The rise and stall of world electricity efficiency:1900-2017, results and implication for the renewables transition

Pinto, Ricardo and Henriques, Sofia and Brockway, Paul and Heun, Matthew and Sousa, Tânia

MARETEC—Marine, Environment and Technology Center, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, 1, Lisboa 1049-001, Portugal, CEFUP, Faculdade de Economia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-464, Porto, Portugal, Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom, Engineering Department, Calvin University, 3201 Burton St. SE, Grand Rapids, MI 49546, USA

15 March 2022

The rise and stall of world electricity efficiency:1900-2017, results and implication for the renewables transition

Ricardo Pinto[a,*], Sofia T. Henriques[b], Paul E. Brockway[c], Matthew Kuperus Heun[d] and Tânia Sousa[a]

[a] MARETEC—Marine, Environment and Technology Center, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, 1, 1049-001, Lisboa, Portugal
[b] CEFUP, Faculdade de Economia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-464, Porto, Portugal
[c] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom
[d] Engineering Department, Calvin University, 3201 Burton St. SE, Grand Rapids, MI 49546, USA

*Corresponding author.

E-mail address: ricardo.c.pinto@tecnico.ulisboa.pt (R. Pinto)

Keywords

Energy efficiency, electricity, Carbon intensity, decarbonisation, energy history, energy end-uses

In the coming renewables-based energy transition, global electricity consumption is expected to double by 2050, entailing widespread end-use electrification, with significant impacts on energy efficiency. We develop a long-run, worldwide societal exergy analysis focused on electricity to provide energetic insights for this transition. Our 1900-2017 electricity world database contains the energy carriers used in electricity production, final end-uses, and efficiencies. We find world primary-to-final exergy (i.e. conversion) efficiency increased rapidly from 1900 (6%) to 1980 (39%), slowing to 43% in 2017 as power station generation technology matured. Next, despite technological evolution, final-to-useful end-use efficiency was surprisingly constant (~48%), due to “efficiency dilution”, wherein individual end-use efficiency gains are offset by increasing uptake of less efficient end uses. Future electricity efficiency therefore depends on the shares of high efficiency (e.g. electrified transport) and low efficiency (e.g. cooling and low temperature heating) end uses. Our results reveal past conversion efficiency increases (carbon intensity of electricity production reduced from 5.23 $kgCO_2/kWh$ in 1900 to 0.49 $kgCO_2/kWh$ in 2017) did little to decrease global electricity-based CO_2 emissions, which rose 380-fold. The historical slow-pace of transition in generation mix and the need to electrify end-uses suggest that strong incentives are needed to meet climate goals.

1. Introduction

1.1. Global electricity demand is projected to have rapid growth

The share of electricity in world total final consumption (TFC) has increased enormously, from 0.1% (1900) to 4% by mid-century (1950), and 19% in 2022 [1]. Importantly, global electricity demand keeps rising, and is projected by the International Renewable Energy Agency (IRENA) to double between 2015 and 2050 [2]. While electricity generation doubled between 1990 and 2014 [3] carbon dioxide (CO_2) emissions associated with electricity increased only slightly less, 87%, from 6.28 $GtCO_2$ to 11.76 $GtCO_2$ [4]. To limit end-of-century warming to 1.5 °C [5] whilst meeting UN Sustainable Development Goal #7 (affordable and clean energy) [6], electrification, renewables, and energy efficiency are thought to be essential [2]. Electrification and renewables will mean rapid growth in electricity generation and consumption into the future, whilst energy efficiency is a complex and nuanced issue, with impacts on economic growth, energy rebound, and aggregate efficiency [7–9].

1.2. Electrification and renewables lead to growth of electricity demand

Electrification of end uses will enable widespread deployment of low-carbon, electricity-producing sources of energy, especially wind and solar. IRENA forecasts by 2050, 33% of final energy used in transport will be provided by electricity, increasing from 1% in 2015 [2]. Buildings are also expected to increase their electricity demand by 70% until 2050, due to an increased cooling demand, electrification of heating, and growing electricity consumption in developing countries [2,10].

Beyond electrification, emerging end uses will add to future electricity demand, especially information and communication technology (ICT). For three specific categories of ICT (communication networks, personal computers, and data centres), Heddeghem et al. [11] found that between 2007 and 2012 electricity consumption grew at 7% per year, while overall electricity use increased only 3% per year, thereby raising the share of total worldwide electricity consumption for ICT to 4.6%.

