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From electrification to decarbonization: Insights from Portugal's experience (1960–2016)

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ABSTRACT

Deep electrification powered by renewable sources has emerged as a pivotal strategy for achieving ambitious CO_2 emission reduction targets. However, the true impact of electrification on decarbonization remains inadequately measured because the whole energy chain has not yet been fully considered. This study combines Societal Exergy Accounting and Logarithmic Mean Divisia decomposition analysis to quantify the main drivers of relative (de)carbonization in Portugal from 1960 to 2016. The results reveal a significant increase in the carbon intensity of useful exergy from 250 to 380 tons CO_2/TJ during the late 1990s, followed by a decline to 280 tons CO_2/TJ in the 2000s. These changes were driven by fossil fuel dependency and the efficiency and structure of the energy system. Decarbonization was facilitated by electrification when the following three conditions were met: (1) end-use electrification was at least a third of total useful exergy consumed, (2) renewable resources were at least a third of overall mix (above 33%) and (3) natural gas was at least a third of the mix of fossil fuels used for electricity generation. (above 30%). Policies promoting fossil fuel use for economic development led to the peak in carbon intensity of useful exergy in the 1990s while investments in renewable resources for electroproduction facilitated effective relative decarbonization later. Based on the current structure and efficiency of the energy system, policy recommendations include prioritizing investments in renewables, enhancing final-useful efficiency, and promoting the electrification of mechanical drive end-uses.

1. Introduction

Electricity has brought many benefits and technological advances for society, such as improved productivity of industrial processes, superior lighting, multiple household appliances, which saved domestic work, and new end-uses such as electronics [1–3]. A crucial advantage of electricity in relation to other carriers has been its flexibility of conversion to an array of end uses and of generation from any primary energy sources [4]. This flexibility makes electrification a highly desirable way to decarbonize modern energy systems.

Historically, non-fossil sources of electricity have been used along with fossil-fuel sources: hydropower from the 1880s, nuclear-power from the 1950s and other renewable forms of electricity, such as wind-power and solar photovoltaic from the early 1980s. Transitions towards less polluting fossil fuels such as natural gas also occurred, although coal has increased its share in the world generation mix in the last decade. Due to climate change concerns, the use of renewables has intensified, and renewable electricity generation almost tripled between 1990 and 2019, reaching 7.2 PWh and 27% of world electricity generation in 2019 [5]. These developments, coupled with great gains in efficiencies of generation, were accompanied by an impressive decline in worldwide carbon intensities of electricity, which were, however, not enough to counterbalance the growth of emissions in the world power sector [6].

The idea of deep decarbonization of the energy system through rapid electrification of all end-uses and 100% use of renewable resources (RES) in electricity production [7–11] is however recent and rather ambitious [12]. In Europe, the commitments of reducing emissions in 40% in 2030 and in 80–95% in 2050 resulted in visions of increasing electricity contribution in final energy use from 30% to 60% [13]. Portugal aims at more than doubling the importance of electricity in final energy to 65% by 2050, through a rapid increase of the contribution of renewable sources in electricity generation from 55% to 90% in

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Abbreviations

Abbreviations	*Definitions*
ACI	Aggregate Carbon Intensity
$C_{F\rightarrow U}$	Final to Useful efficiency and structure factor
C_{ffm}	Fossil fuel basket mix factor
C_{ffd}	Fossil fuel dependency factor
GHG emissions	Greenhouse Gas emissions
HTH	High Temperature Heat
LTH	Low Temperature Heat
MD	Mechanical Drive
MTH	Medium Temperature Heat
$C_{P\rightarrow F}$	Primary to Final efficiency and structure coefficient
RES	Renewable Energy Resources
SEA	Societal Exergy Accounting
C_{ust}	Useful exergy consumption composition coefficient

2030 and 100% in 2050 [14]. The concretization of this scenario requires a substantial adoption of electric cars (30% by 2030 and 100% by 2050), and an increasing contribution of electric use in buildings (80% by 2050) and industry (55% by 2050) [15].

As policymakers consider these electrification measures as essential to meet future environmental goals, it becomes crucial to assess how electrification has contributed to (de)carbonization trends in the last decades. Using Portugal as a case study, this work uses decomposition analysis to investigate the impact of electrification *vis à vis* to other drivers in the evolution of aggregate carbon intensity (ACI) of energy use during the period of 1960–2016. Portugal is an interesting case study because 1) it electrified rapidly during this period, from below average OECD Europe in 1960 to above average in 2016, 2) electrification was promoted either to ensure economic development, energy independence or mitigation of carbon emissions, 3) during this period, there was a substantial deployment of modern renewable energy generation and 4) electrification started at low levels of fossil-fuel dependency (57% of its primary energy was provided by biomass and hydro generation) and relatively low levels of income per capita ($3934 constant 2015 dollars per capita in 1960, 30% of today's average world income).

In OECD Europe and Portugal, the electricity share of Total Final Consumption (TFC) increased significantly from about 9 to 6% in 1960 to about 22 and 25% in 2019, respectively. However, while OECD Europe has exhibited a sharp declining trend in the aggregated carbon intensity of final energy (ACI_{final}) since the 1970s, from 101 kg CO_2/GJ to 69 kg CO_2/GJ in 2019, in Portugal, the ACI_{final} has doubled from 1960 to 2002, when it peaked at 79 kg CO_2/GJ, declining thereafter.

Differences in decarbonization trends during electrification suggest that the relation between electrification and carbon intensity is complex. It depends not only on the evolution of the primary energy mix and primary to final efficiency of electricity but also on how clean and efficient the evolution of the remaining energy system is. Moreover, electrification, decarbonization and efficiency do not always go in tandem.

The role of electrification in decarbonization not only depends on the energy conversion efficiency of the power industry, but also on the efficiency of conversion of final into useful energy (i.e.: household appliances) because the same end-use energy service provided by fuels or electricity may have different final energy requirements. However, the commonly used ACI indicators, which focus on the primary and final levels of energy use, are unable to account for this. As far as we are aware, existing ACI studies (measured in physical units, e.g., ton CO_2 per TJ) do not include the useful stage of energy use, like for example, Moutinho et al. [16] for Europe and Goh et al. [17] for the world.

To address this gap in the literature, this work estimates the carbon intensity of the energy system at the useful stage (ACI_{useful}), i.e., the ratio of CO_2 emissions to useful exergy. It uses the societal exergy accounting method (SEA) to estimate the aggregated useful exergy at the national level [18] which is an intermediate step in estimating the ACI_{useful}. This fully captures the evolution of primary to final and final to useful efficiencies [19–21] extending the indicator proposed by Felicio et al. [20] for electricity. For each final energy carrier, the ACI_{useful} depends on the carbon intensity of the primary resource, e.g., coal, the efficiency of the energy sector in converting primary to final, e.g., coal to electricity, and the mix and efficiencies of end-uses provided by that final energy carrier (heat, electronics, etc). For each end-use, comparing the ACI_{useful} of electricity with that of other energy carriers measures the relative environmental benefit or cost of electrification.

This study quantifies the role of electricity in (de)carbonization by employing the Index Decomposition Analysis (IDA) method. This method breaks down changes in the ACI_{useful} indicator into various contributing factors. Among the many different methodologies of IDA [22], the Logarithmic Mean Divisia Index (LMDI) decomposition has been preferred and applied to energy studies because it provides complete results (without residuals), simplifying the interpretation compared to other decomposition methods [23,24]. Many decomposition studies concentrate on factors driving carbon emissions and carbon intensity with a focus on CO_2/GDP rather than CO_2/energy exploring technological, structural, and demand effects [17,25–30]. These studies do not evaluate the impact of electrification on decarbonization, as they do not estimate the carbon intensity of the overall energy value chain, including all energy carriers, at the useful stage. The studies focusing on electricity show that globally, the average ACI of electricity generation decreased from 5.23 kgCO_2/kWh in 1900 to 0.49 kgCO_2/kWh in 2017 [6] and that the 4% reduction between 1990 and 2013, is mainly due to improved thermal efficiency in generating electricity [29]. At a national level, developing countries initially increased their ACI to meet growing electricity needs, but later reduced it by improving energy efficiency and shifting to natural gas and eventually to renewable energy sources for electricity production [17]. Additionally, even countries with a significant hydroelectricity share, like Myanmar, are likely to increase their ACI in response to rising demand, while countries lacking native renewable resources, such as Brunei and Singapore, might only be able to reduce their ACI by transitioning to natural gas [31].

The aim of this research is to quantify the impact of electrification and other factors driving changes on the carbon intensity in Portugal from 1960 to 2016. This study uses societal exergy accounting (SEA) methods [18] to estimate the ACI_{useful} and the Logarithmic Mean Divisia Index (LMDI) methods to decompose the changes of the ACI_{useful} indicator into five driving factors isolating the effect of electrification. This work seeks to answer the following questions:

a) What were the main drivers of relative (de)carbonization of the energy use in Portugal from 1960 to 2016?
b) Did the electrification of end uses contribute to the (de)carbonization of energy use?
c) How have energy policies influenced the process of electrification and its impact on the relative decarbonization of energy use?

This study stands out from others that measure the effects of electrification on decarbonization by introducing several innovative aspects. Firstly, it comprehensively examines the entire value chain of the system, including all final energy carriers, which is crucial for understanding how electrifying end-uses impact carbon emissions. Secondly, it considers the entire process of energy conversion from its primary form to its useable form, which is key for accurately assessing the differences in efficiency between electricity and other forms of energy at the final to useful stages. Both factors are critical in evaluating the impact of electrification on decarbonization. Furthermore, the scope of this study extends nearly sixty years, providing a longer historical perspective than previous studies, which typically only trace back to 1990.

This work is structured as follows. Section 1 is the introduction. Section 2 describes the SEA and LMDI methods and provides details on the main data sources. Section 3 provides the energy and economic background for the case study as well as a brief description of the main energy-related policies of the period. In section 4, the aggregate carbon intensity ACI_{useful} is presented, and its evolution is discussed using the results of SEA and LMDI analyses. Finally, in section 5, the questions posed in Section 1 are addressed.

2. Methods and data

A decomposition analysis was performed on the ACI_{useful} indicator for the period 1960–2016, as outlined in Section 2.2, utilizing available energy data and the exergy flows at the primary, final, and useful levels. These flows were estimated using the SEA method, described in Section 2.1.

