Portugal societal exergy accounting – Past and Future

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Abstract

Societal transformations have been reliant on the consumption of energy services such as heat, transport and power, being this evolution enabled by a growing consumption of energy and an increase of its use efficiency. The correct way to evaluate the importance of these energy transfers to society is exergy because this property takes into account their quality, i.e., the maximum amount of work a certain amount of energy may originate (e.g. lift a weight, electrical work, etc.).

The current dissertation is based on societal exergy accounting studies for Portugal in order to provide 1) forecasts of exergy demand up to 2030 and 2) a detailed study on the electricity exergy efficiency series 1913-2014. Forecasts show that due to rebound effect it is not possible to have in the same scenario a rapid economic growth and a decrease in greenhouse gas emissions (decarbonized economy) based solely on efficiency improvements. Investing in renewables is mandatory to achieve that goal. Results regarding the aggregated efficiency of electricity show that rather than a continuous increase of efficiency, electricity final-useful aggregate efficiency has grown until the last quarter of the 20th century, around the 1970s and, after that has been decreasing continuously, reaching in 2014 a value similar to 1913 due to the dilution effect caused by the increasing shares of less efficient end-uses. These results emphasize the importance of the rebound and the dilution effects showing that they can partially offset the gains due to technology evolution.

Keywords: Exergy; Exergy efficiency; Electricity; Useful exergy; Consumption efficiency

1 Introduction

Studies on societal exergy accounting have been made for the last decades, showing the relevance of exergy. Works like Williams (2008), Serrenho et al. (2014, 2016), Ayres (2005; 2003), Warr (2010; 2008) and Brockway (2016; 2014) use this property to study exergy efficiency, energy transitions, economic growth and forecasting exergy demand (Sousa et al., 2017).

Williams et al. (2008) is an example of a study focusing on exergy efficiency, using it as a proxy to Japan's economy net efficiency. Based on an exergy analysis that allows comparing different uses of energy, sum different energy needs and account for energy demand. The authors suggest that energy consumption/needs (resources consumption), and respective environmental consequences, might be underestimated.

Ayres et al. (2003) for USA, Warr et al. (2008) for the UK and Warr et al. (2010) for four countries (UK, Austria, Japan and US) are examples of exergy analysis that use exergy efficiency (primary/final to useful) as a proxy to introduce the technological development in economic analysis. Warr et al. (2008) suggest that useful exergy should be used as a factor of production.

More recently, Serrenho and co-authors (2013; 2014; 2016) looked at long-run final and useful exergy consumption series (1856-2009). In his studies for Portugal, Serrenho (2013) found a proportional relation of useful exergy to GDP (1 MJ per € of GDP). Serrenho shows that useful exergy may explain most of the 'Sollow residual', which has been throughout time the unexplained part of GDP (attributed to external events). This is consonant with Ayres et al. (2003) suggestion of this possibility.

Based on this relation, (Santos & Domingos, 2018) calculate the rebound effect for Portugal, showing that an increase in aggregate final-to-useful efficiency leads to an increase in GDP which might lead to an increase in consumption of final exergy. This is also in accordance with Ayres et al. (2003) as they explain how the rebound effect of efficiency improvement could be the driver to economic growth.

Important aspects of exergy, resumed by Moran et al. (2011), are: a) exergy is an extensive property that is a feature of both the environment and the system; b) exergy's maximum work cannot be negative since the minimum work a system can do to move to the dead state is zero (spontaneous processes); and, c) exergy is destroyed by irreversibilities, being the case of a process where the potential to perform work is not used, a case of destruction of systems' total exergy.

Efficiencies are used to account for the losses that happen in systems throughout the energy flow, while undergoing processes where energy carriers are transformed into different forms of energy, on each stage of the flow. Calculating efficiencies can be done using both thermodynamic laws' efficiencies. The 2nd law or exergy efficiency (ε) is given by the ratio of exergy desired output by exergy input, the ratio between the real and the ideal exergy demands (Ford et al., 1975; Moran et al., 2011). Contrarily to the 1st law efficiency, it measures the degradation of energy's quality, so it is always lower than 1.

Exergy studies may be done in one or more of the three stages of the exergy flow: 1) primary exergy, as the exergy that has not undergone any process of conversion or transformation (natural resources) (2017); 2) final exergy, as the exergy delivered to consumers; and, 3) useful exergy, which is exergy in the form used by consumers (heat, light, cooling, etc.). This stage in energy chain is the best measure of energy needs (Serrenho 2013).