1.3. Energy efficiency is a complex subject

Energy efficiency can be calculated between different stages of the energy conversion chain. To estimate final-to-useful efficiency, energy consumption for end uses must be estimated [12]. Three recent studies illustrate the complexities of energy efficiency. First, Serrenho et al. [13,14] showed that the ratio of useful exergy to GDP for Portugal is approximately constant, a finding that holds for the other EU-15 countries if the relative size of heavy industry end uses (High temperature heat (HTH)) and domestic end uses (Low Temperature Heat (LTH)) remain constant. Second, Santos et al. [8] show that an increase in final-to-useful exergy efficiency contributes to higher GDP for Portugal. Third, Ferguson et al. [15] shows electricity consumption and economic development are strongly correlated for more than 100 countries between 1971-1995. Taken together, these three relationships imply increases in final-to-useful efficiency contributes to economic growth and, paradoxically, an increase in the demand of energy, a phenomenon known as energy rebound. Indeed, Ayres et al. [16] state efficiency gains at the final-to-useful stage lead to higher final energy consumption. However, overall effects of final-to-useful efficiency increases on the demand for final energy can be positive or negative [17].

Furthermore, the relationship between final-to-useful electricity efficiency and aggregate final-to-useful efficiency is complex. Ayres et al. [18] concluded that final-to-useful US electricity efficiency was stable (average 55%) between 1900 and 2000. In Portugal between 1900 and 2009, the aggregated final-to-useful efficiency is always lower than 25% [13], while final-to-useful efficiency for electricity is always above 30% [19]. Also, in Mexico between 1971 and 2009, electricity is the energy carrier with the highest final-to-useful efficiency [20]. Thus, the growing use of electricity increases aggregate final-to-useful exergy efficiency. In contrast, in Japan, primary-to-final exergy efficiency decreased and then stagnated due to the use of less efficient technologies [21], a phenomenon called "efficiency dilution," wherein the impact of rising efficiency for one process is "diluted" by increasing consumption of lower efficiency processes. For Japanese electricity, the dilution effect was the result of hydroelectricity saturation and growing use of less efficient fossil fuels to produce electricity. Brockway et al. [22] compare primary-to-useful exergy efficiency of electricity in the UK and USA, for the period 1960-2010. While rising UK electricity exergy efficiency drove increases to UK aggregate exergy efficiency, USA aggregate exergy efficiency remained very stable due to efficiency dilution caused by increasing consumption of low-efficiency air conditioning [22]. In Portugal, the primary-to-useful efficiency of electricity increased between 1900 and 1990 but stagnated afterwards [19] due to increasing share of electricity consumed in less-efficient sectors, mainly residential and commercial.

The emerging picture of the role of useful exergy and efficiency on economic growth and energy consumption (and CO_2 emissions) is indeed complex and nuanced. However, current understanding is based on analyses of single countries [13,18–21,23,24] or a small number of countries [14,22] over short timescales [14,20,22,24] with little-to-no electricity end use detail [21,23]. A few studies [13,18,19] have longer timescales with more detail on electricity consumption, but focus on single countries (Portugal and US). Additionally, these studies use varying methodologies to estimate efficiencies, leading to results inhibiting comparison [12]. At the world level, there are two studies for a single year [25,26] and only one long-run (1900-2010) study [1], which calculated final-to-useful efficiencies using GDP as proxy, thereby linking energy and economic growth. Additionally, the long-run study [1] lacks detail in allocations of electricity to end-uses, assuming constant end-use shares within each sector throughout the period 1900–2010. These assumptions are problematic, because the estimation of overall electricity efficiency is highly dependent on both (a) the detail in allocating electricity to end uses (see [19] and [27]) and (b) the methods used to estimate efficiencies [12].

1.4. Motivation, aim, contribution, and structure

The *motivation* for this paper is based on the increasing importance of electricity in the future, due to both (a) the need to decarbonise energy systems and (b) increasing share of end-uses such as ICT. Previous individual country studies have shown that the efficiency of electricity production and consumption has significant impacts on final-to-useful and primary-to-final efficiencies, economic growth, and greenhouse gas (GHG) emissions. However, our historical knowledge is incomplete, because there is no detailed, world-level exergy-based study covering a long timespan that focuses on electricity end uses. A long-run analysis of past electricity production, efficiency trends, and carbon emissions will provide insights to guide scenarios and policies for electrification, renewables, and energy efficiency.

