Energy Intensity of the Spanish Economy: A Useful Work Study

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Abstract

In this article, the Spanish exergy analysis is carried out for the period 1960 - 2013. The methodology applied is extensively discussed, and two methodological improvements are presented. Firstly, a wider range of temperatures are taken into consideration when computing the useful work time series, so that the underlying physical processes are better represented. Secondly, the non-specified economic subsectors from the IEA data are disaggregated in defined economic subsectors. A few findings are subsequently presented from the exergy analysis carried out. Firstly, the Spanish energy consumption (at each of the three primary; final and useful stages) has increased from 1960 until the economic downturn starting in 2008, when it starts plummeting alongside GDP. This indicates a tight correlation between energy and the economy. Secondly, it is showcased how the growth in useful work availability has been supplied, at least partly, by efficiency gains during the studied period. Thirdly, these efficiency gains are slowing down, which is likely to be due to efficiency dilution, and may represent a hurdle to future economic growth. Fourthly, the correlation between the slow down in energy consumption and the 2008 economic recession is discussed. As useful work is slowing down before the beginning of the crisis, the analysis seems to point to energy constraints predating the economic recession. Lastly, primary energy, final energy and useful work intensities of the Spanish economy are discussed. It is underlined how intensity metrics based on the primary and final stages of the energy conversion chain can be overly optimistic about the decrease of the energy intensity of an economy. Conversely, intensity metrics based on the useful stage, such as useful work, tend to indicate that the connection between energy and the economy remains tight, and that the dependency of the economy on energy services is still high.

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1 Introduction

The dematerialization of economies is commonly presented as a key strand in order to reduce global resource consumption and environmental pressure, for instance climate change [Von Weizsacker et al., 2009]. One can understand dematerialization as a situation where an economy becomes less dependent of material throughput when producing economic output, commonly measured as GDP.

In this article, the focus is not on materials as such, but on energy. Dematerialization, when applied to the field of energy, refers to the decrease of the energy intensity of the economy, usually measured in primary or final energy per unit of GDP. There are caveats to the dematerialization focus, for instance related to the difference between relative (i.e. GDP rising faster than energy consumption, while both increase) and absolute (i.e. GDP rising while energy consumption decreases) dematerialization of an economy - as showcased for global material consumption in [Krausmann et al., 2009] -, and to the fact that an intensity measure is not suited in order to capture the aggregate situation [Heun and Brockway, 2018]. Notwithstanding these caveats, this study focuses on the dematerialization concept and seeks to explore whether the Spanish economy is actually becoming less dependent on energy in order to produce economic output (i.e. less energy intensive) than it was, namely more energy-dematerialized.

In this context, one can question the soundness of the metric used when assessing whether an economy is becoming less energy intensive through time. Indeed, the metric needs to be consistent with the question one seeks to answer. When applied to climate change and greenhouse gases emissions accounting, one could defend the legitimacy of using primary energy intensity, since primary energy consumption is tightly linked to greenhouse gases emissions emissions, at least when the accounting subtleties related to nuclear and renewables have been successfully handled. Conversely, if the focus is to study the role of energy in the economy, and the dependency of the economy on energy, considering the energy that is actually exchanged for energy services (i.e. economic activity) seems more relevant [Percebois, 1979]. These analysis are therefore better undertaken at the energy output stage, which corresponds better to the "satisfied needs". Indeed, useful energy can be regarded as a more relevant measure than primary or final energy, since it excludes both transformation and end-uses losses, which can be regarded as economically unproductive, to the extent that they do not contribute to the final energy service. Consequently, this article takes the output stage approach in order to explore the dependency of the economy on energy.

A useful metric in order to assess the relationship between energy and the economy is exergy. Firstly introduced in Rant [1956], exergy is a physical value, measured in usual energy units, that is based on thermodynamics and represents the ability of a system to perform work. Thus it is a measure of both energy quantity and quality. The quality of thermal energy provided by a low temperature heater is for instance of worse quality than the same amount of energy in an electric form. Conversely to energy, exergy is not conserved, but is partly lost in each process, which is described by the second law of thermodynamics. In physical terms, exergy is the maximum amount of work that can be extracted from a system as it reaches reversibly thermodynamic equilibrium with its environment. In other words, it represents the energy available to perform work.

Exergy has been used in a wide sample of disciplines, including plants and industrial systems optimization [Hernandez et al., 2017, 2018], ecological systems modeling [Chen, 2006, Jørgensen, 1992], energy transition studies [Serrenho et al., 2016, Warr et al., 2010], resource depletion studies [Valero and Valero, 2014], resource accounting studies [Calvo et al., 2015, Wall, 1977], macroeconomics [Brockway and Sakai, 2018]... The branch of Societal Exergy Accounting focuses on the flows of exergy throughout the economy at a defined geographical scale, for instance at the national scale. It enables to track exergy and energy flows throughout an economy, at three stages: primary, final and useful.

As exergy provides a thermodynamically consistent metric adjusted in regards to energy quality, it seems reasonable to assume that it is more closely related to energy services and economic output. The same amount of energy is more valuable in an electrical form than at a low temperature, and hence, also more productive. Consequently, this article is based on the assumption that exergy at the output stage, namely useful work, is the most suitable energy measure in order to study the dependency of the economy on energy. Figure 1 provides an illustration of the Energy Conversion Chain considered in this article. Besides this conceptual argumentation, this stake is defended by different researchers; it has been for instance found that useful work can be successfully used as an additional factor of production (alongside labour and capital) in aggregate production functions in order to describe the historical economic growth in the US [Ayres and Warr, 2010, 2005], in Japan [Ayres and Warr, 2010], and in Portugal [Santos et al., 2018]. The standpoint defended here is therefore backed up by empirical evidence.

Such studies that consider the role of energy in the economy through exergy and useful work lens usually find a tighter link between energy and the economy than primary or final stage based studies, as showcased in the empirical evidence mentioned. In regards to these facts, the present study focuses on Spain as a case study and seeks to answer whether the Spanish economy has become less energy dependent between 1960 and 2013, based on a useful work analysis. The following research questions are addressed:

- What is the Spanish en/exergy history?
- What is the historical relationship between en/exergy consumption and economic output?

The first research question addresses the need to perform the Spanish exergy accounting before being able to conclude about the relationship between energy and the economy. The choice of Spain is made for two main reasons. Firstly, there is currently no detailed exergy

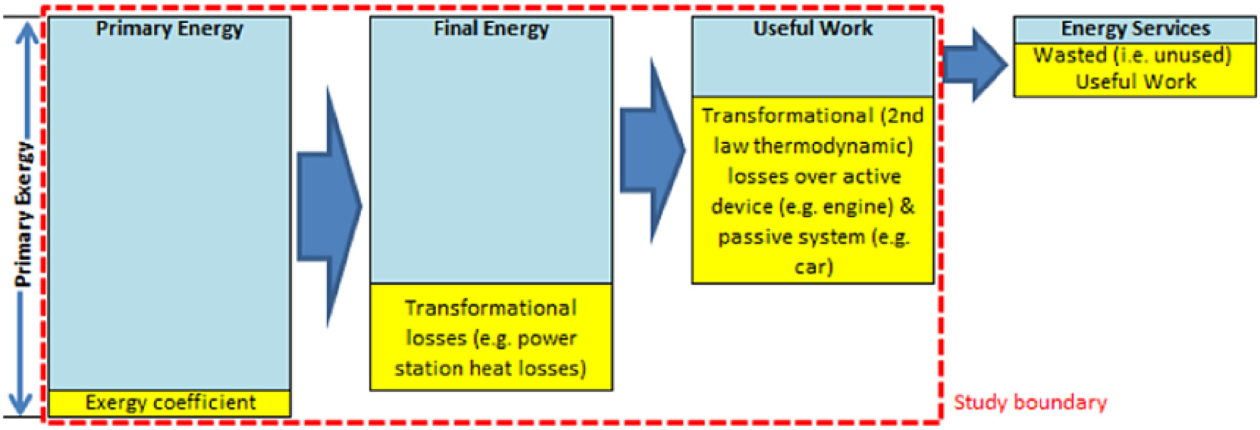

Figure 1: Energy Conversion Chain as considered in this article [Brockway et al., 2015]

analysis available for the Spanish economy. Secondly, the deep economical recession that has struck Spain since 2008 makes it an interesting case study when trying to elucidate whether exergy – economy models are also able to represent periods of constrained growth or even undergone degrowth.