2 Methodology – Primary and Useful Exergy stages

Methodology used for the main sections - 3 and 4 – calculations is resumed in *Table* 1. A 4-step accounting process is used to calculate useful exergy (right column) from final energy, since most of the available data on a national scale is at the final stage. This process is followed by other authors such as Serrenho et al. (2013) and Ayres et al. (2003), while primary exergy is computed with a similar rationale but in 2 steps (left column).

Table 1: Calculation process of final energy to primary and useful exergy

A - Primary-Final calculations	B - Final-Useful calculations
1 - Apply primary-final efficiencies to final energy to obtain primary energy	1 - Convert final energy into exergy
2 - Convert primary energy into exergy	2 - Allocate final exergy consumption per sector to the different end-uses (e.g. mechanical work, high temperature heat, among others)
	3 - Apply final-useful efficiencies to obtain useful exergy
	4 - Sum the disaggregate results per sector to obtain totals

Table 2: Exergy conversion factors per energy carrier

Energy carriers	Exergy factors
Coal and Coal products	1.06
Oil and Oil products	1.06
Natural gas	1.04
Combustible Renewables	1.11
Electricity	1
CHP heat	0.6
Food and Feed	1
Other non-conventional	1

To convert energy into exergy (steps A-2 and B-1) conversion factors are applied by energy carrier, e.g. coal, oil products, combustible renewables, etc (Table 2). Factors are estimated based on combustion enthalpy[1] and, this, varies depending on the combustible's composition and conditions (e.g. if coal is dry or not). To simplify this issue, many studies such as Chen et al. (2009), Ertesvåg et al. (2000), Wall et al. (1994) and Serrenho (2013) consider an average value (Table 2). Electricity, food & feed and other non-conventional carriers have a factor of 1. This means one considers that all final energy of these energy carriers can be converted into work.

Final exergy is disaggregated (step B-2) into four end-uses/categories that were initially considered by Serrenho (2013): mechanical drive (MD), heat, light and other electrical (OE) uses.

Based on the concept of exergy and the general definition of exergy efficiency, it is possible to formulate equations to be applied depending on the end-use and source (final exergy) (*Table 3*).

In *Table 3* the first row is applied to mechanical drive uses, while second and third rows to heating and cooling uses, respectively.

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[1] For all combustibles, it is considered the Low Heating Value, except for coal gases and natural gas, for which the High Heating Value is considered.

Table 3: Exergy efficiency (ε) equations per final and useful uses (Serrenho (2013) based on Ford et al., 1975)

End-Use / Source		**Work**	**Fuel – Heat of combustion**	**Heat Q_1 from hot reservoir at T_1**
		W_{in}	B	$Q_1 \; 1-\frac{T_0}{T_1}$
Work	W_{out}	$\varepsilon = \eta = \frac{W_{in}}{W_{out}}$	$\varepsilon = \frac{W_{out}}{B} \approx \eta$	$\varepsilon = \frac{W_{out}}{Q_1 \; 1-\frac{T_0}{T_1}} = \frac{\eta}{1-\frac{T_0}{T_1}}$
Heat Q_2 added to warm reservoir at T_2	$Q_2 \; 1-\frac{T_0}{T_2}$	$\varepsilon = \frac{Q_2}{W_{in}} \; 1-\frac{T_0}{T_2}$ $= \eta \; 1-\frac{T_0}{T_2}$	$\varepsilon = \frac{Q_2}{B} \; 1-\frac{T_0}{T_2}$ $\approx \eta \; 1-\frac{T_0}{T_2}$	$\varepsilon = \frac{Q_2 \; 1-\frac{T_0}{T_2}}{Q_1 \; 1-\frac{T_0}{T_1}} = \eta \frac{1-\frac{T_0}{T_2}}{1-\frac{T_0}{T_2}}$
Heat Q_3 extracted from cool reservoir at T_3	$Q_3 \; \frac{T_0}{T_3}-1$	$\varepsilon = \frac{Q_3}{W_{in}} \; \frac{T_0}{T_3}-1$ $= \eta \; \frac{T_0}{T_3}-1$	$\varepsilon = \frac{Q_3}{B} \; \frac{T_0}{T_3}-1 \; \approx \eta \; \frac{T_0}{T_3}$ -1	$\varepsilon = \frac{Q_3 \; \frac{T_0}{T_3}-1}{Q_1 \; 1-\frac{T_0}{T_1}} = \eta \frac{\frac{T_0}{T_3}-1}{1-\frac{T_0}{T_1}}$

Notes: η = energy efficiency; W = work; Q = heat; B = exergy; T_0 = environment temperature; 1 > T_2 > T_0 > T_3

Also, columns in *Table 3* can be seen by energy-carrier, in this sense: the first column corresponds to electricity and equations applied to electricity uses; the second corresponds to coal, oil products, natural gas and combustible renewables uses; and, the third, can be linked to co-generation heat uses. This means that, e.g. to calculate exergy efficiency of electricity mechanical drive uses, one would look at the first square of the table (1st column-1st row), which has the equation for the pair work-work (energy carrier – end-use).