The *aim* of this article is to evaluate world long-term trends of past electricity consumption and production, end-uses, efficiency, and carbon intensity. The key *contributions* of this paper are the development of (a) a detailed world long-run database for electricity production and consumption and (b) historical time series datasets for the evolution of primary-to-final, final-to-useful, and primary-to-useful exergy efficiencies.

The *structure* of this paper is as follows: In section 2, we explain the method for constructing a world database for electricity consumption and production. In section 3, we show results for world electricity production and consumption, efficiencies, and carbon emissions. In section 4, we discuss the results in historical perspective and in the context of the ongoing decarbonization transition. Section 5 summarizes.

2. Data and methods

2.1. Final energy stage: Electricity production and sources

Electricity production data provides the starting point for construction of the long run database of primary, final, and useful electricity, as shown in Figure 1 for 1900-1970:

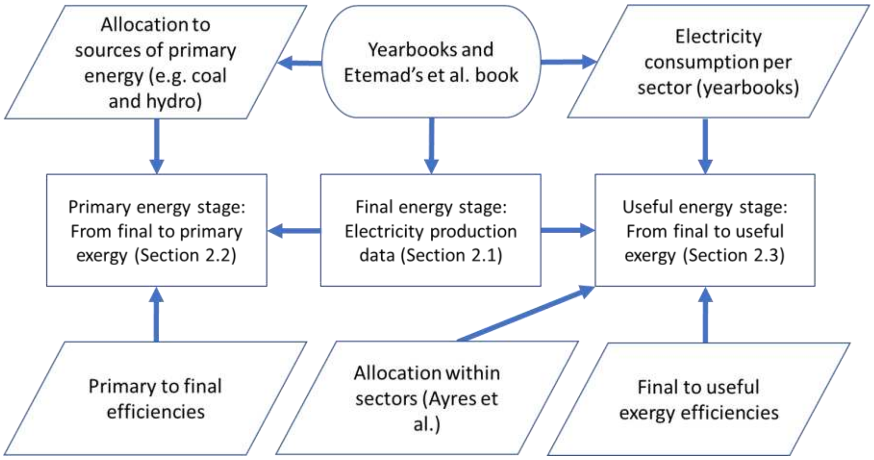

Figure 1: Flow chart summarizing how primary, final, and useful exergy were calculated, prior to 1971.

Similarly, the electricity production data methodology is summarised for 1971-2017 in Figure 2:

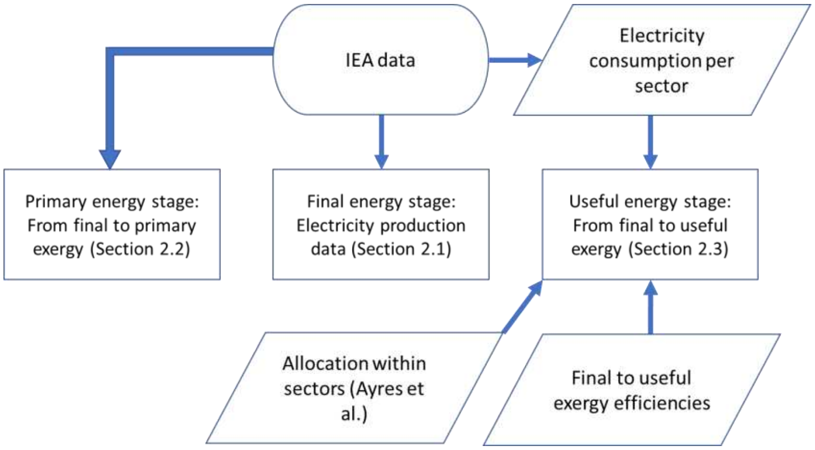

Figure 2: Flow chart summarizing how primary, final, and useful exergy were calculated, after 1971.