The rest of the article is structured in the following way: the methodology and data are described in Section 2, results are described in Section 3, and Section 4 discusses the results and concludes about questions raised by this study as well as further work to be carried out.

2 Methodology and data

The methodology applied for this research is based on two major steps. First of all, the Spanish exergy accounting is carried out. In this step, both the energy and exergy time series (from 1960 to 2013) are constructed, at the primary, final and useful stages (Section 2.1. Secondly, the energy intensities of the Spanish economy are calculated for the whole time period and for both energy and exergy at the three different three stages (Section 2.2. Energy intensity (EI) is described in this paper as:

$$\mathrm{EI}_i = \frac{E_i}{\mathrm{GDP}} \tag{1}$$

where i can stand for each of the six energy measures mentioned. From these intensities, the dematerialization of the Spanish economy is discussed.

2.1 Societal Exergy Analysis

One can distinguish between two main kind of societal exergy analysis. The first one is known as Extended Exergy Accounting (EEA) and consists of a biophysical exergy accounting, which includes the flows of exergy embedded in natural resources flows within an economy. Thus, this first approach takes into consideration both energy and material flows. Indeed, the exergy of a particular substance is chemically defined, as showcased in thermodynamic studies [Szargut et al., 1987]. This first approach has been applied to numerous countries, including China [Chen et al., 2006], Italy [Wall et al., 1994], Norway [Ertesvåg and Mielnik, 2000]... The second kind of societal exergy analysis focuses only on exergy flows within an economy and on the energy conversion chain as presented in Figure 1. Hence the second approach only takes into consideration exergy flows related to energetic uses, and excludes other biophysical flows. The latter approach is taken in this article, as the focus is only on flows of exergy related to energetic uses, which is the correct approach in order to study the relationship between energy and the economy. These last kind of exergy analysis originate from the first national scale analysis carried out for the US in 1975 [Reistad, 1975]. This methodological choice is however not likely to have a substantial impact on the findings, as it has been shown in other studies that the flows of exergy embedded in natural resources are low compared to the flows of exergy related to energetic uses.

The input data for the present societal exergy analysis is extracted from IEA energy datasets, that provide the Spanish primary and final energy consumption from 1960 to 2013. The undertaken societal exergy analysis consists of four main steps, and basically follows the methodology developed in [Ayres and Warr, 2010], and that has been subsequently elaborated in other studies, such as [Brockway et al., 2014]. Firstly, the exergy input is calculated at both the primary and final stages (Section 2.1.1). Secondly, in the mapping phase (Section 2.1.2), the final energy consumption of each economic subsectors are ascribed to a useful work category. Thirdly, the efficiencies are calculated for each final end use category (Section 2.1.3). Lastly, the useful work for each couple (Economic Subsector, Energy Carrier) is calculated (Section 2.1.8). This whole analysis has been carried out and organized using the Physical Supply Use Table (PSUT) framework presented in Heun et al. [2018], which provides societal exergy analysis with methodological consistency and data structure uniformity, and enables a wide range of subsequent analysis based on PSUT matrices.

2.1.1 Energy - Exergy Conversion

The conversion of energy to exergy at both the primary and final stage is made according to the exergy coefficients displayed in Table 1, which can be originally found in [Serrenho et al., 2014] and are common to numerous exergy studies. Exergy can be calculated from energy values and exergy factors values according to Equation 2.

$$\text{Exergy}_j = \text{Energy}_j.\phi_j \tag{2}$$

where ϕ_j stands for the exergy factor specific to the energy carrier j as displayed in Table 1. There is general consensus on how to account for the exergy of fossil fuels and biomass, using chemical exergy coefficients as described in relevant thermodynamic studies [Szargut et al., 1987]. However, there are different options on how to account for renewables and nuclear energy, which can have significant impacts on the accounting results depending on the energy mix of the considered country [Sousa et al., 2017, Miller et al., 2016]. In this study, we choose to account for primary energy from nuclear plants as the heat released by the fuel in the process. Regarding renewable energy, the primary energy is assumed to be equal to the electricity production, method known as the Physical Content Method (PCM). These methodological choices are consistent with the IEA methodology [IEA, 2018] and are the dominant method in societal exergy studies.

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

Table 1: Exergy coefficients (no unit, ratios of exergy-to-energy) used in this study.

2.1.2 Mapping

In this step, the final energy data from the IEA is ascribed to an energetic final use. The IEA provides final energy data as a couple (Economic Subsector, Energy Carrier) for the period 1960 – 2013. These couples are ascribed to one of the energetic final uses presented in Table 2. The considered final uses are classified in 4 main categories: lighting, heating, mechanical drive and specific electricity. Conversely to most societal exergy analysis, it is to be noted that muscle work is not included. The reason is twofold. The goal of this study is to compare the energy intensity of the Spanish economy when calculated with primary and final stage metrics, and when calculated with useful stage metrics. Muscle work is not included as:

- Studies focusing at the primary and final stages typically disregard muscle work. In order to be representative of such studies, muscle work is equally disregarded at the primary and final stages here.
- At the useful stage, it has been showcased that muscle work is negligible for industrialized countries [Brockway et al., 2014]

The details of the mapping and of the IEA data structure is provided in the Supplementary Information.