3 Portugal in 2030 – Exergy consumption and efficiency scenarios

A reproduction of Serrenho's calculations was made, based on the final-useful methodology shown in section 2, to: (1) understand the accounting process, its details and difficulties, (2) facilitate the updates on the long-run series and (3) make explicit the assumptions and proxies that were used.
Following data reproduction, an update of Serrenho's series following the same methodology and assumptions, was made for 2010-2014, since IEA has made new data available for that period.

Based on the updated series, useful and final exergy projections for 2030 were made (final-useful efficiencies and exergy shares). Data series of final energy consumption were taken from IEA (2016).

3.1 MEET2030: the project

MEET 2030 is a project focused on the recent future. Scenarios for 2030 were made in the context of a 4th Industrial Revolution (robotisation and mass automation), having in mind the European goals for carbon neutrality. It is a project developed by Instituto Superior Técnico (IST) – mentioned hereby as the research team -, the Business Council for Sustainable Development (BCSD) Portugal, and BCSD associated (companies such as, e.g., EDP, GALP, Navigator, Brisa and Tecnoplano).
The following subsections were developed under the project MEET2030 and due to a matter of timing, results and assumptions presented are preliminary conclusions of the project. The final report will be available at http://meet2030.pt/.

To make 2030 projections, two scenarios were built following the "extreme world" method, where the worst and best scenarios are built within the plausible universe.
The worst plausible scenario was named Ostrich and represents a scenario for 2030 of stagnation, economic instability, social crisis and a peripheral development that missed opportunities from the 4th Industrial Revolution (digitalization/mass automation). The best plausible scenario was named Iberian Lynx and pictures Portugal in 2030 with a rapid economic growth, achieving sustained growth rates and being a country that took the opportunities created by the 4th Industrial Revolution integrated in a stable geopolitical and demographic EU context.
A closed-loop methodology was developed, where based on an empirical method, aggregate final-useful efficiency series are used to calculate total factor productivity. With this, gross domestic product (GDP) is computed and, using its relation with useful exergy (1MJ/€ of GDP), Portugal's useful exergy

series is calculated. After this, using aggregate efficiency, final exergy series are computed and emission factors are, then, applied to calculate greenhouse gas (GHG) emissions. With the results obtained and BCSD associates' inputs (comments and validation based on their know-how, given in workshops and challenges proposed by the research team), initial share series may be adjusted, closing the loop and restarting another cycle of calculations.

The first input is useful exergy end-use shares disaggregate per sector < energy carrier < type of combustible < end-use, and final-useful exergy efficiencies disaggregated at the same level. Energy carriers considered are: coal, oil products, combustible renewables, natural gas, electricity, co-generation heat and solar photovoltaic, while end-uses are, as mentioned, mechanical drive (MD, divided in 3 categories of mechanical work), heat (divided in 5 categories of temperature: Low Temperature Heat (LTH3<50^{o}C<LTH2<90^{o}C<LTH1<120ºC); Medium Temperature Heat (120^{o}C<MTH<500ºC); High Temperature Heat (HTH>500ºC)), light and other electrical (OE) uses. These series are for the period 2000-2030, where projections for 2015-2030 were already made based mainly on 2000-2014 tendencies and within each scenario narrative. Using these series, aggregate final-useful efficiency is computed.

When the final exergy series (absolute values) is calculate within the loop, the series of shares is applied to the obtained totals, in order to compute GHG emissions because emission factors are disaggregated by type of combustible.

3.2 Final and useful shares and efficiencies

The main assumptions made for exergy calculations for both scenarios are presented in Table 4, where, for useful exergy shares, are mentioned the cases where the 2000-2014 trend was not followed for 2030 projections.