Our starting point was Etemad et al. "World Energy Production" [28]. Two years were assessed first: 1920 (Figure 3) and 1970 (Figure 4). The year 1920 is the first year for which most countries have data available on electricity production in Etemad et al. [28]. The year 1970 is the year before world data are available from the International Energy Agency (IEA). Countries were divided in three groups, large, medium, and small producers, as shown in Figure 5. *Large producers* (Canada, Germany, Japan, UK, USA, and USSR) supplied more than 5% of the world electricity in 1920 or 1970. Figure 6 shows the share of the world total electricity of these countries for the period 1900-1970 (Canada [29], Germany [30–32], Japan [33], UK [34,35], USA [36] and USSR [37–39])[1]. When no other source of data was available, Etemad et al. [28] was used. For years in which no data were available, we interpolated linearly.

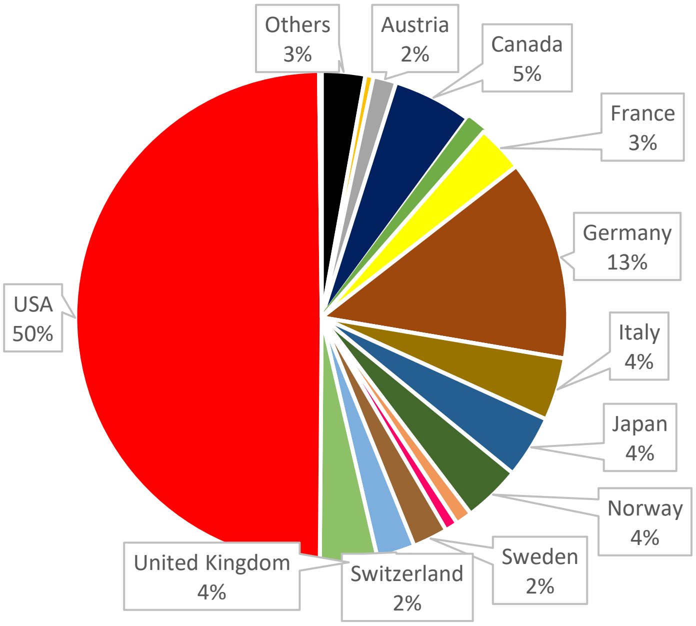

Figure 3: Large and medium producers share of the world electricity production in 1920.

---

[1] Germany data started with a high value of hydroelectricity production, suggesting hydroelectricity production began before 1920, but as no sources were found for the period prior to 1920 we assume the share of Germany's hydroelectricity prior to 1920 was equal to the average of the period 1920-1925.

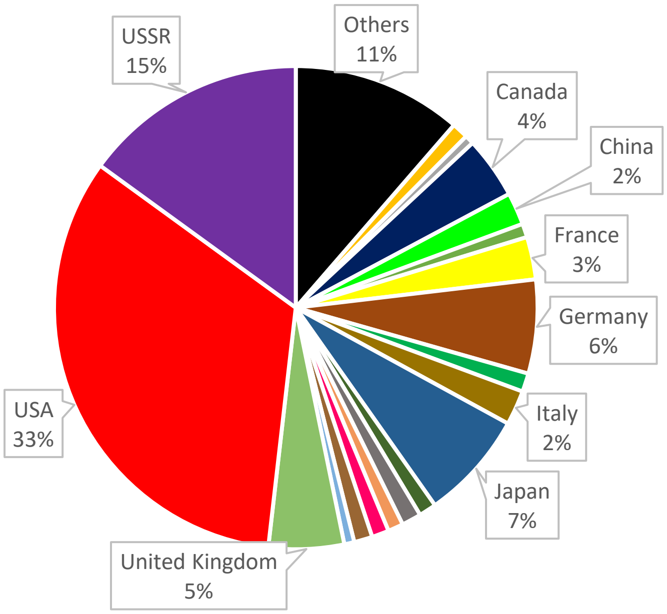

Figure 4: Large and medium producers share of the world electricity production in 1970.

Medium producers are all countries that produced more than 1% of the world electricity in 1920 or 1970: Australia, Austria, China, Czechoslovakia, France, India, Italy, Norway, Poland, South Africa, Spain, Sweden, and Switzerland. Figure 6 shows the share of world electricity production by these countries for the period 1900–1970.