Lighting	Heating	Mechanical drive	Specific electricity
Electric lights	Domestic heat - LTH	Industrial motors	Domestic appliances
Lighting town gas	Industrial heat - LTH 20°C	Commercial motors	Air conditioning
	Industrial heat - MTH 100°C	Domestic motors	
	Industrial heat - MTH 200°C	Static diesel engines	
	Industrial heat - HTH 600°C	Tractors	
	Industrial heat - HTH 800°C	Diesel cars	
	Industrial heat - HTH 1000°C	Biodiesel cars	
	Industrial heat - HTH 1200°C	Petrol cars	
	Domestic electric heaters - LTH	Biogasoline cars	
	Electric heaters - MTH 100°C	Natural gas vehicles	
	Electric heaters - MTH 200°C	Diesel trains	
	Electric heaters - HTH 600°C	Steam (coal) trains	
	Electric heaters - HTH 800°C	Electric trains	
	Electric heaters - HTH 1000°C	Mining engines	
	Electric heaters - HTH 1200°C	Boat engines	
	Electric heaters - HTH 1600°C	Steam boats	
		Airplanes	

Table 2: Final uses by main category

In this step, a few methodological improvements are made compared to other exergy accounting studies. Firstly, the considered final use categories are more detailed than in other studies, particularly for heating end uses, where a wide range of temperatures are considered in order to reflect better the underlying physical processes. Secondly, the IEA economic subsectors “Non-specified (industry)”, “Non-specified (transport)”, “Non-specified (others)” and “Non-specified (energy)” (see Supplementary Information for a short description of the IEA data structure) are split and ascribed to defined IEA economic subsectors. This disaggregation is based on different considerations:

- For some couples (Non-specified (sector), Energy Carrier), the ascription is straightforward taking into consideration which economic subsectors are the main consumers of the considered energy carrier within an economic sector

- For the most recent years (grossly 1970 – 2013) and when the ascription was not straightforward, the couple (Non-specified (sector), Energy Carrier) was split in the economic subsectors according to their relative energy consumption within the economic sector
- For the anterior years, the disaggregation was extrapolated according to patterns in the energy data in the period 1970 - 2013. For instance, the share of a given economic subsector within the economic sector was used to extrapolate backwards its share.

2.1.3 Efficiencies Calculation

In this step, it is crucial to distinguish between first and second law efficiency. First law efficiency is defined for a given process as the ratio of energy output to energy input, and, when applied to final end uses, is defined as ratio of useful energy to final energy. Likewise, second law efficiency is defined for a given process as the ratio of exergy output to exergy input, and of useful work to final exergy in regards to final end uses. Consequently, we define the first law efficiency $\eta_{i,j}$ and the second law efficiency $\varepsilon_{i,j}$:

$$\eta_{i,j} = \frac{\text{Useful energy}_{i,j}}{\text{Final energy}_{i,j}} \tag{3}$$

$$\varepsilon_{i,j} = \frac{\text{Useful work}_{i,j}}{\text{Final exergy}_{i,j}} \tag{4}$$

where i stands for the economic subsector and j for the energy carrier. The list of economic subsectors and energy carriers is included in Supplementary Information alongside the description of the IEA data structure. One can also define the second law efficiency $\varepsilon_{i,j}$ as a function of the first law efficiency $\eta_{i,j}$ and of the exergy coefficients ϕ_j and ϕ_l, where j corresponds to the energy carrier and l to the final use (see Table 2 for the list of final uses) of the couple (Economic Subsector, Energy Carrier).

$$\varepsilon_{i,j} = \eta_{i,j} \cdot \frac{\phi_l}{\phi_j} \tag{5}$$

For each final end use defined in Table 2, the first and second law efficiencies are calculated for the Spanish economy from 1960 to 2013 as explained in the following subsections.

2.1.4 Lighting

For lighting, the first and second law efficiencies are set equal and derived through an indirect method. Considering that 683 lumen/Watt is the maximum luminous efficacy of a light source when beaming at the particular wavelength to which the human eye is most sensitive to, one can write [Serrenho et al., 2014]:

$$\varepsilon = \eta = \frac{l}{683} \tag{6}$$

where l stands for the luminous efficacy of the regarded source. Consequently, the efficiency of the light source is totally defined by its luminous efficacy. Historical luminous efficacies for the UK are provided in Fouquet [2008]. These values are adapted for Spain by introducing a 10 years delay in order to model the technological gap between both countries.

2.1.5 Heating

As described in Table 2, heating is distinguished in different subcategories: low temperature heating LTH (20°C), medium temperature heating MTH (100 and 200°C), and high temperature heating HTH, which includes a wide range of temperatures in order to represents the underlying physical processes. In the case of heating, the second law efficiency is defined as:

$$\varepsilon_{i,j} = \frac{\eta_{i,j} \cdot \eta_{\text{Carnot}}}{\phi_j} \tag{7}$$

where ϕ_j stands for the exergy coefficient factor associated to the energy carrier j, as defined in Table 1 and η_{Carnot} is defined as

$$\eta_{\text{Carnot}} = 1 - \frac{T_0}{T_l} \tag{8}$$

where T_0 stands for the reference environment and T_l stands for the temperature associated to the final use l. Hence the importance of using a wide range of temperatures for describing the underlying processes.

LTH - Domestic heat and domestic electric heaters: As first law efficiencies were not available in the Spanish context, they are taken from [Fouquet, 2008], which provides efficiencies for the UK. A 10 years delay is applied in order to represent better the technological gap between both countries. The time series obtained is smoothed as is for instance done in Brockway et al. [2014]. The smoothing carried out is showcased in Supplementary Information. Second law efficiencies are derived according to Equation 7. Inside temperatures T_l are taken similar to UK inside temperatures according to [Brockway et al., 2014], however a 10 years delay is also applied. Only the Spanish coldest regions are taken into consideration for outside temperature, as they are representative of most of the heating used in Spain. The outside temperature T_0 is taken as the mean for the winter months (December - January - February), and data from the Agencia Estatal de Meteorología is used (see Supplementary Information for details).

MTH - 100°C: Outside temperature is taken equal to the yearly national mean according to the Agencia Estatal de Meteorología (see Supplementary Information for details), and final use temperature are taken equal to 100°C. First law efficiencies are calculated differently depending on whether the heater is electric or not:

- For non-electric heaters, the efficiency time series is constructed taking as point of departure Table 1 in Ayres et al. [2005]. The efficiency of industrial boilers is taken equal to 84% in 1950, and then a decaying exponential with a limit at 95% is used in order to model technical progress.
- For electric heaters, the point of departure is Table 5 in Ayres et al. [2005]. Likewise, a decaying exponential with limit 95% and a constrained point of 87% in 1960 is used.

For both electric and non-electric heaters, a 10 years delay is subsequently applied in order to model the technological gap between Spain and the US.

MTH - 200°C and HTH: Outside temperature is also taken equal to the yearly national mean according to the Agencia Estatal de Meteorología, and final use temperatures are taken equal to the temperature specified in the final use name. MTH2 and HTH heating categories correspond to energy-intensive industries and drive endothermic processes such as steel production, coke production, mineral processes, machinery manufacturing... As these categories include a wide range of different endothermic processes, it is not possible to take them all into consideration when calculating efficiencies. As such, two processes for which there is more data are used as representative of these final uses: steel and ammonia production.

The first law efficiency is calculated differently for non-electrical and electrical heating. For non-electrical heating, the first law is taken as the mean of the efficiency calculated for ammonia production and steel production through the blast oxygen furnace (BOF) route. For electrical heating, the efficiency is taken equal to the steel production through the electric arc furnace (EAF) route. Details of these efficiencies calculation for the whole period are provided Supplementary Information. The principle was however to calculate the energy intensity of the process and to compare it to the theoretical minimum amount of energy that could drive such a process, as formalized in Equation 9.

$$\eta = \frac{\text{Theoretical minimum energy / ton}}{\text{Actual enegy / ton}} \tag{9}$$

The theoretical minimums are taken from Fruehan et al. [2000] for steel and from Rafiqul et al. [2005] for ammonia. Intensities time series construction is performed combining methods: scientific publications review [Worrell et al., 1994], adaptation and smoothing of the UK intensities provided by recent studies [Brockway et al., 2014], and application of 10 years delay for modeling the technological gap. The methodology is further described in

Supplementary Information. The second law efficiency is calculated in the same way than for the MTH - 100°C category.