2.1. Societal exergy accounting

In SEA, the quantification of exergy is used to meaningfully add different forms of energy such as work and heat, accounting flows at primary, final, and useful stages, while estimating efficiencies at the societal level [18,20].

This study follows the 4-step method illustrated in Fig. 1 [19] and described in section 2.1.1 to estimate useful exergy by end-use and aggregated final to useful efficiencies. Section 2.1.2 describes how primary exergy and primary to final efficiencies were estimated.

2.1.1. Final exergy and useful exergy

Final energy data was taken from IEA [32] and then, converted to exergy applying the energy conversion factors from Serrenho et al. [33] (step 1 in Fig. 1).

From final exergy series useful exergy (U_i) was estimated by, first, identifying the end-uses for each final energy carrier and consumer (step 2 in Fig. 1) and then, multiplying the respective final to useful exergy efficiencies by end-use, $\varepsilon_{FU,i}$ to F_i (step 3 in Fig. 1). Finally, the useful exergy was aggregated per carrier and per end-use to obtain the end-use and country's total results (step 4 in Fig. 1):

$$U = \sum_i U_i = \sum_i F_i \varepsilon_{FU,i},$$

The exergy efficiencies by end-use used in this study were taken from Felício et al. [20]. For all energy carriers with exception of electricity, two main end-uses were considered: mechanical drive (MD), and heat. Heat uses were divided by temperature into five different categories. In contrast, MD for all carriers except electricity is mostly mobile, e.g., transports.

Regarding electricity, four other end-uses were also considered: cooling (air-conditioners and refrigerators), lighting, electrochemical processes (electrolysis) and electronics. The MD associated with electricity was mostly stationary mechanical work, e.g., machinery in industry, as before 2016 Portugal did not have a significant share of electric transport.

2.1.2. Primary exergy

Primary energy data by energy carrier were also taken from IEA [32]. Additionally, the Resource Content Method was used to account for the primary exergy of renewables flows, which considers the physical energy of each resource, e.g., the potential energy in a dam or the kinetic energy of the wind. The efficiencies by energy carrier were taken from Felício et al. [20]. Particularly, for cogeneration, the method proposed by Tereshchenko and Nord [34] was followed to split the proportion of primary exergy of co-generation plants which goes into electricity or heat production.

Finally, primary-final exergy efficiencies per carrier were obtained dividing final by primary exergy.

For more details on the methodology used for primary energy see Appendix A.

2.2. ACI decomposition model

The aggregated carbon intensity is the ratio of carbon emissions to useful exergy (e.g., the sum of all CO_2 emissions divided by Portugal's total useful exergy):

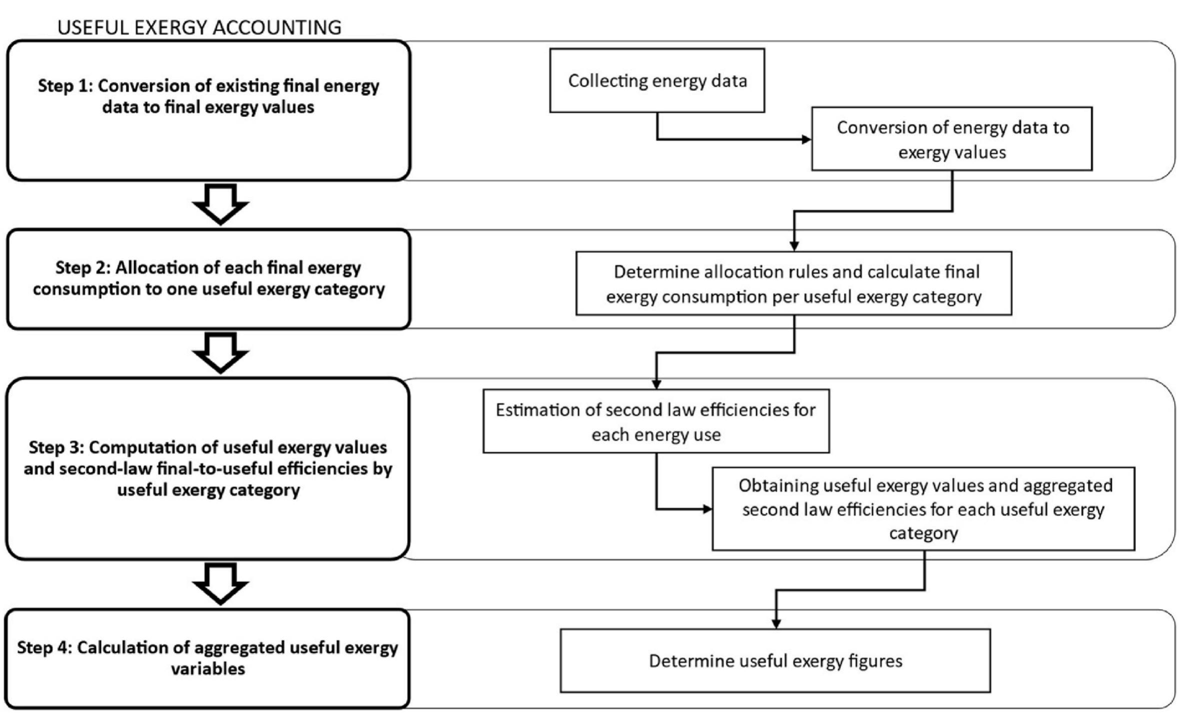

Fig. 1. Useful exergy accounting methodology. Adapted from Guevara et al. [19].

$$ACI_{useful} = \frac{C}{U} = \frac{C}{P \bullet \varepsilon_{PF,i} \bullet \varepsilon_{FU,i}} \quad (1)$$

The carbon intensity can also be defined for electricity and other energy carriers and for each end-use as:

$$ACI_{useful,i} = \frac{C_i}{U_i} \quad (2)$$

Therefore, the aggregated carbon intensity can also be seen as the weighted average of the carbon intensity of electricity and all other final energy carriers:

$$ACI_{useful} = ACI_{useful,electricity}\epsilon + ACI_{useful,other\ carriers}(1-\epsilon) \quad (3)$$

where ϵ is the ratio of useful exergy provided by electricity (U_i) to total useful exergy, i.e., $\epsilon = U_{electricity}/U$, also known as the end-use electrification rate.

The $\boldsymbol{ACI_{useful}}$ of an economy is modelled as follows:

$$ACI_{useful} = \frac{C}{U} = \sum_i \frac{C_i}{P_{fossil\ fuels_i}} \frac{P_{fossil\ fuels_i}}{P_i} \frac{P_i}{F_i} \frac{F_i}{U_i} \frac{U_i}{U}, \quad (4)$$

where C are the total CO_2 emissions produced by the economy, C_i are the CO_2 emissions produced by energy carrier, P_i is the total primary exergy by energy carrier, $P_{fossil\ fuels_i}$ is the primary exergy of fossil fuels by energy carrier, F_i is the final exergy by energy carrier, U_i is the useful exergy by energy carrier, U is the useful exergy of the economy (total), and i is the energy carrier considered ("electricity" or all "other carriers").

Finally, by simplifying eq. (4), the final ACI_{useful} model is obtained as:

$$ACI_{useful} = \sum_i ffm_i \bullet ffd_i \bullet P_{\rightarrow}F_i \bullet F_{\rightarrow}U_i \bullet ust_i \quad (5)$$

where ffm_i is the fossil fuel basket mix factor; ffd_i represents the fossil fuels dependency factor; $P_{\rightarrow}F_i$ is the primary-final factor; $F_{\rightarrow}U_i$ describes the final-useful factor; and ust_i is the useful exergy consumption composition factor.

In the context of the multiplicative IDA approach, the relative change in ACI_{useful} between two years (the ratio ACI_t/ACI_0) is given by the product of decomposition coefficients of all ACI_{useful} factors as:

$$ACIu_t \Big/ ACIu_0 = \prod C_X \,. \quad (6)$$

The C_X is the decomposition coefficient of factor (X) describing the relative contribution of this factor to the variation of ACI_{useful} in the period t −0 or, in other words, the relative change in ACI_{useful} that would have occurred had all other factors remained constant.

For calculating the decomposition coefficients, this study uses the multiplicative LMDI approach by Choi and Ang's [35] – also referred to as model 6 of the LMDI-I family of approaches by Ang [36]– which estimates each C_X as:

$$C_X = \left[\sum_i w_i^{'} \left(\frac{X_i^T}{X_i^0} \right) \right]$$

where $w_i^{'} = \frac{L\left(\frac{CO2_i^T}{U^t}, \frac{CO2_i^0}{U^0}\right)}{L\,(ACIu^T, ACIu^0)}$ and $L(x,y) = \frac{(x-y)}{\left(\frac{x}{y}\right)}$.

The meaning of the decomposition coefficients associated to the factors of the ACI_{useful} in eq. (5) is the following:

- C_{ffm}, the fossil fuel basket mix coefficient, is the aggregate carbon emissions factor of the mix of primary fossil fuels. A relative increase of coal consumption implies a higher aggregate carbon emissions' factor;
- C_{ffd}, the fossil fuels' dependency coefficient, is the share of fossil fuels in the primary exergy mix. An increase in renewable resources consumption contributes to a lower coefficient;
- $C_{P\rightarrow F}$, the primary-final conversion coefficient, combines two effects, the efficiency of conversion between primary and final as well as the structure of the energy system (upstream from end consumers). A change in structure such as closing coal-powered plants and/or changes in the efficiency leads to changes in this coefficient;
- $C_{F\rightarrow U}$, the final-useful conversion coefficient, addresses both the efficiency of conversion and structure of energy end-use system (composed by every end-use energy conversion device in each sector in the economy such as furnaces, refrigerators, light bulbs and motors). A variation in final to useful efficiency such as the fuel efficiency of cars, and/or changes in the system's structure e.g., the transition from industry to services are reflected in this coefficient's value; and
- C_{ust}, the useful exergy consumption composition coefficient, shows the fraction of useful exergy consumption by energy carrier (electricity vs all other carriers).

3. The Portuguese context: background and energy policies

This section provides a background of the Portuguese energy system (Table 1) and a timeline of relevant electrification and decarbonization-related policies/decisions that provide policy context to the analysis of the contribution of electrification to (de)carbonization over the period 1960–2016 (Table 2).