Table 4: Main variables and configurations for exergy use by category in the Ostrich and Iberian Lynx scenarios

	Ostrich	Iberian Lynx
Useful exergy shares (exergy by end use category)	Unchanged trend except for some heat and for mechanical drive uses from Oil products (i.e., HTH, MTH, LTH3, MW2, MW3 and navigation) and in Electricity shares. For oil products uses, the scenario considers the maintenance of the average observed in the most recent years (2009-2014). For electricity, consumption for stationary MD uses grows up to 60% of industrial electricity consumption.	Electrification: MW2 share decreases approx. 1.5 p.p. to be approx. 2% of total useful exergy; Diesel uses decrease drastically to almost half of their share from 15.4% (2014) to 9% (2030); Heat needs from electric appliances diminish circa 1.6 p.p. to be 3% of total useful exergy; Consumption for stationary MD uses grows to be 70% of industrial electricity consumption and up until 30% in non-industrial sectors
Electrical vehicles circulating by 2030 (EV and H_2)	Slow adoption – approximately 6% of vehicles circulating by 2030	Fast adoption - 20% of vehicles circulating by 2030
Final-to-useful exergy efficiencies	Technology specific final-to-useful efficiencies are constant [Although, aggregated exergy efficiency has marginal increases]	NG vehicles' efficiency increase 1.4 p.p. by 2030; Lighting efficiency increases 5 p.p. by 2030 (stock replacement)
Energy efficiency in buildings (LTH3)	Useful exergy decreases between 0.6 and 1p.p. by 2030 (improved efficiency)	Exergy for heating decreases 1.4 p.p. by 2030 (improved efficiency)

Table 4 Acronyms: HTH – High temperature heat; MTH – Medium temperature heat; LTH3 – Low temperature heat 3; MW2 – Gasoline/ LPG engines; MW3 – Diesel engines; MD – Mechanical drive; EV – electrical vehicles (including hydrogen vehicles).

Portugal aggregate final-useful efficiency has been relatively constant in the recent past (since 2000) and so, to develop a conservative scenario as the Ostrich, efficiency is considered to maintain the tendency until 2030. As following the trend, aggregate efficiency increases about 1.3 p.p. from 2014 to 2030 and about 2.4 p.p. from 2000 to 2030, reaching 23.5%. The slight increase is due to assumptions made at the disaggregate level of energy's several end-uses, mention in Table 4.

Portugal slight increase in final-useful efficiency is intrinsically linked with the increasing uses of electricity in Portuguese society and the increase in efficiency of electrical appliances which in time have been substituting less efficient uses – that do not use electricity. Considering this and the fact the use of electricity has a higher efficiency than the use of any other energy carrier, it is expected that the general efficiency trend would be positive.

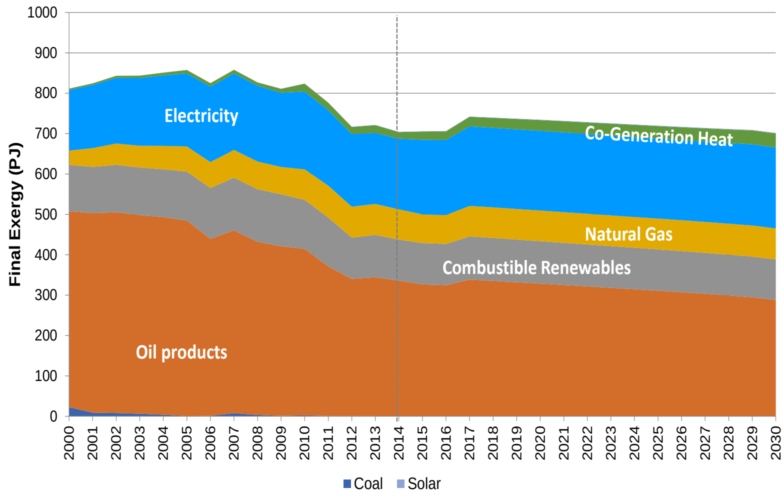

Figure 1: Final exergy consumptions per energy carrier (Ostrich scenario)

For the Ostrich scenario, in terms of the overall consumption of Portuguese society (Figure 1), it does not change much: 704 PJ (2014) compared to 702 PJ (2030) of final exergy and 156 PJ (2014) compared to 165 PJ (2030) of useful exergy. In this scenario, there is a relatively small increase in total useful exergy consumption, associated to a slow growth in the economy.

Within the plausible universe, Iberian Lynx aggregate efficiency projected for 2030 develops quickly, growing approximately 5 p.p. compared to 2014, up to 27.3% in 2030. The rapid economic growth, leads to higher total useful exergy consumption, in 2030, 229 PJ. This also happens for final exergy consumption with 839 PJ consumed, by 2030, in this scenario (Figure 2).