2.1.6 Mechanical drive

The methodology for mechanical drive efficiencies is subdivided in two main sections. Industrial, commercial and residential motors are firstly treated together with a point of departure in Ayres et al. [2005]. Subsequently all other final uses are calculated based on Brockway et al. [2014].

Industrial, commercial and residential motors First law efficiencies are taken raising linearly accordingly to [Ayres et al., 2005, Table 5]. For the most recent years, first law efficiencies are extrapolated according to the linear model. A 10 years delay is applied in order to model the technological gap between Spain and the US. Finally, a 95% first law efficiency limit is applied, and as such, efficiency gains are smoothed for Industrial motors when the linear model reaches 90% efficiency (the other motors do not reach this efficiency in the considered time period). Second law efficiency is calculated according to Equation 5, where both ϕ_j and ϕ_l are taken equal to 1, as both electricity and mechanical drive are "pure work".

Miscellaneous engines As data regarding efficiencies of engines is not available in the specific Spanish context, first law efficiencies are taken from an earlier UK study [Brockway et al., 2014]. Table 3 presents the methodology used for each of the considered engines in the mentioned study. A slight difference is introduced here to the extent that the formulas presented in Table 3 are used in order to calculate first law efficiencies instead of second law (calculated according to Equation 5). The time series have subsequently been adapted to Spain by applying a 10 years delay, and by smoothing the time series so that only the trend is kept and the yearly variations, that can be regarded as noise, are removed. An example of this smoothing can be found in the Supplementary Information.

2.1.7 Specific electricity

Electricity consumed in the "Residential" and in the "Commercial and Public Services" economic subsectors need to be disaggregated in the following final uses: Commercial motors and Residential motors (both treated in Section 2.1.6), Domestic electric heaters (treated in Section 2.1.5), Electric lights (treated in Section 2.1.4), and Domestic appliances and Air conditioning, that are both treated in the present Section. The disaggregation performed is further presented in Supplementary Information, but basically time series from the UK [Brockway et al., 2014] have been adapted using specific Spanish values [García López and Sendra, 2017, IDAE, 2011].

Final use subcategory	Methodology
Static diesel engines	Linear increase from 25% in 1960 to 30% in 2010
Mining engines	Same efficiency as Static diesel engines
Petrol cars	$\eta_{i,j} = 35.(1 - e^{-0.025.x})$
Biogasoline cars	Same efficiency as Petrol cars
Diesel cars	$\eta_{i,j} = 43.75.(1 - e^{-0.025.x})$, taken as 25% more efficient than petrol cars
Biodiesel cars	Same efficiency as Diesel cars
Natural gas vehicles	Same efficiency as Diesel cars assumed
Tractors	Assume 50% efficiency of Diesel cars
Diesel trains	$\eta_{i,j} = 50.(1 - e^{-0.065.x})$
Steam (coal) trains	
Electric trains	$\eta_{i,j} = 50.(1 - e^{-0.065.x})$, where the electricity consumption is converted in USg fuel consumption
Boat engines	Same efficiency as Diesel trains
Steam boats	Same efficiency as Steam (coal) trains
Airplanes	$\eta_{i,j} = 50.(1 - e^{-2.250.x})$

Table 3: Methodology applied for mechanical drive efficiencies, mostly based on Brockway et al. [2014]. x represents the fuel efficiency in mpUSg.

Efficiencies are calculated differently for the Air conditioning and the Domestic appliances subcategories.

Air conditioning: Equation 7 remains valid for calculating the second law efficiency of air conditioning. However, the Carnot efficiency η_{Carnot} is written as

$$\eta_{\text{Carnot}} = \frac{T_0}{T_l} - 1 \tag{10}$$

in the case of air conditioning. The outdoor reference temperature T_0 is taken equal to 35°C. This value seems to be a sensible and representative value of warm summer days in Spain, that are responsible for most of the air conditioning in the country. The cooling temperature T_l is taken equal to 24.4°C, which is the same value that has been used for the US in [Brockway et al., 2014].

The air conditioning first law efficiency is taken as raising linearly according to the values published in Table 5 in Ayres et al. [2005].

Domestic appliances: The domestic appliances final use is subsequently subdivided in 5 types of devices: cold (e.g. refrigerators and freezers), wet (e.g. washing machines and dryers), consumer electronics, computing appliances, and cooking appliances. The split of domestic appliances by types of devices is taken as equal to the split carried out in a former UK exergy study [Brockway et al., 2014], adding a 10 years delay in the shares of domestic appliances.

This disaggregation is presented in Supplementary Information. Efficiencies are calculated differently for each of these devices.

Cold First law efficiency is taken from Ayres et al. [2005], using the residential motors category and applying a 10 years delay. Second law efficiency is calculated according to Equation 10, with T_0 equal to 20°C and T_l equal to 0°C, similarly to Brockway et al. [2014].

Wet First law efficiency is taken as for Cold devices. Second law efficiency is taken according to Equation 7 where T_0 equal to 20°C and T_l equal to 100°C.

Consumer electronics First law efficiencys is taken according to Table 5 in Ayres et al. [2005], namely raising from 0.1% in 1980 to 1% in 2010. A 10 years delay is applied for Spain. The second law efficiency is taken as 100%: it is considered that consumer electronics perform "pure work".

Computing appliances The methodology is exactly the same as for Consumer electronics.

Cooking appliances First law efficiency is taken as 90% according to Brockway et al. [2014], and second law efficiency is taken according to Equation 7 where T_0 equal to 20°C and T_l equal to 100°C.

2.1.8 Useful work and energy calculations

Once all the efficiencies are calculated, the useful work and useful energy of each couple (Subsector, Energy Carrier) is calculated for the whole period. These calculations are straightforward when the first and second law efficiencies are set up. Indeed, one can write:

$$\text{Useful energy}_{i,j} = \eta_{i,j}.\text{Final energy}_{i,j} \tag{11}$$

$$\text{Useful work}_{i,j} = \varepsilon_{i,j}.\text{Final exergy}_{i,j} \tag{12}$$

where the final exergy is calculated according to Section 2.1.1.

2.2 Spanish Energy Intensities

Once the societal exergy accounting is performed, the Spanish time series of energy and exergy consumption are available at the primary, final and useful stages. The following step is to add economic data; real GDP data is obtained from the Penn World Tables [Feenstra et al., 2015] (more precisely, the variable "*rgdpe*" is used). The energy intensities are thereafter calculated as described in Equation 1.

3 Results

The first graph presented in Figure 2 showcases time series indexed in 1960 for primary energy, final energy, useful energy and useful work. Primary and final exergy are not displayed as they do not provide any additional information; they basically follow closely the evolution of respectively primary and final energy time series. A few remarks can be drawn from this first graph:

- The trend is similar for these four energy measures, they tend to evolve together, which was expected as primary energy drives, at least partly, the evolution of downstream energy variables.
- The energy consumed by the Spanish economy has increased over the years until the mid 2000s, with some short slowdowns, e.g. in the early 80s, corresponding to an economic recession stemming from the second oil shock.
- Useful work is the energy measure that seems to be increasing the most until the peak in the mid 2000s, although closely followed by useful energy. This supports the idea that energy analysis that stop at the primary or final stages are missing an important part of the energy service supplied at the useful stage, and that conclusions on the dependency of the economy on energy or about the role of the energy in the economy are likely to be misleading when stopping at the primary or final stage, as the role of energy is overlooked.
- The energy consumption has peaked in the mid 2000s according to the 4 indicators, and has started a decline until 2013. This decline has happened simultaneously to the economic crisis that has struck Spain in 2008, which also supports the idea of a tight connection between the economy and energy.