Table 1 shows the evolution of key economic and environmental indicators. During this era, Portugal witnessed a fivefold increase in its GDP per capita, undergoing significant structural transformations. The country evolved from a predominantly agrarian, middle-income nation to a developed economy characterized by a substantial service sector, aligning itself with the world's most advanced economies. Changes in the economy were accompanied by a slower growth in total final consumption, increasing by a factor of three and a half, alongside an impressive increase in electricity, which rose by a factor of seventeen. The growth in energy use required a disproportionately large increase in CO2 emissions, which rose sevenfold. Meanwhile, the ACI of final energy doubled, which was less than the approximately fourfold increase in the ACI of final electricity.

Table 2 provides a summary of the key energy policies and major political events post-World War II that influenced the structural transformation of Portugal's energy system. Policies listed included (1) electrification by incentivizing electric end-uses in households, agriculture and industry (Law no. 2:002 in 1944), the construction of powerplants and/or hydroelectricity (development plans in 1953–1973), rural electrification (1979), and the electrification of the transport sector (RCM 20/2009); (2) the use of renewable endogenous resources (DL 188/88, DL 195/94, Solar Thermal 2009, RCM 20/2013), (3) the introductionof natural gas in electricity production (DL 195/94), (4) the production of renewable electricity by establishing renewable electricity targets of 39% in 2010 (2001/77/EC), 60% in 2020 (2009/28/CE) and 80% in 2030 (RCM 53/2020) and feed-in-tariffs (DL 312/2001), and (5) energy conservation and efficiency in industries (DL 58/82, DL 188/88, DL 71/2008), in buildings (DL 80/2006, DL 118/2013) and in all sectors of society (RCM 80/2008, DL 50/2010, RCM 20/2013). Electrification was pursued first as a path to economic development, while other policies were pursued after the 1973 oil crisis to increase the security of energy supply and decrease the dependency of oil and then after 1997 (Kyoto Protocol) to limit GHG emissions.

4. Results and discussion

The evolution of the importance of electricity in the Portuguese energy system can be seen in Fig. 2a and b.

Fig. 2a shows that the share of electricity increased substantially from 20% of total useful exergy in 1960 to 45% in 2016, while total useful exergy has grown by a factor of six until early 2000s, slightly decreasing thereafter. The data shows two continuous electrification

Table 1
Some relevant indicators of Portuguese energy system 1960–2016. TFC is total final energy use and ACI is aggregated carbon intensity.

	Unity	1960	1970	1980	1990	2000	2010	2016
GDP per capita	2015 US$	3935	7659	10817	14572	18795	19670	19701
CO_2[a]	10^6 t	6.4	13.4	24.5	36.3	58.5	46.6	47.2
Population	10^6 hab	8.9	8.7	9.8	10.0	10.3	10.6	10.3
CO_2 per capita	t/hab	0.7	1.5	2.5	3.6	5.7	4.4	4.6
TFC	PJ	174	235	355	477	716	735	633
ACI_{final}	tCO_2/TJ	37.0	57.1	68.9	76.0	81.7	63.4	74.5
TFC per capita	GJ	19.6	27.0	36.3	47.8	69.6	69.5	61.3
Electricity	PJ	9.9	22.6	51.6	85	138	180	167
% Electricity in TFC	%	5.7%	9.6%	14.6%	17.8%	19.3%	24.4%	26.4%
$ACI_{final,\ electricity}$	tCO2/TJ	22.1	66.0	95.6	168.3	145.1	71.5	95.1

[a] The CO_2 total is only related to energy use.
Source: GDP and Population from World Bank [37], see section 3 for energy and CO_2 data.

periods 1960–1986 and 2000–2016. They were intertwined by a period of constant electricity share (1986–2000), where the rates of growth of useful exergy were the highest.

The first end-use electrification period (1960–1986) resulted from the Electrification Law (Law no. 2:002) from 1944 and 1st and 2nd development plans (1953–1958 and 1959–1964), which promoted the electrification of residential and industrial sectors and the installation of electric intensive industries in the country. This was followed by a 1979 Rural Electrification Plan, which had the goal to ensure electricity coverage for all houses within five years. These efforts resulted in an increase in electricity consumption that reached ca. 36% of total useful exergy in 1986. In the second electrification period (2000 onwards), renewable electrification was promoted by the international awareness of climate change and the need to decrease greenhouse gas emissions (e.g., Kyoto Protocol). In 2001, the European Directive 2001/77/EC established that the country had to increase the fraction of renewable electricity compared to 1997 which led to a continuous increase in end-use electrification as different sectors adopted new uses of electricity– e.g., electronics – and electrified old ones like heat, e.g., solar thermal panels to heat the water in residential sector.

Fig. 2b shows the total emissions in the country and the share of emissions associated with the generation of electricity. Total emissions, exhibited the same overall trend as useful exergy, growing until 2000s by a factor of six and declining afterwards. The share of electricity in total emissions increased alongside with electrification to 30% in 1990s remaining relatively constant afterwards.

The carbon intensity, ACI_{useful}, is shown in Fig. 3. It exhibits an inverted U-shape, increasing from a minimum of 250 tCO_2/TJ in 1960 to a maximum of 384 tCO_2/TJ in 1999, and decreasing until 2010 to 280 tCO_2/TJ, slightly increasing again afterwards. Consequently, between 2000 and 2010, Portugal's energy system underwent a relative decarbonization, as shown in Fig. 3, and from 2005 to 2014, it achieved an absolute decarbonization, depicted in the bottom graph of Fig. 2. In this latter period, the level of useful exergy either remained stable or experienced a decline.

4.1. The driving factors of carbon intensity

The decomposition results for ACI_{useful} are concisely presented by decade in Figs. 4 and 5. Fig. 4 specifically illustrates the cumulative impact of the five factors on changes in ACI_{useful}. Until 2010, the fossil fuel dependency factor, *ffd*, was the primary driver of changes in ACI_{useful}. After 2010, this role was taken over by the primary-final conversion coefficient ($P_{\rightarrow}F$). The final-useful conversion coefficient ($F_{\rightarrow}U$) ranks as the second most significant factor, particularly during the 1960s and 1970s, although its influence diminished after this period.

In the first row of Fig. 4, it is shown that the decade from 2000 to 2010 was the only one when the energy system at the useful stage underwent relative decarbonization, marked by a 21% reduction in ACI_{useful}. Notably, Portugal's ACI_{useful} experienced its most significant increases, approximately 20%, during two distinct periods: 1960–1970 and 2010–2016.

Fig. 5 shows the contribution to changes on ACI_{useful} by energy carrier (electricity and other carriers). The decomposition coefficients prior to 2000 (shown in the first column) closely resemble those linked to other carriers (displayed in the third column). This indicates that the consumption changes in carriers other than electricity were the main driving force of ACI variations before 2000. However, post-2000, electricity became a more significant factor.

4.1.1. The impact of the fossil fuel dependency and fossil basket mix

The changes in the fossil fuel basket mix, *ffm*, express the changes in the portfolio of fossil fuels used in the economy; while the fossil fuel dependency, *ffd*, is the share of fossil fuels in the primary exergy mix. For all periods, with exception of the most recent (2010–2016), fossil fuel dependency, *ffd*, has been clearly the most important driving factor of ACI_{useful} variation (Fig. 4).

The *ffd* factor contributed to an increase of the ACI_{useful} of approximately 52% in 1960-70 and 23% in 1970-80; electricity and other carriers' contributions are both positive (second and third column in Fig. 5). Between 1960 and 1980, because of global cheap oil prices and the increasing demand, there was a transition to oil: from hydro to oil in electricity sector and from biomass and coal to oil in other carriers (Fig. 5). This explains the contribution of *ffd* to increase ACI_{useful}.

Oil replaced coal as the primary fossil fuel in power generation and throughout the broader primary energy system. This shift accounts for the impact of the factor *ffm*, which led to a decrease in ACI_{useful} by about 4% between 1960 and 1970, and a further 3% decrease from 1970 to 1980, owing to oil's lower carbon factor compared to coal. In Portugal, this transition was a consequence of the implementation of the Development Plans: the first (1953–1958) and second (1959–1964) promoted hydroelectricity, and the intercalary and third plans (1965–1973) promoted the construction of fuel-oil thermopower plants and refineries.

Following the oil crisis of 1973 and 1979, the energy policies of the 1980s pursued a strategy of increasing the security of the fossil fuel mix in the power sector, hence favouring the replacement of oil with coal. This strategy continued from 1982 onwards with the National Energy plan (PEN 1982), which focused on increasing security of supply and reducing external dependence by reducing foreign exchange expenditure – as coal was cheaper than oil. In this process, a big new coal power plant in Sines began production in 1985 with one power unit, followed by other three large power units added between 1987 and 1989 to Sines' powerplant system. Consequently, the electricity mix became more carbon intensive, with coal representing 40% of the electricity generation resource mix in 1990. This was equal to the share of oil at that time, while hydroelectric power contributed less than 20%. In this period, the contributions of *ffm* and *ffd* coefficients to increase the ACI_{useful}, with each factor contributing to a 4% rise, is mostly explained by changes in the electricity production resource mix (Fig. 5).

In the following decade (1990–2000), there was a reduction of 11%

Table 2
Timeline of relevant energy policies/decisions in Portugal related to electrification and/or decarbonization since 1944 (relevant events are also shown in the table).