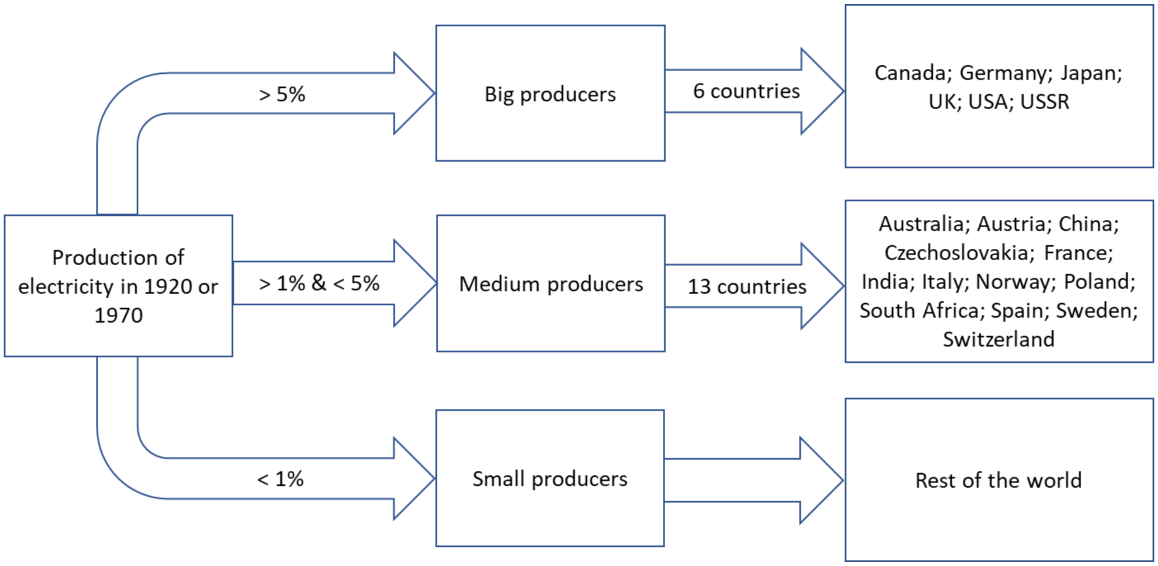

Figure 5: Flow chart summarizing the countries which were allocated three different groups based on size of production share.

Data for thermal and hydroelectricity production for France, Italy, and Spain were found in [40–43]. The primary reference for Spain [41] includes only total production values, so hydroelectricity production until 1928 was estimated based on Rodríguez [44]. Missing values for hydroelectricity production in France prior to 1925 [40] were estimated based on [45]. For France, we determined the share of oil in thermal electricity for 1952 [46] and natural gas share for 1957 and 1958 [40]. Together with data for 1960 from the IEA [47], we interpolated other years. In the case of Italy, for 1925–1960, we identified the share of each fuel in thermal electricity generation [48].

Norway and Sweden data series started with high values of hydroelectricity, indicating that production started before Etemad et al. series [28], so we looked for other data to complete the series until 1900. For Norway 1900–1936, we estimated hydroelectricity production using a report for all hydropower plants in use in 1943 [49]. (See supplementary information (SI) A.) For Norway 1930–1960, we estimated thermal electricity sources using statistical yearbooks [50]. For Sweden 1900–1928, we estimated hydroelectricity production using shares of hydro generation available in Kander et al. [51].

Data for total, hydro, geothermal, and nuclear electricity production for other countries was obtained from Etemad et al. [28]. Switzerland started with a high value of hydroelectricity, so we assumed that the share of hydroelectricity for the early years was equal to the average share of hydroelectricity for the first five years of available data. For medium producer countries for 1900–1960, we assumed electricity not generated from hydropower, nuclear or geothermal sources was produced from coal (except France, Italy, and Norway), as oil was the only other credible source, and no large oil producers are classified as medium producers. IEA data from 1960 onwards for OECD countries provides carrier-level electricity production data for almost all the medium producers, the non-OECD exceptions being China, Czechoslovakia, India, and South Africa (their IEA data starts in 1971).

Small producers comprise all remaining countries that, individually, each produced less than 1% of world electricity in 1920 and 1970. For small producers, total electricity and hydroelectricity values were taken from Etemad et al. [28], with the exception of hydroelectricity values for Latin America which were obtained from Rubio and Tafunell [52]. The share of thermoelectricity produced by each energy carrier was assumed equal to the weighted average of medium and large producers, including only non-hydro energy carriers.