As discussed above, useful energy and work have been raising quicker than the 2 other energy indicators. This means that primary energy supply cannot be fully hold responsible for the rise at the useful stage (otherwise the primary energy curve would follow closely those of useful energy and work). Consequently, efficiency gains that explain this discrepancy must have occurred over the years. Here the focus is on useful work, as it has already been discussed in Section 1 how exergy accounts for the energy quality and how there is empirical evidence that useful work enable to successfully account for economic growth. The efficiency of primary exergy conversion to useful work is therefore discussed. In order

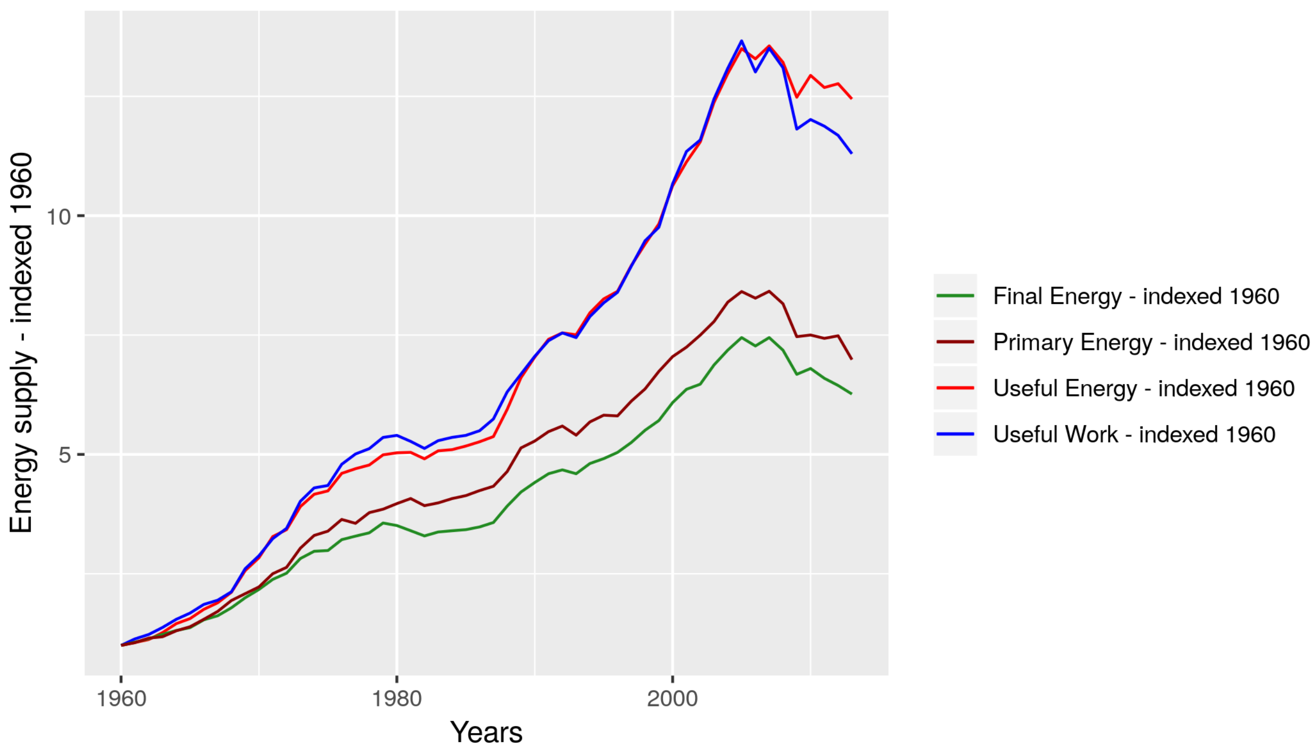

Figure 2: Primary, Final and Useful Energy alongside Useful Work, index 1960

to do so, the aggregated national exergy efficiency is defined according to Equation 13 as useful work provided per unit of primary exergy at the national scale:

$$\varepsilon_{\text{aggregated}} = \frac{\text{Total useful work}}{\text{Total primary exergy}} \tag{13}$$

Figure 3 showcases the aggregated national exergy efficiency time series for Spain. As the efficiency has indeed been raising from 1960 to the 2000s, it seems that the overall increase in efficiency has supplied, at least partly, the useful work consumption showcased in Figure 2. However a decomposition analysis would be needed in order to determine more precisely to which extent the rise of useful work consumption can be related to the rise of final uses efficiencies and to other factors (namely primary exergy increase and structural changes within the economy). One other worth noting strand is that efficiency gains, at the national scale, have been slowing down from the 2000s. This is probably the sign of *efficiency dilution*, which occurs when the less efficient processes are taking an increasing share of the national energy use, thereby slowing down efficiency gains despite final uses level

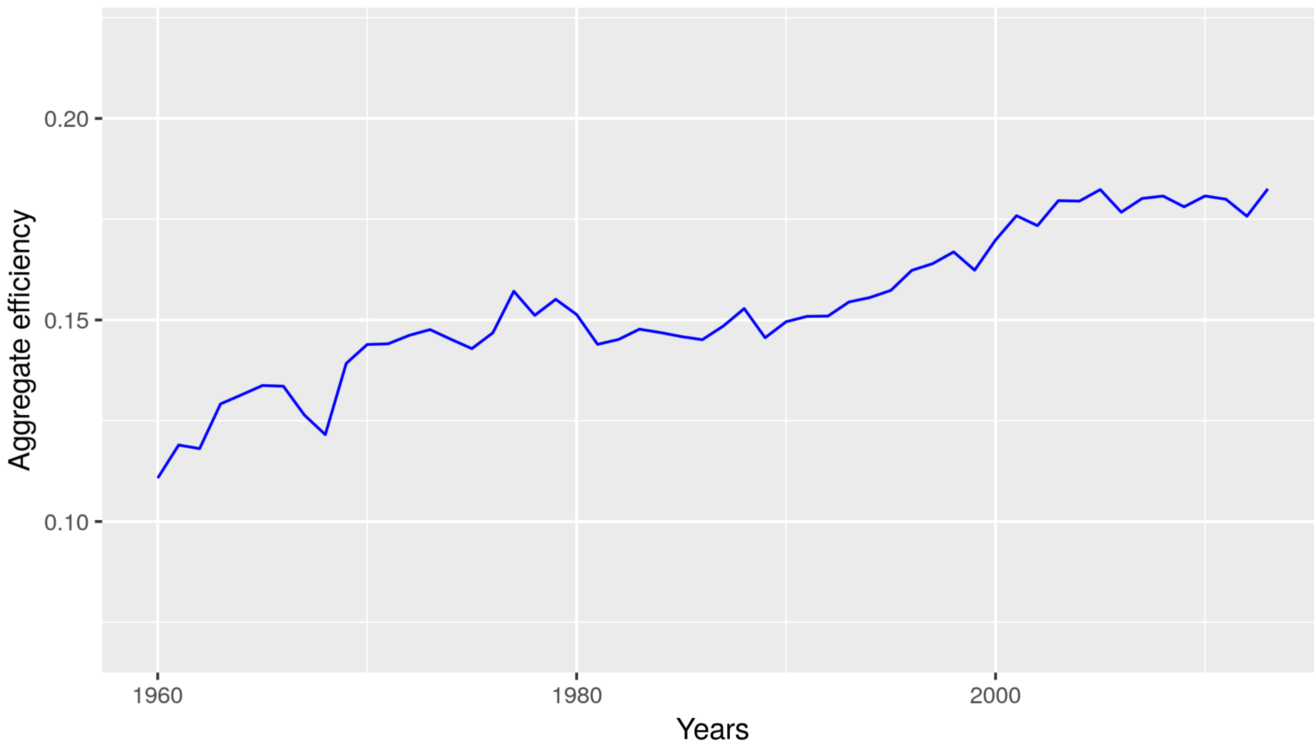

Figure 3: Aggregated Spanish national exergy efficiency

efficiency gains. Here a decomposition analysis would also be of great help in understanding to which extent this effect is influencing the aggregated efficiency. This kind of efficiency dilution has been noticed for instance for countries such as Japan [Williams et al., 2008] and the US [Brockway et al., 2014].