Year	Policy/Decision	Description	Source
1944	Electrification Law	Promote the electrification of the country (increase supply for irrigation, industries, households and new electric intensive units such as iron metallurgy, copper metallurgy, cyanamide and nitrates and cellulose) while replacing thermo-production with hydro sources (with coal power plants as a reserve burning domestic coal) and developing a network for the transport and distribution of electricity.	Law no. 2:002
1945	Industrialization Law	Promote new industries and reorganize existing industries to increase their economic viability.	Law no. 2:005
1953–1958	First Development Plan	Investment plan in hydroelectric dams (with reservoir) to reduce the reliance in thermo-power in urban areas, with use of electrochemical industries as consumers of excess power.	[38]
1959–1964	Second Development Plan	Investment plan in hydroelectric (mostly run-of-the-river) power and coal-power plants using domestic coals as a power reserve during the dry season.	[38]
1965–1973	Intercalary and Third Development Plans	Investment plan in fuel-oil power plants and refineries. The hydro-power investments are abandoned.	[38]
1973: 1st Oil Crisis			
1974: April 25 (Carnation Revolution)			
1976	Nationalization of electric system	Nationalization of electricity system. The public enterprise EDP will produce, transport and distribute all electricity in Portugal	DL 502/76
1978: Sines' Refinery starts production			
1979: 2nd Oil Crisis			
1979	Rural Electrification Plan	Ensure electricity coverage for all households within five years.	[39], p.150
1982	RGCE – Energy Consumption Management Regulation	Energy rationalization plans for industries that are intensive energy consumers	DL 58/82
1982	National Energy Plan (PEN 82)	Aims to meet the energy needs arising from the country's economic development and social progress and three complementary objectives: a) to reduce as much as possible the cost of energy for consumers, b) to increase the security of supply (through diversification of sources, greater participation of national energy resources and decentralization) and c) to reduce external dependence (reducing foreign exchange expenditures). Nuclear energy was considered in this plan, but it was not deployed.	PEN 82
1985: Sines' coal powerplant 1st unit starts production (1987: 2nd unit, 1988: 3rd unit & last unit started in 1989)			
1986: Portugal joins European Economic Community			
1988	Promotion of the rational use of energy: SIURE	The main goal is to decrease the dependence of oil. The plan promotes energy conservation and efficiency in industries and services and the development of energy production renewable technologies.	DL 188/88
1993: Pêgo Coal Powerplant starts production			
1993	UN Framework Convention on Climate Change	Party to the United Nations Framework Convention on Climate Change since June 13, 1992, and ratified it on June 21, 1993.	DL 20/93
1994	Energy Program	The main goal is to diversify the use of energy carriers decreasing the dependence of oil. • To achieve this goal the plan promotes: the use of natural gas and electricity in energy supply, the use of renewable resources and energy efficiency and conservation	DL 195/94
1997: Natural gas imports from Algeria start via gas pipeline and Kyoto Protocol adoption by the international community			
2001	Promotion of electricity produced from renewable energy	European Directive established a target for 39% renewable electricity production in Portugal in 2010 (38.5% in 1997)	2001/77/EC
2001	Energy efficiency and endogenous energies Programme: E4 Programme	Goals: • Decrease energy dependency on other countries • Decrease energy intensity • Improve energy supply • Reduce energy bill and improve the environment	RCM 154/2001
2001	Feed-in tariffs system	Promote renewable electricity production	DL 312/2001
2001	National Programme for Climate Change: PNAC 2001	Promotes mitigation measures regarding climate change	
2002	Kyoto Protocol	Ratification of the Kyoto Protocol by the European Union. The EU compromises at 8% reduction in emissions relatively to 1990, while Portugal can limit growth of emissions in +27%.	DL July 2002
2004	National Program for Climate Change: PNAC 2004	Promotes more mitigation measures regarding climate change	RCM 119/2004
2004: MIBEL - Agreement established for the creation of the Iberian Electricity Market			

(continued on next page)

Table 2 (*continued*)

Year	Policy/Decision	Description	Source
2005	Kyoto Protocol	Kyoto protocol enters into force in the international community	
2005	National Plan for the Allocation of Emission Allowances: PNALE	Allocates 38.161 Mt CO of emission allowances to 248 CO_2 intensive units in the context of the cap-and-trade scheme of the European Union Emission Trading System. Sectors covered include fossil-fuel and biomass power-plants (including co-generation units), oil refineries, ferrous metals, pulp, clay, bricks and glass.	RCM 53/2005
2005	National Energy Strategy: ENE	Establishes the following policy orientation lines: • Liberalization of electricity, fuel and gas markets • Restructuring competitive electricity and gas markets • Increase of renewable energy sources (39% of final electricity with renewable generation in 2010) • Promote energy efficiency • Promote participation of public sector in efficiency measures • Adopt fiscal measures such a carbon tax • Promote R& D in renewable energy technologies	RCM 169/2005
2006	Regulation for the thermal characteristics of buildings: RCCTE	Regulation that promotes the construction and renovation of buildings that need less energy for thermal comfort and that have more efficient equipment	DL 80/2006
2006	Portuguese Carbon Fund	Created to finance measures that facilitate compliance with the Portuguese State's commitments under the Kyoto Protocol. This fund was already stipulated by RCM 53/2005	DL 71/2006
2006	National Program for Climate Change: PNAC 2006	Promotes mitigation measures regarding climate change	RCM 104/2006
2007	Feed-in tariffs revision	Revision of the Feed-in tariff system	DL 225/2007
2008	Energy Management System for Intensive Energy consumers: SGCIE	• Increase in final to useful efficiency in Industry • Increase in renewables • Carbon intensity of energy use cannot increase	DL 71/2008
2008	National Action Plan for Energy Efficiency: PNAEE 2008	Reduce 10% the final energy consumption between 2008 and 2015. Promotion of renewable energy and more efficient technologies in transports, residential, industry, services and government	RCM 80/2008
2009	Solar Thermal Program	Incentive of 50% financing for solar thermal panels installation	
2009	Mobi.e	Electric Mobility Program	RCM 20/2009
2010	National Action Plan for Renewable Energy: PNAER 2010	Targets for renewable energy in 2020: • 31% in gross final energy consumption • 55% of electricity produced • 10% in transport sector consumption • 30.6% in heating and cooling	Under 2009/28/CE directive
2010	National Energy Strategy: ENE	Defines the global context for the PNAER and the PNAEE revision. Promotes renewables energies, energy efficiency and environmental sustainability.	RCM 29/10
2010	Energy Efficiency Fund	Promotes energy efficiency measures and behavioural changes in the residential and service sectors.	DL 50/2010
2013	Energy efficiency in buildings	• Better renovation and construction (buildings that need less energy for thermal comfort) • Net-zero energy buildings	DL 118/2013
2013	PNAEE 2016	Reviewed and approved for the period 2013–2016. Reduce 25% the primary energy consumption until 2020.	RCM 20/2013
2013	PNAER 2020	Reviewed and approved for the period 2013–2020. Targets for renewable energy in 2020: • 35% in gross final energy consumption • 60% of electricity produced	
2014	Green Taxation Law		Law no. 82- D/2014
2019	Low Carbon National Roadmap: RNC2050	Main implications of scenario-based modelling to reach −90% emissions in 2050 (relative to 2005): • 65% of electricity in TFC • 85% renewables in TFC • 100% renewables in electricity sector • 90% renewables transport sector • Reduction of Primary Energy (−44% to −47%) and TFC (−25 to-28%) relative to 2015	RCM 107/2019
2020	PNEC2030	• 45–55% CO2 emissions reduction compared to 2005 • 35% less primary energy consumption • 47% renewable energy in final energy consumption, by 2030, including sectorial goals of:	RCM 53/2020

(*continued on next page*)

Table 2 (*continued*)

Year	Policy/Decision	Description	Source
		o 80% RES in electricity, o 20% RES in transports o 49% RES in heating and cooling	
2020	EN-H2	National Plan for Hydrogen. Main goal is to promote and boost both production and consumption of hydrogen in the various sectors of the economy	RCM 63/2020
2021: Sines and Pêgo coal power plants are deactivated and closed			

Sources: Authors' review with the sources listed, Carvalho et al. [40] and Guevara and Domingos [41].

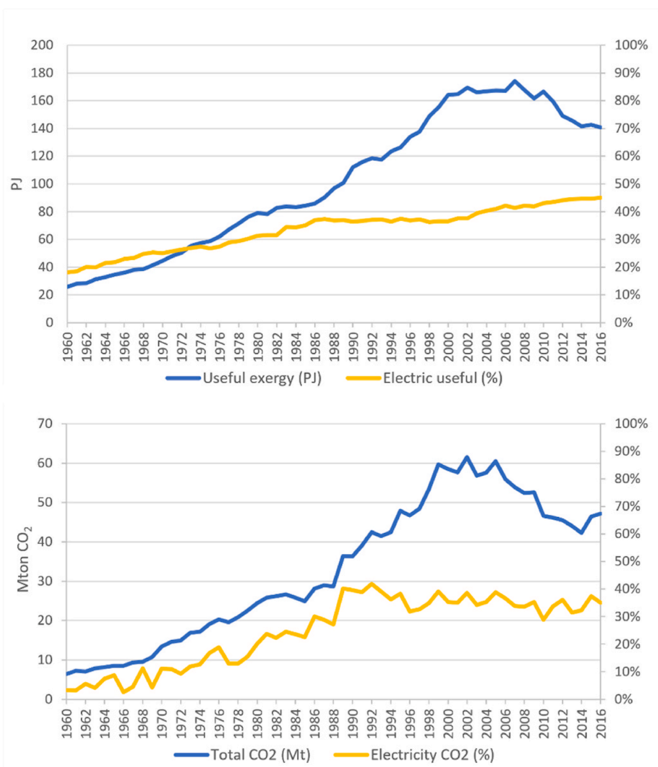

Fig. 2. a) Portugal's total useful exergy and the share of electric useful exergy – electrification rate; b) Portugal's total CO_2 emissions and the share of CO_2 emissions of the electric sector.

in biofuels consumption within the other carriers' category (mostly in residential sector) that had an impact on the fossil fuel dependency, *ffd*, contributing to increase the ACI_{useful} (+8%). During this decade, the impact of electricity was almost negligible due to conflicting policies. On one hand, the second-largest coal power plant commenced operations in 1993. On the other hand, 1994 saw the implementation of an energy program that encouraged the consumption of natural gas and the increased use of renewable energy sources, followed by a rise in natural gas imports (Fig. 5).

Between 1990 and 2010, the contribution of changes in the fossil fuel basket mix, *ffm*, to ACI_{useful} (−3% and −5%) resulted from the introduction of natural gas, via the Algerian gas pipeline, in the fossil fuel basket mix from 1997 onwards. This came as consequence of a key objective of the 1994 Energy Programme: the use of natural gas in

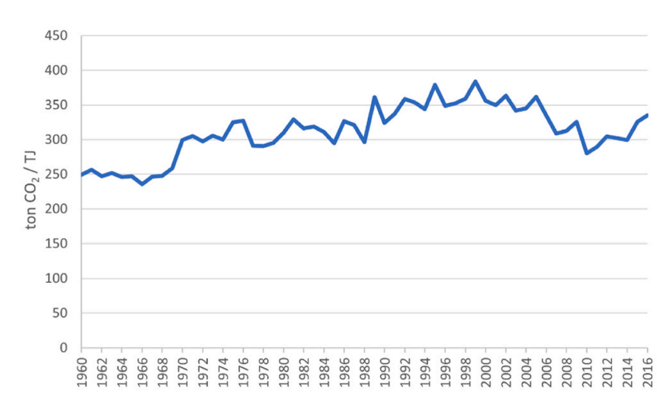

Fig. 3. Portugal's ACI_{useful}.

energy supply. Natural gas was more relevant in other carriers' flows during the first years, contributing to the impact of these flows to the decrease of ACI_{useful} (−2%) (Fig. 4). After 2004, natural gas increased its relevance in electricity production [42], following the PNAC2004's greenhouse gas emissions mitigation measures, aligned with the Kyoto Protocol in 2002. Thus, electricity's natural gas flows became the biggest contributor to the magnitude of the *ffm*'s coefficient of approximately - 5% (ca. −3,3% from electricity) between 2000 and 2010.