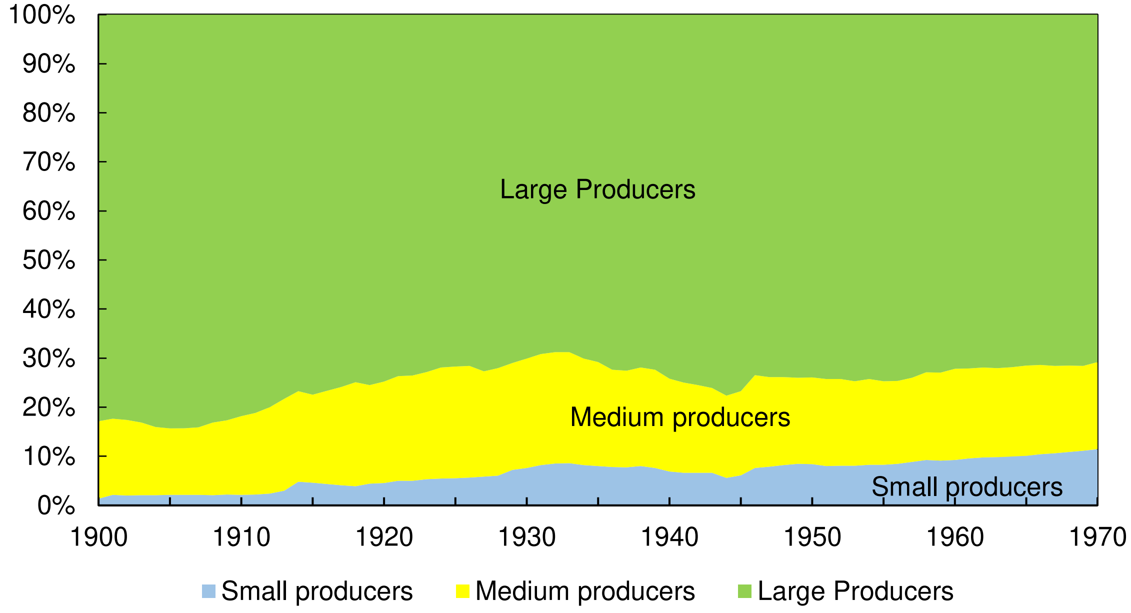

Figure 6: Share of world electricity production for 1900–1970 for large, medium, and small producers

2.2. Primary energy stage: From final-to-primary exergy

Primary energy gives information about the resources necessary to produce the energy we purchase (final energy, such as electricity). Moving from final-to-primary energy requires electricity generation efficiencies for fossil fuels (coal, oil, natural gas) and renewables (e.g., hydro).

For Japan, UK, USA, and USSR (the biggest producers) for 1900–1970, fossil fuel electricity generation efficiencies were calculated directly from available primary energy consumption and electricity production data. However, for Canada, Germany, and all medium producers, primary-to-final efficiencies were obtained from Etemad et al. [28]. For small producers for 1900–1970, electricity generation efficiencies for each energy source were taken from Etemad et al. [28] assuming these countries had the lowest efficiency recorded in each year. From 1971, the IEA [47] has primary energy for electricity production for all countries.

For renewables, three options exist for estimating the equivalent primary energy source value: resource content method (RCM), physical content method (PCM) and partial substitution method (PSM) [12]. We choose PCM, the method used by the IEA. In the PCM definition, primary energy is the first form of energy that is commercially available, meaning wind and solar gross electricity produced is considered primary energy [12], with no losses from primary-to-final energy stage.

Last, we convert from primary energy to exergy, via multiplication of exergy coefficients, shown in Table 1 [19,53].

Table 1: Exergy conversion factors per energy carrier

Energy carrier	Exergy coefficient
Coal and Coal products	1.06
Oil and Oil products	1.06
Natural gas	1.04
Combustible Renewables	1.11
Electricity	1.00

2.3. Useful energy stage: Final exergy to useful exergy

To move from final-to-useful exergy, we multiply by end-use efficiencies. Useful exergy (also called useful work) is defined as "the minimum amount of work (or exergy) required to produce a given energy transfer" [11,p.2]. Unfortunately, data in yearbooks and other statistical sources rarely allocates final energy to end-use tasks. Available references sometimes allocate electricity to the sector or subsector in which it is consumed. Thus, the first step was collecting data for the consumption of electricity in sectors and subsectors from multiple sources for 1900–1971 [18,19,30–33,35,37,40,41,43,50,54–59]. Detailed descriptions of country-level references are given in Table A1 of SI A. After 1971, sectoral electricity consumption is available from the IEA [47]. Refer to Sections 2.1 and 2.2 of SI-A for a more detailed description of the methodology used for allocating electricity consumption to sectors and subsectors.