Figure 2 has showcased the rise of useful work provided within the Spanish economy over the years, as well as the obvious correlation between the energy consumption decrease and the economic recession starting in 2008. However, the causality is unclear. Do energy constraints trigger an economic recession, or does the economic recession decrease energy demand because of a lack of economic activity? Or do these two mechanisms happen simultaneously and interact? These questions demand further analysis, that are beyond the scope of this work. However, a few observations can be made from Figure 4.

Firstly, useful work supply (or consumption) as well as primary and final energy supply (see Figure 2) - has slowed down before the economic downturn. Indeed, useful work has remained grossly constant for 4 years before the beginning of the actual economic crisis. This coincides with the raise of oil prices that started in 2004 and reached a peak with the financial

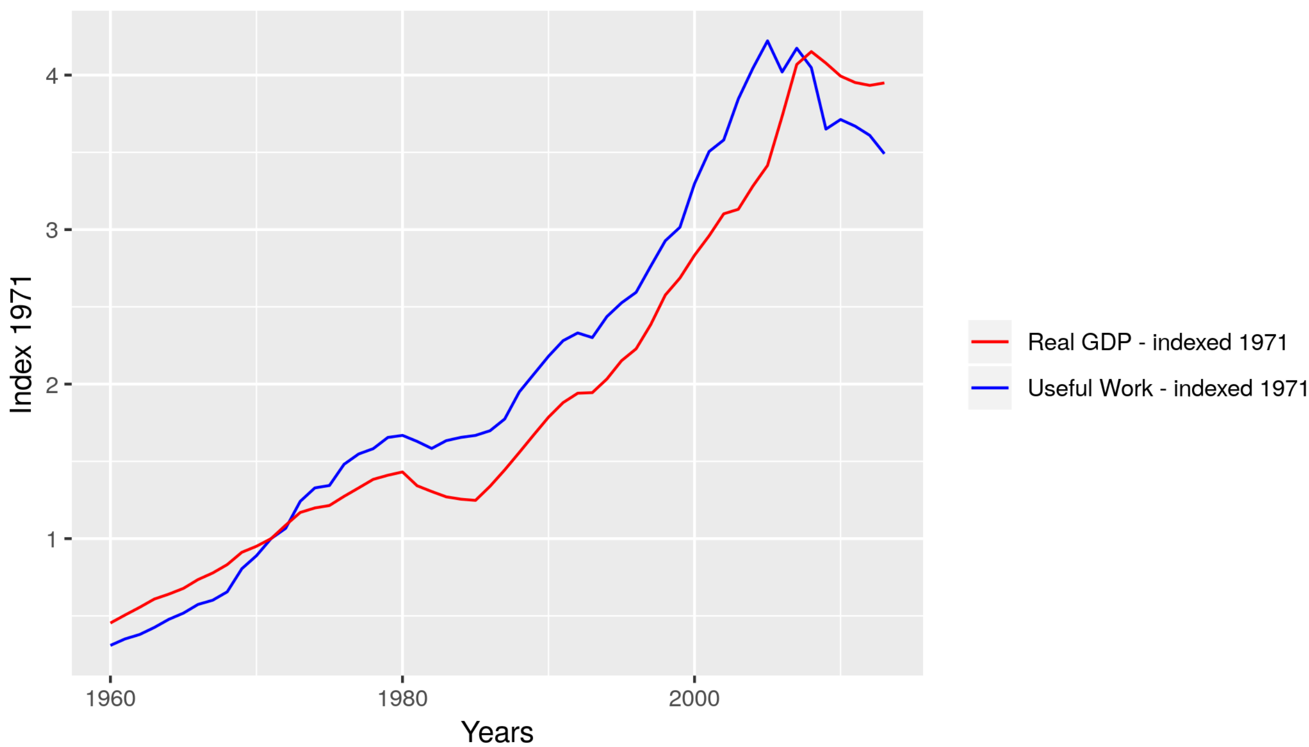

Figure 4: Useful Work and real GDP, index 1971

crisis in 2008, thereby constraining global oil (and consequently energy) supply, particularly for OECD countries (which are oil mostly importers) [Tverberg, 2012]. Then useful work begins a sharp decline alongside a decline in GDP during the economic crisis. This is consistent with a bidirectional causal relationship: high energy prices (taking oil prices as a proxy) entail the economic crisis due to unaffordable energy, products and services (since most of prices go along with energy prices), and then the economic crisis entails a steep reduction in the demand of energy as economic activity decreases. This thesis is developed further in Tverberg [2012]. Although this work is not enough for claiming causality, results are compatible with the thesis presented.

Finally, Figure 5 displays the primary energy, final energy and useful work intensities of the Spanish economy. A few things are worth noting. Firstly, useful work intensity has been raising more than the other intensities until 1985 (according to the index taken in 1960). This stems directly from the results presented in Figure 2. Secondly, primary and final energy intensities have been grossly decreasing steadily, excepting a small upswing in the early 2000s, which would support the idea of a Spanish economy getting more energy-