Between 2000 and 2010, the negative value of the *ffd* factor is attributed to the Portuguese Government's investments in renewable resources, predominantly wind power. This initiative contributed to a 16% reduction in ACI_{useful} (Fig. 4). These investments were promoted by the E4 Programme (2001), the implementation of a feed-in tariff system and national programmes for climate change PNAC2001 and PNAC2004. These plans and programmes, following European Directives such as 2001/77/EC, promoted renewable electricity production as well as the decrease in greenhouse gas emissions through several mitigation measures. From 2000 to 2010, other energy carriers also played a role in lowering ACI_{useful}, owing to a modest rise in biofuel consumption. Biofuels accounted for 15.6% of the primary consumption of these carriers in 2000 and increased to 18% by 2010. This shift was also a result of the energy policies.

The energy policy shift towards renewable resources (which influence *ffd*) was also promoted by the SGCIE programme which incentivized the increase in renewables (2008) in industries, the solar thermal programme that financed 50% of solar thermal panels installation (2009) and the PNAER2010 and PNAER2020 that had ambitious targets for renewable consumption for 2020.

4.1.2. The impact of efficiencies

The evolution of primary to final ($P_{\rightarrow}F$), final to useful ($F_{\rightarrow}U$) and primary to useful ($P_{\rightarrow}U$) efficiencies throughout the period are shown in Fig. 6.

Throughout the entire period, except for 2000–2010, the $P_{\rightarrow}F$ exergy efficiency has declined contributing to an increase in ACI_{useful}. This is the combination of two factors. First, between 1960 and late 1990s, fossil fuels, i.e., coal and oil, primarily utilized for direct end-uses with near-perfect efficiency (around 100%) $P_{\rightarrow}F$ began transitioning towards electricity generation. However, the efficiency of producing electricity from fossil fuels was about 20%, markedly less than the efficiencies previously attained in other uses of fossil fuels. This was prompted due to two types of energy policies: those incentivizing investments in coal powerplants, and those promoting electrification of the country's energy system (i.e., Rural Electrification Plan in 1979). Then, after the 2000s, the change towards "new renewables" (e.g., wind and solar power), that has mainly affected the *ffd* factor, had also some impact on $P_{\rightarrow}F$ efficiency. This impact is influenced by the methodology chosen to estimate primary exergy. In this work, with the resource content method, the

Fig. 4. Multiplicative decomposition results per decade. First row: ACI_{useful} total variation ratio (minus 1); all other rows: ACI_{useful} decomposition coefficient for each factor (minus 1).

transition meant a decrease in $P_{\to}F$ aggregate efficiency because wind power has a lower conversion efficiency compared to other resources. In the last period of this study (2010–2016), the $P_{\to}F$ factor was the factor that influenced ACI_{useful} the most. The decrease in $P_{\to}F$ efficiency resulted from the growth in the energy sector's own consumption associated with the hydrogen production (not mentioned in the Portuguese statistics before this period) and the increase in coal-fuelled electricity generation. Between 2010 and 2016, the $P_{\to}F$ would have pushed ACI_{useful} upwards 12% if other factors had not changed despite the direct measures towards increasing the energy efficiency in the PNAEE plan of 2008 (RCM 80/2008).

Fig. 7 shows the evolution of exergy efficiencies for electricity, other energy carriers, and the overall system. Until the mid-1980s, the overall exergy efficiency saw an increase, driven by greater electrification and improved efficiency from final to useful electricity. Subsequently, the overall $F_{\to}U$ exergy efficiency stabilized. The final-useful conversion

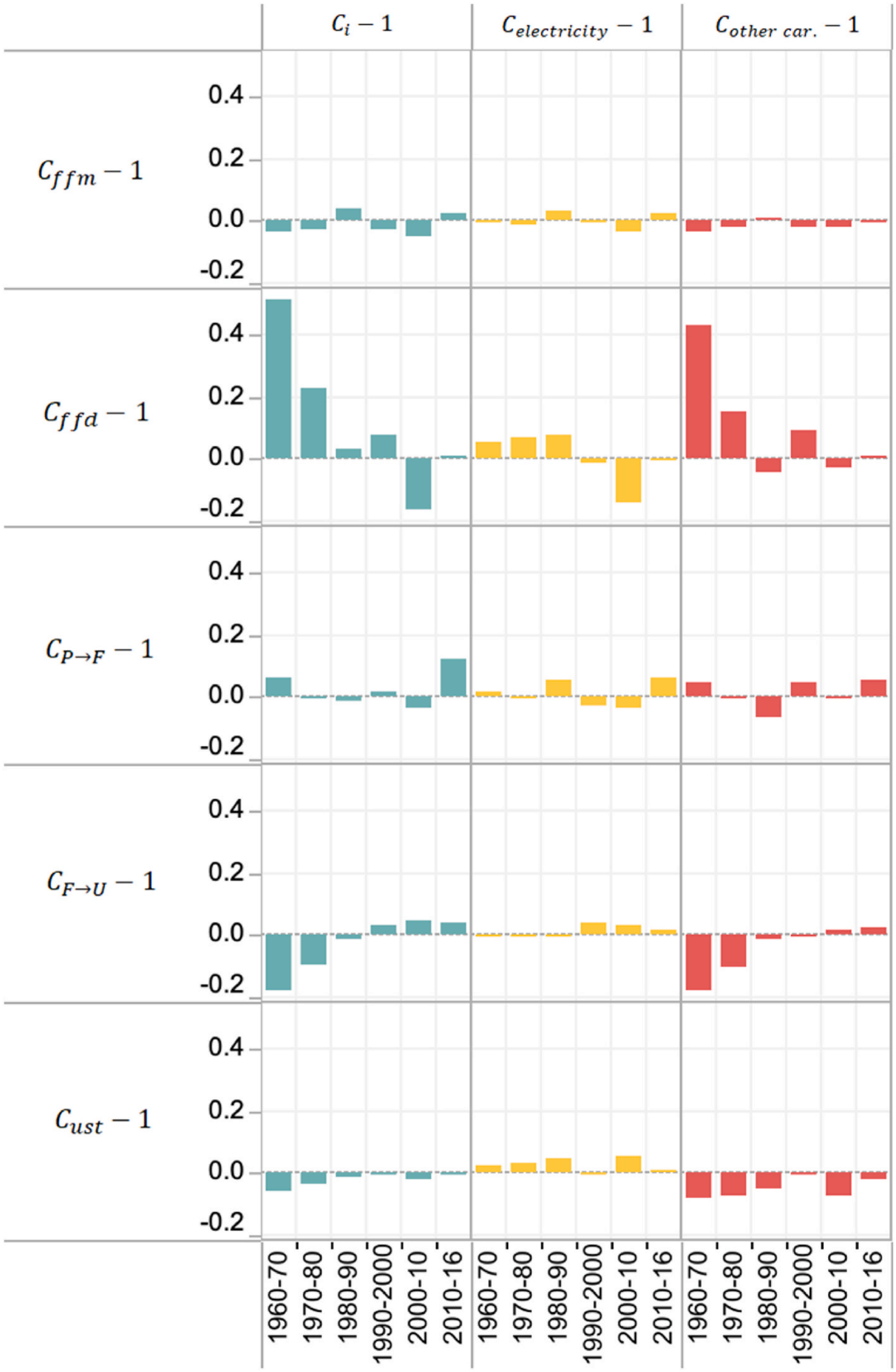

Fig. 5. ACI_{useful} multiplicative decomposition results by factor per decade. Left column: factor coefficient (minus 1); centre and right column: Electricity's and Other carriers' coefficients (minus 1), respectively.

efficiency pushed carbon intensity down 20% between 1960 and 1970 and 10% between 1970 and 1980. The overall $F_{\rightarrow}U$ exergy efficiency depends on the mix of end-uses provided by electricity and other carriers. Throughout the period, in the mix of end-uses being provided by electricity (Appendix B, Figs. 12 and 13): (1) cooling and electronics became more relevant, (2) static mechanical drive became less important and (3) low temperature heat applications became more important, especially in the residential and services sectors (see Appendix C), having increased from the 1970s onwards from approximately 30% to circa 80% in 2016. For higher and medium temperatures, end-use electrification increased from 2000 onwards respectively to 14% and 7%. In the mix of end-uses being provided by other carriers (Appendix B, Figs. 14 and 15): (1) mobile mechanical drive (transport) became much more relevant while (2) low temperature heat uses became less significant.

In the first three decades (1960–1990), there were structural changes at the sectorial level and carrier-end-use level (Appendix B and D) that contributed to an almost stagnant final to useful electricity efficiency and an increasing final to useful efficiency for the other energy carriers. The importance of industry in electricity consumption declined relative to the residential/services while the opposite happened for other energy carriers. The decrease in the consumption of electricity in industries resulted from the reduction in electricity consumption in electrochemical industries promoted by the Second Development Plan

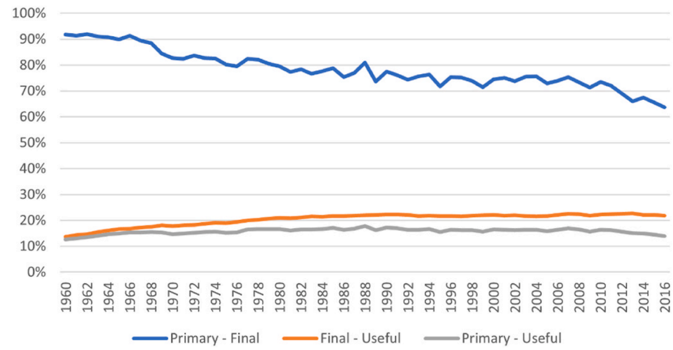

Fig. 6. Portugal's exergy efficiencies: Primary-Final (blue) and Final-Useful (orange).