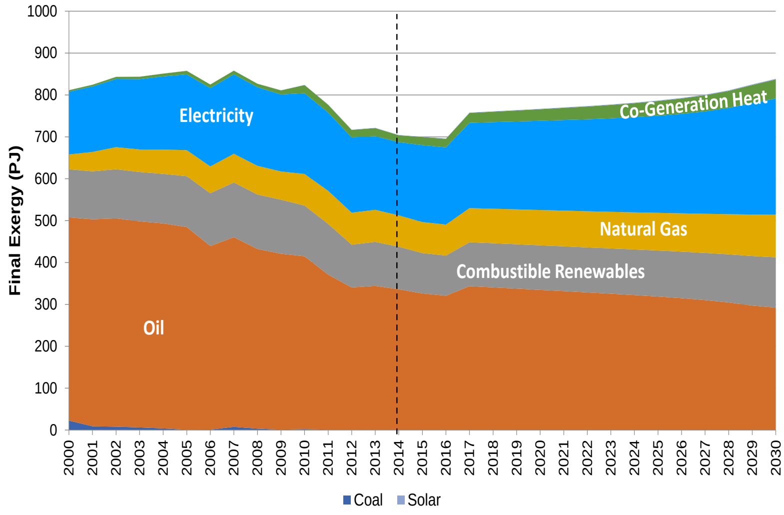

Figure 2: Final exergy consumption per energy carrier (Iberian Lynx scenario)

Once again, the evolution of efficiency is explained at the end-use level, being mainly based on the substitution of energy carriers' and a more accentuated shift in electrification. The main changes made to past trends in order to make projections are related to oil products and electricity uses. This because gasoline, diesel and heat have high useful and final exergy shares but low efficiencies (pushing aggregate efficiency to lower values), while electricity has high shares and efficiency, replacing oil products' MD uses by electric uses, e.g., vehicles. This leads to increases in aggregate efficiency. For that, in the Iberian Lynx, the trends for oil products and electricity uses are steeper than in the Ostrich.

3.3 Fossil fuel GHG Emissions for 2030

GHG emissions' calculations were computed using IPCC (2006) emission factors as followed by APA (Agência Portuguesa do Ambiente) and in the NIR (National Inventory Report on GHG emissions).

The context of MEET2030 fits in IPCC's Energy category, which means that studied GHG emissions are all related to fossil fuels combustion but do not consider emissions from other sources (namely the majority of CH_4 and N_2O emissions). This means that the results presented correspond to circa 70% of Portugal total GHG emissions.

The mix of resources consumed to produce electricity is the same for both scenarios: 60% from renewable resources (Biomass, Hydro, Wind, Geothermal and Solar) and 40% from non-renewable (Thermo-electricity production excluding the use of Biomass). This is in order to make a plausible comparison between both scenarios.

Interestingly, the Iberian Lynx is the scenario with the most GHG emissions associated, approximately 55 Mt $CO_{2\ eq}$ compared to the 46.2 Mt $CO_{2\ eq}$ projected for Ostrich in 2030. This is explained by the economic growth of the Iberian Lynx scenario and consequent rebound effect.

With the computed values for GHG total emissions, both scenarios comply only with the less stringent scenario of the National Low-Carbon Roadmap (APA & Comité Executivo da Comissão para as Alterações Climáticas, 2012), which is not in track to achieve EU goals for GHG emissions – less 80% compared to 1990 totals. However, an adjusted version of the Iberian Lynx – with higher share of renewables in the electroproduction mix and carbon sequestration - is being developed to comply with the most stringent scenario of the Low-Carbon Roadmap, which is in track with EU 2050 goals.

4 Electricity – the relevance of specific data and methodology choice

The point of departure is Serrenho work on final to useful exergy accounting calculations for Portugal over the period 1856-2006: Serrenho (2013) and Serrenho et. al (2016). Palma (2014) has performed some tests on Serrenho's useful exergy accounting work for Portugal. These tests were made exclusively for the period after 1960. Some of these tests made by Palma, i.e. introducing the cooling end-use category (which showed improvements to the original series), are incorporated in this work.

In order to perform detailed calculations, benchmark years for which data was available were defined to minimize the use of proxies as much as possible. Years were chosen accordingly with their energy historical importance as well as the availability of specific data that could be found, being those years: 1913, 1950, 1973, 1986, 2005 and 2014. These years are characterized by changes in the evolution of energy consumption in Portugal, either to a different growth rate or into a period of decreasing or stable consumption (e.g. as seen in Henriques (2011) work).

Then, the four-step methodology described in Table 1, column B, knowing that for electricity the method applied has its specificities, namely the fact that allocation is done by applying end-use shares to total final exergy. It was in the allocation step that the new end-use category (electrochemical uses) was introduced.

To calculate each sector's share from the total electricity consumed in the country, energy consumption data from DGSE (1927-1984) and IEA (1960-2014) was used, considering the following sectors: 1) Industrial, 2) Domestic/Services and 3) Transports.