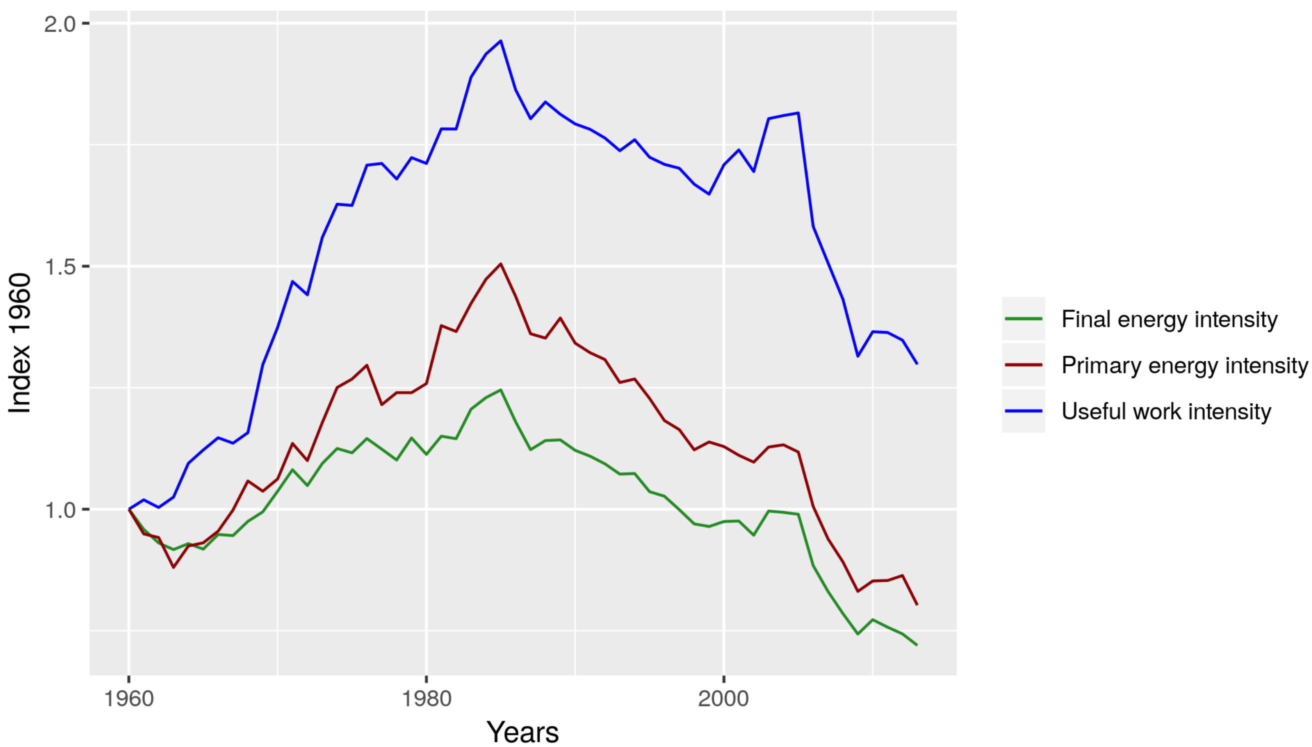

Figure 5: Primary Energy, Final Energy and Useful Work intensities

dematerialized and less energy dependent since 1985. However, the useful work intensity decrease has been far less pronounced, with a major upswing in the early 2000s, although the intensity plummets subsequently with the economic crisis. The mismatch between the three time series is due to efficiency improvements over time. Primary to final energy efficiency gains are responsible for the discrepancy between primary and final energy time series, while primary energy to useful work efficiency gains are responsible for the discrepancy between primary energy and useful work time series. The decrease in energy intensity metrics for the three time series starting in the 80s are characteristic of structural changes in the economy, which are to some extent due to offshoring highly energy intensive processes to developing countries. A decomposition analysis would shed some light on the relative impact of efficiency gains and structural changes over the covered time period.

Last but not least, the energy intensity values for primary and final energy intensities are lower in 2013 than they have been in the whole covered period, while useful work efficiency is still at the level of the early 1970s. Hence, it can be said that a useful work intensity metric offers a less optimistic view of the energy-dematerialization of the Spanish economy.

Although it seems that useful work intensity also indicates a decrease in the reliance of the economy to energy services, this decrease is far less pronounced than primary and final energy intensities suggest. Besides, useful work intensity remains at non-negligible values around the values in the early 1970s, while it can be said that primary and final energy intensities have reached historical minimums (at least when considering the time period covered in this analysis), which would - erroneously - suggest that the Spanish economy has never been as less energy dependent as it is presently.

4 Discussion

As presented in Section 1, this article seeks to answer two main research questions :

- What is the Spanish en/exergy history?
- What is the historical relationship between en/exergy consumption and economic output?

This societal exergy analysis carried out and extensively described in Section 2 as well as in Supplementary Information enabled to answer these questions. The first research question was discussed using Figures 2, 3 and 4, while the second research question was discussed building on Figure 5.

It has been firstly showcased with Figure 2 how the the Spanish energy consumption has been grossly raising from 1960 until the mid 2000s, and how the energy consumption has started decreasing alongside the economic crisis that started in 2008, which pinpoints the tight connection between energy and the economy. Subsequently it has been underlined that efficiency gains underlie the steep growth in useful work supply, and the aggregated national exergy efficiency has been computed to support this argument (Figure 3). This efficiency has been indeed found to be raising from 1960 to the mid 2000s, although gains are slowing down thereafter. It has been mentioned that a decomposition analysis could help to understand the evolution of this aggregated efficiency, although it is likely that the current slowing down in efficiency gains is due to efficiency dilution, whereby less efficient processes, such as air conditioning, are consuming an increasing share of the energy supply.

Then, the causality between the energy consumption decrease and economic recession starting in 2008 has been discussed. Useful work and real GDP time series have been compared in Figure 4, which shows how useful work slows down before the beginning of the economic crisis. These temporal observations are insufficient in order to claim causality, but they are compatible with a bidirectional causality: energy constraints, due to high energy prices (and therefore high prices in general), entail the economic crisis, and the decrease in overall economic activity brings about decrease in energy demand and consumption.

Finally, the primary energy, final energy and useful work intensities of the Spanish economy have been showcased in Figure 5. It has thereby been showcased with the Spanish case that the choice of the indicator is really sensitive when measuring the energy intensity of a geographical area, here a country. On the one hand, indicators such as primary or final energy intensity tend to support the idea that the economy is becoming steeply less energy intensive, namely more energy-dematerialized, and less energy dependent. On the other hand, indicators that are more closely related to economic output and activity, such as useful work, question the fact that the energy intensity of the economy is steeply decreasing, and tend to support the idea that economic output remains closely energy dependent, although this dependency may, as in the Spanish case, decrease. This result is consistent to earlier findings in the societal exergy analysis literature [Serrenho et al., 2014, 2016], which showcase how useful work intensities are particularly constant over time, conversely to primary stage based intensities.

This study questions the validity of analysis based on simpler units such as primary and final energy intensity. Indeed, such analysis would conclude in the Spanish case that the role of energy in the economy has been steeply declining since 1985, and that it is currently lower than it has ever been in the analyzed time period. Useful work analysis rejects this result and suggests that the connection remains tight, although it may be decreasing. Consequently, this study pinpoints the underestimated role of energy in the economy, and supports the idea that more research is needed to understand its key role.

It is worth mentioning different ways in which the present research could be extended so that other aspects are covered. Firstly, the exergy analysis carried out here is production based, and consequently excludes trade between countries and the processes that underlie an economy when these happen in foreign countries. As such, when considering the dependency of a society on energy, a consumption based approach could be of interest in order to complete the present analysis. Differences between production and consumption based approaches could thereafter be tracked down so that the whole specificity of a country is fully understood.

Secondly, even though the key role of energy in the economy is defended in this article, no formal relationship between these is provided. Therefore, one key strand in order to strengthen this research and to make the most of the societal exergy accounting carried out would be to formalize the relationship between economic output (considered equal to real GDP) and energy. Such works have for instance been carried out using aggregate production functions for Japan and the United States [Ayres and Warr, 2010], and in a cointegration analysis for the Portuguese economy [Santos et al., 2018]. A detailed review of the aggregate production function approach when including energy is provided in Brockway et al. [2017], and the impacts of the modelling choices on the interpretation of the economy are discussed in Heun et al. [2017]. Both studies provide a solid basis for extending the present study.