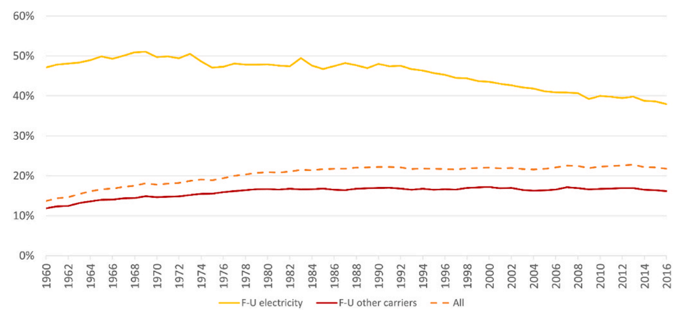

Fig. 7. Portugal's final-useful exergy efficiencies from 1960 to 2016. Electricity (yellow), other carriers (red), all carriers aggregated (orange dashed).

(1959–1964) while the increase in the consumption of electricity in the residential sector resulted from the reduction of the electricity price promoted by the National Energy Plan (1982). Concurrently, the industrial sector became the main consumer of other carriers explaining the growth in $F_{\rightarrow}U$ efficiency of these flows throughout the three decades, as the industry had end-uses with higher exergy efficiency compared to residential sector end-uses.

For this same period, 1960 to 1990, changes in the structure of the consumption of each sector were accompanied by changes in the structure of end-use demand. Mechanical drive uses increased their share on total final consumption from 16.5% to 41% and the category of lower and less efficient temperature heat uses – Low Temperature Heat (LTH) 3 – decreased their share from 57.9% to 22.7%. This led to an increase in other carriers' $F_{\rightarrow}U$ efficiency, seen in Fig. 6. Moreover, throughout the same period, the predominant electrical end-use was MD (44% in 1960 and 45.7% in 1990), which rose the overall $F_{\rightarrow}U$ efficiency of end-uses.

From 1990 onwards, the overall $F_{\rightarrow}U$ efficiency stagnated. In electricity, there was a dilution effect on final-useful efficiency due to the introduction and increased relevance of new, less exergy efficient uses, i. e., electronics, since the 1990s [20]. At the same time, there was a sectorial structural shift in the final exergy consumption of other energy carriers as the industrial sector consumption share decreased from 39% in 1990s to 27% in 2016, while the transports' consumption share increased from 34% to 52% in the same period. The combination of these changes set the overall $F_{\rightarrow}U$ efficiency to an approximately constant value of 22% between 1990 and 2016. Despite electricity's declining efficiency the overall $F_{\rightarrow}U$ efficiency is stagnant, as the electrification of end-uses is progressing at a faster pace than the decrease in electricity's efficiency.

Technical innovation and the many energy-efficiency-promoting policies implemented in 1990–2016 period had positive sectorial effects but were not able to push aggregate $F_{\rightarrow}U$ energy efficiency upwards.

4.1.3. *The impact of the fraction of useful exergy derived from electricity*

The coefficient, *ust*, measures the impact that the composition of end-use useful exergy has on aggregated carbon intensity. During the electrification periods (1960–1986 and 2000-onwards) the impact that *ust* has had on ACI_{useful} is the impact that electrification would have if the aggregated carbon intensities of electricity and other carriers were constant. All other things being equal, it would have contributed to relative decarbonization, especially throughout the 1960s (-6%) and the 1970s (-4%), while the ACI_{useful} of electricity was much lower than the ACI_{useful} of other carriers. It would have also contributed, but less, to relative decarbonization between 2000 and 2010.

However, the factor *ust*, which is a measure of electrification does not quantify the impact of electrification because electrification has upstream effects on fossil fuel dependency, fossil basket mix, $P_{\rightarrow}F$ and $F_{\rightarrow}U$ efficiencies of electricity and of the other energy carriers. Thus, electrification has an impact on the aggregated carbon intensities of electricity and of other carriers.

4.2. *Electrification of end-uses as a driving factor of carbon intensity*

Electrification results from the increase of 1) the consumption of electricity at a higher rate than other energy carriers and 2) the $F_{\rightarrow}U$ aggregate efficiency of electricity at a higher rate than other carriers' $F_{\rightarrow}U$ aggregate efficiency. The $F_{\rightarrow}U$ aggregate efficiency of electricity (see Fig. 7) increased only during the 1960s and therefore it had a negligible effect in electrification from the 1970s onwards. Thus, electrification from 1970 to 1986 and from 2000 onwards resulted mainly from an increase of the percentage of electricity in final energy.

Fig. 8 shows the impact of electricity and other carriers on the variations in ACI_{useful} across different decades, combining the contributions of all decomposition factors. Meanwhile, Fig. 9 shows the ACI_{useful} for both electricity and other carriers, along with the specific impact of electricity on the total ACI_{useful} variation, indicated by arrows. The arrows in Fig. 9 correspond to the decomposition outcomes shown in Fig. 8 for electricity, indicated by either positive or negative coefficients of the yellow bars. In the first electrification period (1960–1986), the increase in electrification rate was accompanied by an increase in the ACI_{useful} of electricity because of an increasing dependence on fossil fuels and decrease in $P_{\rightarrow}F$ efficiency. Between 2000 and 2010, the increase in electrification rate was accompanied by a decrease in the ACI_{useful} that resulted from an increasing dependence on renewables for electricity production. During this period, increased electrification led to a 2% reduction in ACI_{useful}. However, post-2010, as the rate of electrification rose, there was also an increase in the ACI_{useful} of electricity. As a result, the overall impact of electricity led to a rise in the overall ACI_{useful}, a trend that was further intensified by other energy carriers. Thus, although electricity's ACI_{useful} was well below other carriers' ACI_{useful}, except for late 1980s and 1990s, electrification only contributed to relative decarbonization (2000–2010) when the aggregated carbon intensity of electricity decreased.

Electricity's ACI_{useful} can be further disaggregated into end-uses.

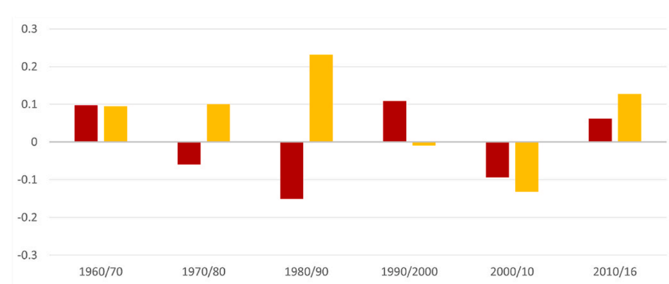

Fig. 8. Decomposition results by energy carrier – electricity vs other carriers' contribution to ACI_{useful} variation.

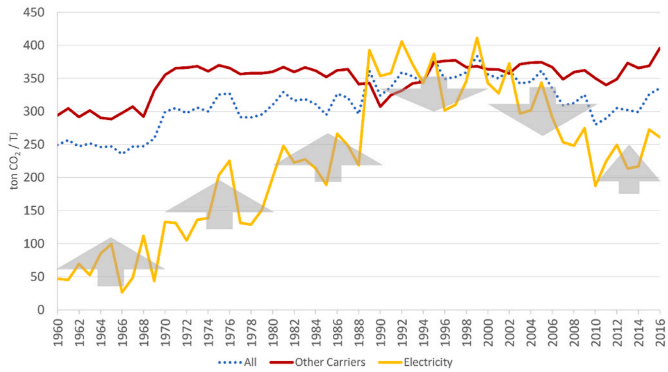

Fig. 9. Portugal, electricity, and other carriers' ACI_{useful}. Arrows signify the cumulative effect of electricity-related decomposition factors on changes in ACI_{useful}, turned upwards indicates increase whereas downwards a decrease.

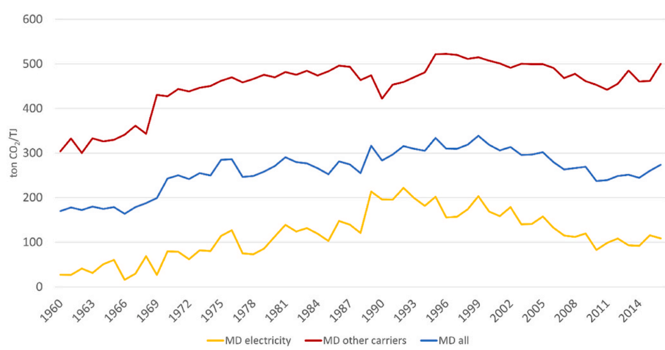

Fig. 10. ACI_{useful} of mechanical drive end-uses per energy carrier category. Total (blue line), electricity (yellow line) and all other carriers (red line).

Fig. 10 shows ACI_{useful} for MD uses provided by different carriers, while Fig. 11 presents ACI_{useful} for heat with the same disaggregation level (electricity vs other carriers). For end-uses that are provided by both electricity and other energy carriers (heat and mechanical drive), the ACI_{useful} of electricity is lower for mechanical drive throughout the period (Fig. 10), which indicates that the electrification of this end-use has led to a decrease in ACI_{useful} or, in other words, decarbonization.

For heat, the ACI_{useful} (Fig. 11) can be further disaggregated (Figs. 18 and 19 in Appendix E) by temperature (heat categories) for electricity and other carriers. The ACI_{useful} of heat provided by electricity was lower in the 1960s and in the 1970s for all heat end-uses and from 2010 onwards for HTH but only slightly. The ACI_{useful} of electric heat is lower for higher temperatures because efficiency increases with temperature.

4.3. Limitations

Analysing long-term data series comes with limitations related to statistical errors. Paoli et al. [6,43] point out that historical statistical data often lacks information on uncertainty ranges or potential errors, making error calculation challenging. A primary source of uncertainty in our study is the allocation of end-uses and individual efficiencies in SEA. Palma et al. [44] addressed the effects of a more detailed allocation for Portugal. Their sensitivity analysis reveals that the crucial factors substantially affecting the country's aggregated F–U efficiency include adding the cooling category and the granularity of electric end-uses. The analysis indicates that these factors lead to a maximum variation of 3% in the 1960s and 1% in the 2010s in the aggregated F–U efficiency. Additionally, Pinto et al. [6] assessed the effect of inaccuracies in individual F–U efficiency measurements for the World. Their analysis reveals an average fluctuation of 3%, which, however, does not affect the overall trend of the aggregated F–U efficiency. This study includes a detailed examination of the cooling category, offering greater specificity compared to the study by Palma et al. [44] and a more thorough allocation (based on local data) compared to Pinto et al.'s analysis [6]. Consequently, it is anticipated that the margin of error in this study is reduced.