For the 1913 benchmark, due to the lack of available information, calculations were mainly done with extrapolations based on the following benchmark years' consumption data. And, although the objective of the work is to have better estimates based on years rich on information, this benchmark is relevant to have a glimpse of the beginning of electricity consumption in Portugal. Also, for recent years, despite the IEA data available from 1960 to 2014, it was necessary to assure the consistency of data from different sources, which imposed the necessity to use some proxies.

Comparing Serrenho's series with the new results some differences between allocations may be noted but there is no change in the main end-uses, i.e. mechanical drive end-uses have the highest share in both cases. Yet, this category has a higher share in the new allocation.

Regarding light, it has a higher share in 1913 due to end-use allocation in the Residential/Services sector being considered 100% rather than 38%. However, for all other benchmarks it has a lower share than Serrenho's allocation, which is a result of computing shares disaggregate per sector. For this, also, MD and Heat shares, in the new allocation, are higher in Industry and, consequently, in Portugal totals.

Electrochemical uses were disaggregated from OE uses category. These are **u**ses in which electricity is used to perform chemical reactions, i.e. electrolytic processes in industry. Consumption data from national statistics institute, INE, (INE, 1950, 1969) was used in order to achieve better estimations, being those based on consumption tendencies, while efficiencies were taken from Ayres et al.(2005) and Serrenho et al.(2016).

It is estimated that electrochemical uses in Portugal represent, nowadays (2014), around 13.7% of the total electricity consumed in the Industrial sector, which is approximately 5% of the total electricity consumed in the whole country. When comparing original OE shares and the new allocation for these uses, the new shares are lower, with the largest difference occurring in 1986.

Also, the highest shares are in 1973 and 1986. This could be due to two effects. The first is related directly to the values, as these are the benchmarks immediately after the installation of the electrochemical industry in Portugal. The second effect is that the OE uses category, increase its share in more recent benchmarks, leading to the decrease of other end-use categories shares such as electrochemical.

Palma and co-authors (2014; 2016), have already introduced Cooling as a new end-use category to be considered. Their work shows how relevant it is a further disaggregation of the end-use categories of this energy carrier for data between 1960 and 2009. They show a decrease of 3.4% in overall aggregate efficiency for 2009 data (ibid). However, the lack of data for the period before 1960 makes it difficult to proceed to a very detailed disaggregation.

For the current dissertation, the cooling category was considered accordingly with Palma's assumptions. This means that the Cooling uses are disaggregated from stationary mechanical drive (stationary) category, as mentioned, and include air-conditioners and refrigerators.

When comparing allocations for mechanical drive uses, with and without cooling end-use what is clear is an accentuated variation in MD uses evolution. This means, for the first two benchmarks, despite considering the cooling uses in 1950, new allocation presents higher shares for MD. However, in 1950 the difference between shares is partially the cooling category and, for the following more recent benchmarks, MD uses have lower shares in the new allocation if excluding the cooling category.

4.1 Final-Useful efficiencies

In order to estimate the impact on results of the new categories considered aggregate final-useful efficiency was calculated.

Electrochemical uses increase the aggregate efficiency, while cooling has the opposite effect. This is because electrochemical uses have higher exergy efficiencies than OE, which was the category they were aggregated with. Using the same reasoning, cooling uses have a lower efficiency than MD, leading than to a decrease in aggregate efficiency.

When combining both ("New" series in Figure 3), the effect of cooling appears to outweigh electrochemical influence, resulting in a decrease of efficiency since 1950. The explanation is twofold: (1) on one hand electrochemical uses are only part of the industry consumption and, throughout time, this sector's share decreases; and, (2) on the other hand, cooling uses are present in both industry and domestic/services sectors. Besides that, not only cooling shares are around 20% of domestic/services final consumption – which is the double of its share in industry – but, also, the overall domestic/services consumption grows faster than the industrial, which leads to a growing share of the first and, consequently, a growing influence of cooling uses efficiency.

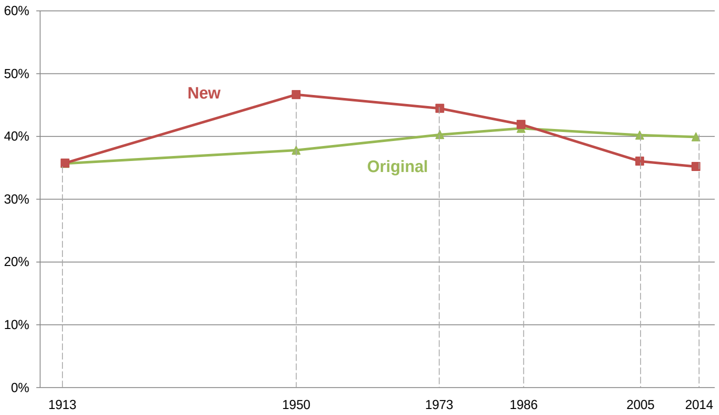

Figure 3: Electricity aggregate final-to-useful efficiency 1913-2014 (New: new series with all new categories; Original: Serrenho series and allocation)

While Serrenho's aggregated efficiency has a growing tendency, the new series efficiency grows circa 9 p.p. from 1913 to 1950 and, then, proceeds to decrease reaching 36% by 2014 – 4 p.p. lower than Serrenho's 2014 result.