References

R. U. Ayres and B. Warr. Accounting for growth: the role of physical work. 16:181–209, 2005. ISSN 0954-349X.

R. U. Ayres and B. Warr. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Edward Elgar: Cheltenham, U. K., 2010.

R. U. Ayres, L. W. Ayres, and V. Pokrovsky. On the efficiency of US electricity usage since 1900. *Energy (Oxford)*, 30(7):1092–1145, June 2005. ISSN 0360-5442.

P. Brockway and M. Sakai. Thermodynamic efficiency is a key "engine of economic growth". *Under review*, 2018.

P. E. Brockway, J. R. Barrett, T. J. Foxon, and J. K. Steinberger. Divergence of Trends in US and UK Aggregate Exergy Efficiencies 1960?2010. 48:9874–81, 2014. ISSN 1520-5851.

P. E. Brockway, J. K. Steinberger, J. R. Barrett, and T. J. Foxon. Understanding China?s past and future energy demand: An exergy efficiency and decomposition analysis. 155: 892–903, 2015. ISSN 0306-2619.

P. E. Brockway, M. K. Heun, J. Santos, and J. R. Barrett. Energy-extended ces aggregate production: Current aspects of their specification and econometric estimation. 10, 2017. ISSN 1996-1073.

G. Calvo, A. Valero, A. Valero, and O. Carpintero. An exergoecological analysis of the mineral economy in Spain. 88:2–8, 2015. ISSN 0360-5442.

B. Chen, G. Chen, and Z. Yang. Exergy-based resource accounting for China. *Ecological Modelling*, 196(3):313–328, July 2006. ISSN 0304-3800.

G. Chen. Scarcity of exergy and ecological evaluation based on embodied exergy. *Communications in Nonlinear Science and Numerical Simulation*, 11(4):531–552, July 2006. ISSN 1007-5704.

I. S. Ertesvåg and M. Mielnik. Exergy analysis of the Norwegian society. *Energy*, 25(10): 957–973, Oct. 2000. ISSN 0360-5442.

R. C. Feenstra, R. Inklaar, and M. P. Timmer. The next generation of the penn world table. *American Economic Review*, 105(10):3150–82, October 2015.

R. Fouquet. *Heat, power and light: revolutions in energy services*. Edward Elgar Publishing, 2008.

R. Fruehan, O. Fortini, H. Paxton, and R. Brindle. Theoretical Minimum Energies to Produce Steel for Selected Conditions. Technical report, United States, May 2000.

J. García López and J. J. Sendra. *Mixed method for determining the Air-Conditioning consumption in households. Application to Ansdalusia*. Universidad de Sevilla. Escuela Técnica Superior de Arquitectura., 2017. ISBN 978-84-617-8428-8.

A. G. Hernandez, L. Paoli, and J. Cullen. Resource efficiency in steelmaking: energy and materials combined. 142:2429–2434, 2017. ISSN 1876-6102.

A. G. Hernandez, L. Paoli, and J. M. Cullen. How resource-efficient is the global steel industry? 133:132–145, 2018. ISSN 0921-3449.

M. Heun and P. Brockway. Meeting 2030 primary energy goals and economic growth goals: Mission impossible? *Under review*, 2018.

M. K. Heun, J. Santos, P. E. Brockway, R. Pruim, T. Domingos, and M. Sakai. From Theory to Econometrics to Energy Policy: Cautionary Tales for Policymaking Using Aggregate Production Functions. 10:203, 2017. ISSN 1996-1073.

M. K. Heun, A. Owen, and P. E. Brockway. A physical supply-use table framework for energy analysis on the energy conversion chain. *Applied Energy*, 226:1134–1162, Sept. 2018. ISSN 03062619.

IDAE. Análisis del consumo energético del sector residencial en España. Technical report, 2011.

IEA. World energy balances - 2018 edition - database documentation. Technical report, International Energy Agency, 2018.

S. E. Jørgensen. Parameters, ecological constraints and exergy. *Ecological Modelling*, 62(1): 163–170, July 1992. ISSN 0304-3800.

F. Krausmann, S. Gingrich, N. Eisenmenger, K.-H. Erb, H. Haberl, and M. Fischer-Kowalski. Growth in global materials use, GDP and population during the 20th century. *Ecological Economics*, 68(10):2696 – 2705, 2009. ISSN 0921-8009.

J. Miller, T. J. Foxon, and S. Sorrell. Exergy Accounting: A Quantitative Comparison of Methods and Implications for Energy-Economy Analysis. 9:947, 2016. ISSN 1996-1073.

J. Percebois. Is the concept of energy intensity meaningful? *Energy Economics*, 1(3):148 – 155, 1979. ISSN 0140-9883.

I. Rafiqul, C. Weber, B. Lehmann, and A. Voss. Energy efficiency improvements in ammonia production–perspectives and uncertainties. 30:2487–2504, 2005. ISSN 0360-5442.

Z. Rant. Exergy, a new word for technical available work. *Forsch Ingenieurweser*, 22(1):36 – 37, 1956.

G. Reistad. Available energy conversion and utilization in the united states. *Journal of Engineering for Power*, 97(3):429–434, 1975.

J. Santos, T. Domingos, T. Sousa, and M. St Aubyn. Useful Exergy Is Key in Obtaining Plausible Aggregate Production Functions and Recognizing the Role of Energy in Economic Growth: Portugal 1960?2009. 148:103–120, 2018. ISSN 0921-8009.

A. C. Serrenho, T. Sousa, B. Warr, R. U. Ayres, and T. Domingos. Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009. 76:704–715, 2014. ISSN 0360-5442.

A. C. Serrenho, B. Warr, T. Sousa, R. U. Ayres, and T. Domingos. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. 36:1–21, 2016. ISSN 0954-349X.

T. Sousa, P. E. Brockway, J. M. Cullen, S. T. Henriques, J. Miller, A. C. Serrenho, and T. Domingos. The Need for Robust, Consistent Methods in Societal Exergy Accounting. 141:11–21, 2017. ISSN 0921-8009.

J. Szargut, D. R. Morris, and F. R. Steward. Exergy analysis of thermal, chemical, and metallurgical processes. 1987.

G. E. Tverberg. Oil supply limits and the continuing financial crisis. *Energy*, 37(1):27 – 34, 2012. ISSN 0360-5442. 7th Biennial International Workshop "Advances in Energy Studies".

A. C. Valero and A. D. Valero. *Thanatia: The Destiny of the Earth's Mineral Resources.* World Scientific, 2014. ISBN 978-981-4273-93-0.

E. U. Von Weizsacker, C. Hargroves, M. H. Smith, C. Desha, and P. Stasinopoulos. *Factor five: Transforming the global economy through 80% improvements in resource productivity.* Routledge, 2009.

G. Wall. *Exergy-a useful concept within resource accounting.* Chalmers tekniska högskola, Göteborgs universitet, 1977.

G. Wall, E. Sciubba, and V. Naso. Exergy use in the italian society. 19:1267–1274, 1994. ISSN 0360-5442.

B. Warr, R. Ayres, N. Eisenmenger, F. Krausmann, and H. Schandl. Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100years of economic growth. 69:1904–1917, 2010. ISSN 0921-8009.

E. Williams, B. Warr, and R. U. Ayres. Efficiency Dilution: Long-Term Exergy Conversion Trends in Japan. 42:4964–70, 2008. ISSN 0013-936X.

E. Worrell, R. F. A. Cuelenaere, K. Blok, and W. C. Turkenburg. Energy consumption by industrial processes in the European Union. 19:1113–1129, 1994. ISSN 0360-5442.