5. Conclusions

5.1. What were the main drivers of relative (de)carbonization of the energy use in Portugal from 1960 to 2016?

Relative decarbonization in Portugal only occurred between 2000 and 2010. In this decade, ACI_{useful} decreased approximately 20% mostly due to the investments and electricity production with RES. Portugal's ACI_{useful} increased the most, i.e., approximately 20%, between 1960 and 1970 because of the increase in fossil fuel dependency and between 2010 and 2016 because of the decrease in primary to final efficiency.

The main drivers of decarbonization were the decrease in fossil fuel dependency associated with the increase in RES and the improvement of the final to useful conversion in the energy system.

5.2. Did electrification of end uses contribute to (de)carbonization of energy use?

The impact of electrification on carbon intensity depends on both the electrification rate of end-uses and the ACI_{useful} of electricity which is

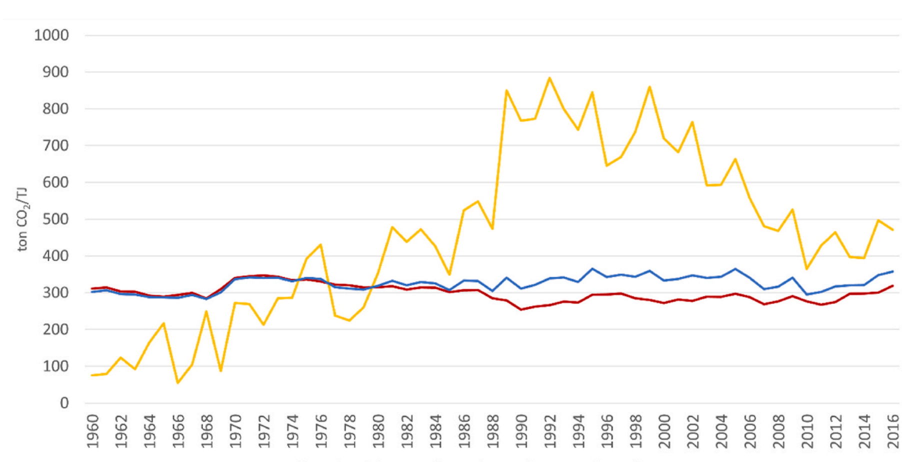

Fig. 11. ACI_{useful} of heat end-uses per energy carrier category considered. Total (blue line), electricity (yellow line) and all other carriers (red line).

controlled by the electricity generation resource mix and primary to final and final to useful efficiencies. The 1980s were the decade where electricity had the most detrimental role for the decarbonization path, the electrification rate was high (36%) and the ACI_{useful} increased circa 20% due to the increasing relevance of coal and oil in the electricity generation mix. In contrast, the 2000–2010 decade was when electricity had its most relevant contribution towards decarbonization due to the significant use of renewable resources rather than fossil fuels, leading to a steep decrease in the ACI_{useful} of electricity by approximately 30%.

Between 1960 and 2016, in Portugal, electricity contributed to decarbonization when the following three conditions were met: (1) end-use electrification was at least a third of total useful exergy consumed, (2) RES were at least a third of overall mix (above 33%) and (3) natural gas was at least a third of the mix of fossil fuels used for electricity generation (above 30%).

5.3. How have energy policies influenced the electrification process and its impact on relative decarbonization?

During the process of electrification of the Portuguese energy system, policies were key in driving the carbon intensity of the energy system. Policies driving towards the use fossil fuels and economic development without RES, in 1970s, 1980s and 1990s (e.g., Intercalary and Third Development Plans, 1965–1973) pushed the Portuguese ACI_{useful} towards its peak (in the 1990s). On the contrary, policies promoting investments in RES for electricity production (consequences of PNAC2001) contributed to the beginning of an effective decarbonization of the Portuguese economy. Energy efficiency policies that impact final to useful efficiencies (e.g., 2010 RCM 29/10) designed to achieve climate targets have had positive sectorial impacts but were not able to counter the effect of changes in the structure of end-use demand towards less efficient end-uses.

Thus, energy policies were effective in promoting electrification and controlling the primary energy mix, first with the goal of increasing energy independence, and after 2000, with the aim of reducing carbon emissions. In contrast, energy policies were not effective in increasing final-useful efficiency of the system, as this has been mostly controlled by changes in the system structure and not by the increase in individual efficiencies which were the focus of these policies.

5.4. Insights and recommendations

The methods followed to estimate and quantify the driving factors of the ACI_{useful} can be applied to other countries or regions. The specific findings obtained in this study for Portugal may not be directly applicable to other areas. For example, the minimum level of electrification required at the end-use stage to influence ACI_{useful} could differ based on the diverse mix of end-uses in different countries. However, Ang and Su [29] and Goh et al. [17] suggest that the pattern of energy mix evolution in electricity generation is widespread: starting with an increased use of traditional fossil fuels, moving to natural gas, and eventually transitioning to Renewable Energy Sources (RES). Portugal's journey from 1960 to 2016 exemplifies these transitions. Thus, the insights gained from Portugal's experience can be relevant to other countries undergoing similar transitions. It is noted that while there is an increase in the use of traditional fossil fuels alongside rising energy demand, electricity impact on carbon intensity may not be significant until it plays a more dominant role in overall consumption, as observed in the case of Portugal.

This study's findings indicate that the implementation of the following energy policies and measures could help reduce carbon intensity in Portugal and other nations:

1) The continuation of incentives, such as the solar power auction and feed-in tariffs, for renewable electricity generation.
2) The promotion of renewable electricity through self-consumption and energy communities.
3) The promotion of conservation measures such as insulation in buildings that increase the efficiency of converting useful exergy into energy services.
4) The promotion of renewable heat through thermal solar power on existing buildings.
5) The promotion of technology substitution in residential electric heat to heat pumps with high coefficients of performance.
6) The promotion of technology substitution in road transport to electric cars.

Measures 1,3 and 4 would also aid in reducing the primary energy consumption relative to GDP [45].

Currently, electrification must be promoted for end-uses that, with the current technologies and electricity production mix, already contribute to decarbonization, such as, mechanical drive in the transport sector. In the future, investments and measures must be made to increase further the penetration of RES and the efficiency in electric carbon-intensive end-uses, so that the electrification of all end-uses contributes towards decarbonization.

CRediT authorship contribution statement

Laura Felício: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Sofia Teives Henriques:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, review & editing. **Zeus Guevara:** Conceptualization, Methodology, Writing – review & editing. **Tânia Sousa:** Conceptualization, Methodology, Writing – original draft, review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Laura Felicio reports financial support was provided by Foundation for Science and Technology. Sofia Henriques reports financial support was provided by Foundation for Science and Technology. Sofia Henriques reports financial support was provided by Jan Wallander and Tom Hedelius Foundation. Sofia Henriques reports financial support was provided by Crafoord Foundation.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114419.

Appendix

A. *Exergy series accounting and updates*

To perform the decomposition analysis and assess the role of electrification on carbon intensity it was necessary to split estimates of exergy at primary and final stages by energy carrier. For this purpose, both International Energy Agency database IEA [32], previously employed by Serrenho [46] for the first aggregate estimates of the Portuguese useful exergy accounting and the Portuguese Energy Balances (BEN) [47] were used in this work.

Portuguese Energy Balances were needed for the separation of primary resources for cogeneration electricity from cogeneration heat, which are not available from the IEA dataset. This also assures consistency with previous estimates of Felício et al. [20] for cogeneration electricity.

1 Accounting for all energy carriers, except for cogeneration and electricity

Primary energy data was taken from IEA [32], excluding non-energy uses and adding statistical differences. To compute the "other carriers" series, fuels for electricity and cogeneration were excluded. Data on electricity was processed separately, along with the resources dedicated to cogeneration heat (refer to subsection B for details on cogeneration). Subsequently, the primary energy from cogeneration heat was incorporated into the 'other carriers' series.

Note that the series for combustible renewables from 1960 to 1970 was corrected with firewood estimates from Henriques [48, 49] for industry and household uses.

Accounting for Cogeneration Heat Primary Exergy

i. Cogeneration primary-final exergy efficiency

Based on Portuguese BEN the shares of each energy carrier consumed for cogeneration were determined. "Other gases" category was split between coal and oil carriers as IEA does. Once the total primary energy consumption is broken down by energy carrier according to the established shares, conversion energy/exergy factors are then utilized to calculate the primary exergy consumed in cogeneration. Finally, primary-final exergy efficiency was calculated dividing the exergy of cogeneration products (electricity and heat) by the total primary exergy.

ii Cogeneration heat primary exergy

Unlike all other carriers, primary exergy from the heat was determined based on the final energy taken from IEA [32]. First, the end-use shares of all heat categories within cogeneration heat's final energy were used to disaggregate final energy by end-use. Then, corresponding Carnot efficiencies (varying with each category's average temperature) were multiplied to obtain cogeneration heat's final exergy by end-use, and all were summed to obtain the total final exergy of cogeneration heat. Finally, primary-final exergy efficiency previously calculated in (i) is applied to calculate the corresponding primary exergy.

Electricity useful exergy series allocaticon updates and corrections

Data regarding electricity exergy at all stages was taken from Felício et al. [20], including the electricity allocation of end-uses. However, minor updates and corrections were made to separate sectors that were aggregated. Therefore, rather than three, data is disaggregated in five sectors: Industry, Residential, Commercial, Agriculture/Forestry, Fishing and Transport. To split Agriculture/Forestry and Fishing from Industrial sector and the Commercial from the Residential, these adjustments were made:

1) Medium Temperature Heat (MTH) and High Temperature Heat (HTH) were separated for Industry's Heat category, considering 50% for each heat category end-use
2) HTH and MTH efficiencies corrected (previously the energetic efficiency was not considered 100% as it should)
3) Agriculture/Forestry and Fishing's Heat category considered all to be Low Temperature Heat 2 end-uses
4) No Electrolysis processes were considered to occur in Agriculture nor Fishing. Electrolysis' share was added to the Mechanical Drive category
5) All Cooling in Fishing is considered for refrigeration (so only refrigeration efficiency is used. The efficiency considered was the same as in the Commercial sector)
6) The Cooling efficiency considered for Agriculture is the same used in Industry.