The evolution in the electricity aggregate final to useful efficiency is explained by the "dilution" effect, where even though technologies have been increasing their individual efficiencies, the growth in consumption is towards less efficient uses. This effect is also verified by Ayres et al. (2005) for the United States in 1900-2000.

4.2 Primary exergy calculation methods

To calculate primary exergy data, primary-to-final efficiencies were used, tracing back values from final energy – gross electricity produced. Final energy data used to compute calculations was taken from Henriques (2009; 2011) and national energy balances – 2005 and 2014 (DGEG, 2017).

There are three different methods pointed by Sousa et al. (2017) to compute primary energy associated with electricity produced directly from renewable sources (hydro, wind, geothermal, solar, etc.): the Resource Content method (RCM), the Physical Content method (PCM) and the Partial Substitution method (PSM). All have been used in the last decades, although the RCM is the most common and has been used in works such Brockway et al. (2015), Warr et al. (2008), Rosen et al. (1992) and Wall et al. (1987).

The RCM is a method in which it is considered that primary energy is the energy of the resources, so the technologies' efficiencies used to produce electricity from renewable sources, are taken into account. The PCM is based on the notion that the primary form of energy is the first form of energy available to be commercialized or, in other words, the gross electricity production is the primary energy considered (Sousa et al., 2017) for all renewable except for geothermal (Sousa et al., 2017). In this case, heat is the first form of energy that can be commercialized, being considered for this work an efficiency of 10%.

Finally, the PSM is a method that quantifies primary energy as the quantity of coal necessary in a conventional thermoelectric power plant to produce the same electricity produced by the renewable resources, ignoring the structure of the energy sector (Sousa et al., 2017).

For this work, unfortunately, it was not possible to find all fuel-specific efficiencies of thermoelectric production for all benchmarks (1986 is missing). Therefore, the efficiency used when applying this method was the aggregate thermoelectric production efficiency.

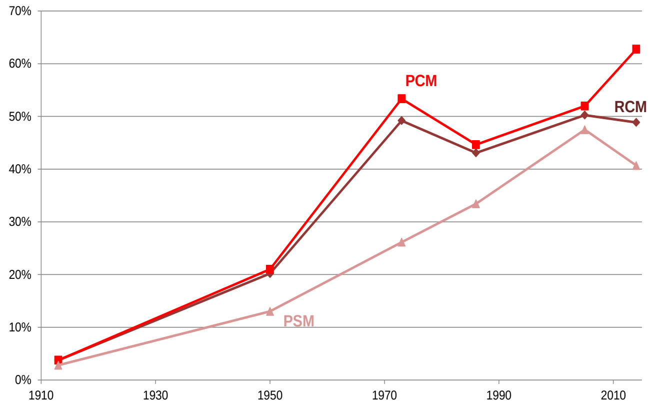

Figure 4: Primary-Final exergy efficiencies using RCM, PCM and PSM 1913 – 2014

Comparing efficiencies calculated for all methods (Figure 4 and Figure 5), the Physical Content method presents the highest efficiencies because renewable resources have had an important role in the country's electricity production mix throughout time and this method highlights the use of those resources.

The relation of higher shares of renewables with higher efficiencies at the primary-final stage is also noticed by Williams et al. (2008) in a study for Japan, for the 20th century. The authors mention how a dilution effect, previously seen for Portugal in final-useful calculations, happens also at the primary-final stage in electricity generation for that country.

In Portugal's case, there is no dilution effect in primary-final and primary-useful efficiencies evolution. This is because the share of renewables has increased in the 2000s once again. Contrarily to this, in Japan, hydro power decreased its share throughout time, as fossil fuel and nuclear plants were used to meet the growing electricity demand.

However, the inverted U shape of final-useful efficiencies influences the primary-useful efficiency because it does not grow (using any of the methods) as much as primary-final efficiency does. In fact, for PCM and RCM methods, efficiency in 1986-2005 is practically constant. This is due to the decrease in final-useful efficiency observed.

