0420*** (0.0124) | −0.0634*** (0.0234) | −0.0677*** (0.0144) | −0.0898*** (0.0248) |
| $R^2$ | 0.6092 | 0.2750 | 0.3408 | 0.0000 |

of energy carriers that included food for humans and feed for working animals, in addition to the conventional commercial energy carriers. Such an analysis should not be performed using an energy approach; otherwise it entails problems of consistency. An energy approach accounts energy flows using "energy units", which refer to carrier-specific thermodynamic potentials: internal energy for food and feed, and enthalpy for the remaining. An end-use exergy approach provides a consistent accounting of the useful work delivered to end-uses that only considers exergy flows, regardless the carrier or type of end-use.

In this paper a general methodology was employed to calculate useful work for each EU-15 country for each year in the period 1960–2009 from the IEA energy balances. This was accomplished using a general map of economic sectors to types of energy end-uses and a generalized estimation of second-law efficiencies for each end-use category. This mapping enables us to obtain energy data by end-uses directly from the disaggregated version of IEA energy balances. The results provide data on exergy consumption, useful work and aggregate second-law efficiencies for these countries and time span, accounting for end-uses of a broad set of energy carriers: oil and coal products, natural gas, combustible renewables, food for humans and feed for working animals. However, this general methodology does not provide detailed country-level data on specific efficiencies and end-uses, but rather a general picture of trends, capturing the main structural changes.

Results show energy end-use transitions and capture the deindustrialization process in Western Europe and the consequent shift to a service economy. Overall, EU-15 countries are reducing substantially the share of high temperature heat uses demanded by heavy industries and increasing the demand for mechanical drive, namely transport uses. In spite of a decrease in high temperature heat uses, aggregate second-law efficiencies slightly increased over this time span. A decrease in these very efficient uses is being compensated by technological improvements and still increasing industrial electrification.

Final exergy intensities follow the same pattern of conventional energy intensity measures. They exhibit a clear decreasing trend, more pronounced in the countries with higher intensities. The behavior seems to be mainly motivated by efficiency improvements, as useful work intensities do not exhibit a clear trend.

The results on the decomposition of useful work intensities show that changes are mainly motivated by (i) variations in the intensity of high temperature heat uses; (ii) and, with a lower magnitude, by the intensity of the domestic exergy consumption. High temperature heat uses are almost exclusively used in the iron, steel and cement industries. Overall, these heavy industries lost their relative weight in Western European energy uses. The economic growth and development of the last 50 years is compatible with a process of offshoring these industries, decreasing their intensity. The relative size of the domestic exergy consumption (here measured by the intensity of the residential exergy consumption) has also been decreasing, with a correspondent increase in other (non-industrial) sectors, namely transports. Both decreasing effects lead to a decrease in useful work intensities.

As expected from above, the most industrialized countries in the 1960's experience a more pronounced decrease in useful work intensities. Other countries, such as Greece and Portugal, show an increasing trend over this time span due to the absence of a strong industrial sector in 1960 and due to significant increases in the relative size of the domestic exergy consumption, mainly in the 1970's and 1980's, following important social and economic changes [44].

We conclude that useful work intensities in these countries and time span depend only on changes of two kinds of end-uses: high temperature heat uses and residential uses. Contrarily to final exergy intensities, useful work intensities are constant when the relative size of heavy industries and domestic consumption is constant.

Useful work intensities imply an analysis at the level of satisfied exergy needs that accounts for the quality of the energy actually employed in end-uses. These intensities capture only end-use changes, discounted from additional effects such as technological transitions, efficiency improvements and changes in energy-carriers, providing supplementary and useful information for sustainability and policy analyses.


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## Appendix A. Information available as supplementary material

| Section | Description |
|---|---|
| A | Mapping useful work categories for IEA energy balances for the EU-15 countries (1960–2009).<br>This section presents the mapping of the pair energy carriers – economic sectors into disaggregated end-use categories as defined in Table 1. This mapping is presented for all energy carriers and economic sectors defined in the IEA energy balances. |
| B | Second-law efficiencies by end-use category for the EU-15 countries (1960–2009).<br>This section presents the second-law final-to-useful efficiencies ($\varepsilon_{t,k}$) considered for each end-use category, country and year. |
| C | Shares of electricity end-uses by sector for the EU-15 countries (1960–2009).<br>This section presents the shares of electricity end-uses by sector, according to the definitions presented in Table 7. These shares were assumed to be the same for all countries. |
| D | Second-law efficiencies of electricity end-uses for the EU-15 countries (1960–2009).<br>This section presents the second-law final-to-useful efficiencies of electricity end-uses, according to the methods and references presented in Table 8. Except for heating, these efficiencies were considered to be the same for all countries. |
| E | Final energy, useful work, and efficiencies for the EU-15 countries (1960–2009).<br>This section presents the time series of final exergy, useful work (disaggregated by end-use) and aggregate second-law final-to-useful efficiencies for each country for the entire time span. |

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2014.08.068.

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