Furthermore, note that: as the Winter temperature used in Low Temperature Heat 3 category does not show any variation throughout time, and h = 100%, the exergy efficiency of this category is constant during the whole period of the study.

B. End-uses shares per carrier – final and useful exergy

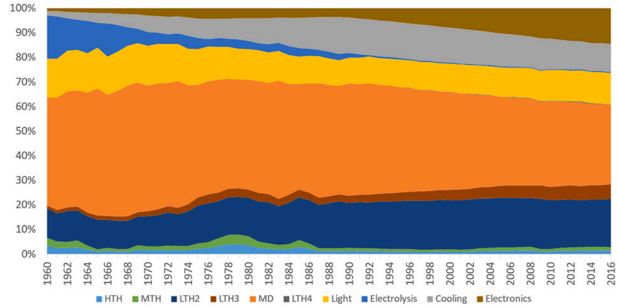

Fig. 12. End-uses shares of electricity's final exergy.

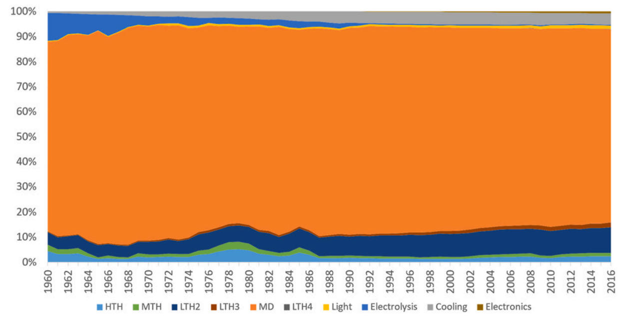

Fig. 13. End-uses shares of electricity's useful exergy.

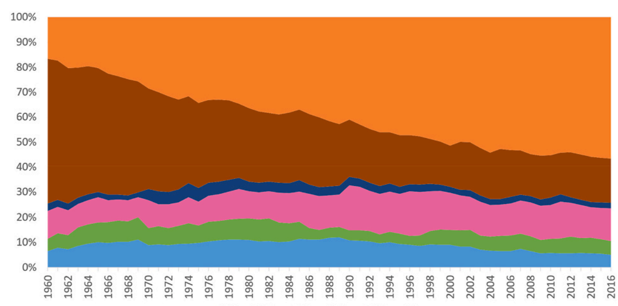

Fig. 14. End-uses shares of other carriers' final exergy.

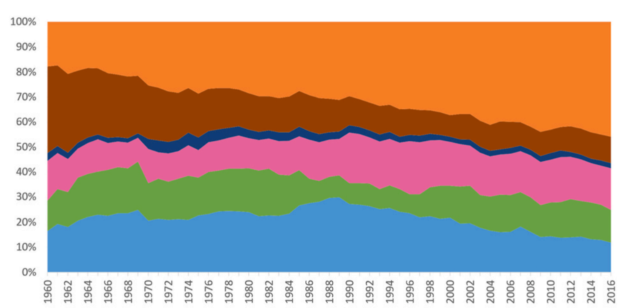

Fig. 15. End-uses shares of other carriers' useful exergy.

C. Electrification of heat end-uses

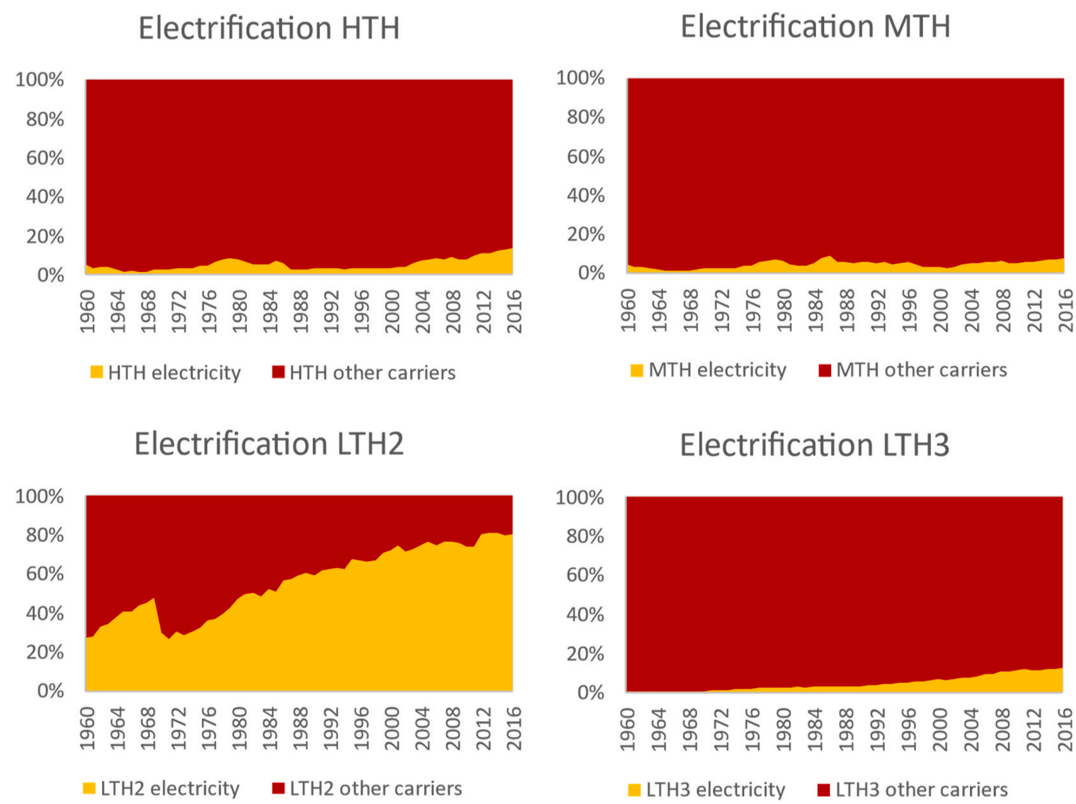

Fig. 16. Share of heat end-uses. Electricity (yellow) or other energy carriers (red). Top-left: Hight temperature heat, top-right: Medium temperature heat, bottom-left: Low temperature heat 2, bottom-right: Low temperature heat 3.

Only the heat categories that are performed by both energy carrier categories are shown in Fig. 16, excluding LTH1 (no electrical heat considered in these temperatures) nor LTH4 (considered only for electric AC heating).

D. Final Exergy consumption of other carriers per sector in percentage

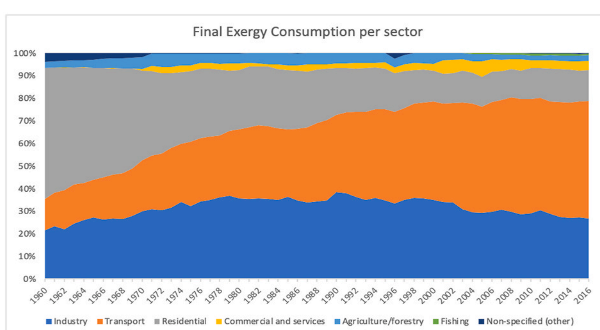

Fig. 17. Final Exergy of other carriers per sector.

From IEA database, Fishing values of consumption start only in 2004. This could mean that part of the share of "non-specified" sector consumption in previous years could be exergy consumed for Fishing.

E. Aggregated carbon intensity per end-use

Most end-uses that have higher exergy efficiencies, such as HTH and MTH, have lower ACI_{useful}, as expected. All MD end-uses are accounted together; thus, the ACI_{useful} of MD is a weighted average of the ACI_{useful} of mobile and static MD. The ACI_{useful} of end-uses that are provided by both electricity and other energy carriers (heat and MD) can be further disaggregated to further understand the impact of the electrification at the end-use level.

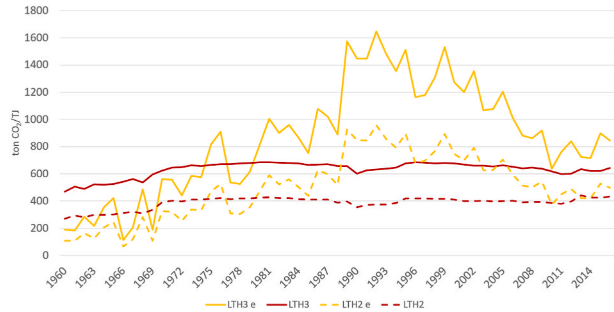

Fig. 18. ACI_{useful} of Low Temperature Heat 2 and 3 end-uses. Electricity (yellow) and other energy carriers (red).

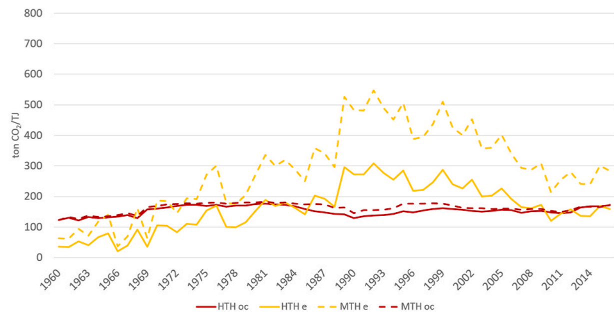

Fig. 19. ACI_{useful} of High, Medium and Low Temperature Heat end-uses. Electricity (yellow) and other energy carriers (red).

Electric heat has a higher ACI_{useful} than other carriers' heat since the 1980s, which can be explained by the increase of electricity consumption for the Residential and Services sectors. In those sectors, heat is used at lower temperatures and, therefore, the uses have lower efficiencies, leading to higher ACI_{useful}. Thus, with the current penetration of RES in electricity production, electrical heat is still more carbon intensive than heat provided by other carriers and a total electrification of these type of end-uses could mean an increase in carbon intensity rather than decarbonization unless there is a change in technology. However, for high temperatures (Figure, HTH $\geq$500 °C, electric heat has had a lower ACI_{useful} then other carriers' heat since 2010 which indicates that the electrification of industrial HTH end-uses contributed to decarbonization in the last decade of this study.

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