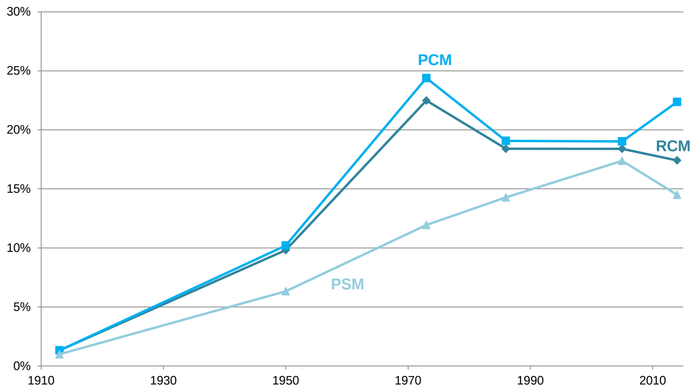

Figure 5: Primary-Useful exergy efficiencies using RCM, PCM and PSM 1913 – 2014

As mentioned by Sousa et al. (2017) the choice of method should depend on the purpose for which calculations are being computed. However, as it is seen for Portugal, it is important to keep in mind that for cases where renewable resources have high shares in electricity production mix, efficiencies may differ significantly from one method to the other, e.g. around 10 p.p. difference in primary-useful 1973 RCM and PSM efficiencies, and primary-final efficiency approximately 20 p.p. lower in 2014 PSM than in PCM.

5 Conclusions

Within the core subject of useful exergy accounting, this dissertation explored: forecasts of useful exergy and exergy efficiency, as well as the use of detailed data for electricity to improve exergy accounting.

Forecast results show a rebound effect in both scenarios. In the Ostrich scenario, the decrease in final exergy (0.3 p.p.) is lower than the increase in efficiency (1.3 p.p.) between 2014 and 2030 while in the Lynx scenario the final exergy increases by 19 p.p. instead of decreasing. The explanation is that the increase in aggregated efficiency causes an economic growth (an increase in GDP); however, as higher GDP is directly liked to useful exergy (1 MJ /€ of GDP) there is always an increase in the consumption of useful exergy. The final exergy is then obtained by the ratio between the useful exergy and the aggregated efficiency.

Regarding GHG emissions, the main conclusion that can be taken is that a gain in aggregate exergy efficiency does not necessarily mean a decrease in emissions. What was observed in this case was a consequence of the mentioned rebound effect in consumption, as a significant increase in aggregate efficiency (Iberian Lynx scenario) leads to more consumption and, consequently, GHG emissions.

For that, the obtained results show that it is important to have policies that address possible rebound effects associated with higher exergy efficiency. Results show that policies must be directed to both energy consumption and production (electricity).

The inclusion of a new end-use category, i.e. electrochemical uses, as well as other changes showed significant differences in electricity aggregate final-useful efficiency when compared to the series obtained by Serrenho (2013). The new results show that rather than a continuous increase of efficiency, electricity final-useful aggregate efficiency has grown until the 1970s and, then, it has been decreasing continuously, reaching in 2014 a value similar to 1913. This decrease is due to the “dilution effect”.

Results obtained in section 4, make us question the increase of almost 5 p.p. in aggregated efficiency between 2014 and 2030, assumed for the Lynx scenario. Replacing the new electricity series on Portugal’s aggregate final-useful series and making a linear projection to 2014-2030 reveals a difference of approximately 2 p.p. with the linear trend forecast based on Serrenho’s values. This means that, to assure an increase in aggregate efficiency at a national level, besides increasing thermodynamic efficiencies with technologic development, it is important to take into account consumers habits and behaviour, and how this “part of the equation” may influence the calculations.

For cases such as the Portuguese, efficiencies may differ significantly between methods, due to a production mix with a high share of renewables, i.e. about 60% for 2014. Primary-useful efficiencies show an evolution that is similar to primary-final, however, the dilution effect influences the primary-useful efficiency as it does not grow (using any of the methods) as much as primary-final efficiency.

In other words, throughout time, by observing all efficiencies calculated, one understands that savings of natural resources increase along with primary efficiency increase and the use of alternatives to fossil fuels. Yet, the technological evolution leads to a growth in electricity consumption due to the dilution effect at the useful stage. So, it is as if two different forces lead the evolution of electricity production-consumption chain. At the primary stage, towards the consumption of less resources, and at the useful stage towards the opposite way.

Based on the work developed in this dissertation, some topics that are worth developing in the future have emerged, such as: (1) upgrades in Serrenho's useful exergy series for Portugal by improving coal related calculations and including city gas as an energy carrier, (2) detailed analysis of the impact that rebound and "dilution" effects have had in the past for energy consumption and efficiencies evolutions in Portugal.

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