The second step was the allocation to end-uses within each sector and subsector. We considered the following 11 end uses: lighting, communication and electronics, electrochemical, high temperature heat (HTH) low temperature heat (LTH), cooling, transport, residential appliances, commercial appliances, and machine tools and pumps. Allocation to end-uses was previously completed for Portugal and the USA

[18,19]. Electricity consumption in residential and commercial sectors for the remaining countries was allocated to end-uses using Ayres et al. [18] without modification. Electricity consumption in industrial subsectors was allocated to end-uses assuming one main end-use for each subsector: HTH for iron and steel, electrochemical for the electrochemistry and electrometallurgy industries, and machine tools and pumps for other industries. All industrial subsectors have end uses of varying proportion among lighting, communication/electronics, and cooling, with shares taken from the industrial sector of Ayres et al. [18]. A more detailed description is available in section 2.3 of the SI A.

The last step was the calculation of useful exergy via multiplying end-use electricity consumption by associated final-to-useful exergy efficiencies. Final-to-useful exergy efficiencies were calculated with the equations in Table 2 or obtained from the literature [18,60]. Exergy efficiencies for heating/cooling end uses depend on the temperature of the surrounding environment and that required for the task. Different end-use temperatures were used depending on the end-use application. Refrigeration and space cooling efficiencies were calculated by dividing an average real Coefficient of Performances (COPs) for machines in each year by the ideal COP shown in Table 2. For refrigerators, the ideal COP was calculated assuming that a third of the electricity was consumed by the freezer, at –18 °C, while the remaining two thirds were consumed by the refrigerator at 5°C, following Palma [27]. The environmental temperature was assumed to be 20°C. For space cooling, the ideal COP was calculated assuming a 25°C environmental temperature and 20°C end-use temperature. End-use temperatures for heating were taken as 100°C for cooking, 60°C for water heating and 20°C for space heating. LTH exergy efficiencies were calculated assuming an energy efficiency, η, of 100% and a Carnot efficiency based on the end-use temperature (T_1) and environment temperature (T_0). For cooking and water heating, T_0 was taken as the average annual world temperature. For space heating, T_0 was taken as the average world temperature for the coldest month of each year. HTH exergy efficiencies were calculated by multiplying the energy efficiency from Ayres et al. [18] by the Carnot efficiency from Table 2. T_1 was assumed to be 500°C and T_0 the average world annual temperature. A table with the references for exergy efficiency per end use is available in section 2.4 of the SI A as well as more details about real COP values.

Table 2: Cooling and heating efficiencies.

Ideal COP Cooling	$\frac{T_C}{T_0 - T_C}$
Cooling exergy efficiency	$\mathcal{E} = \frac{COPcooling,real}{COPcooling,ideal}$
Heat exergy efficiency	$\mathcal{E} = \eta(1 - \frac{T_0}{T_1})$

2.4. Carbon intensity

In order to estimate CO_2 emissions, we used Intergovernmental Panel on Climate Change (IPCC) emission factors [61], which do not include life cycle emissions of each electricity production technology. Thus, renewable technologies have emission factors equal to zero. Carbon intensity is the ratio of emissions / exergy, calculated at both the final stage and the useful stage [19].

3. Results

This section contains results obtained for electricity production and consumption as well as efficiencies and carbon intensities associated with electricity use. The data used to create each graph is available in SI B. This section is focused on overall trends while a detailed discussion of shorter-term trends is left to section 4.

3.1. World electricity production

Figure 7 shows world shares of electricity production by energy source (left axis) and total electricity production (right axis). Fossil fuels (in grey scale colours) are responsible for a relatively stable fraction of electricity production (about 60%) from 1900–2017. Renewables, especially wind, have increased their share in the last decade. The fuel sources for electricity production have become more varied through time.

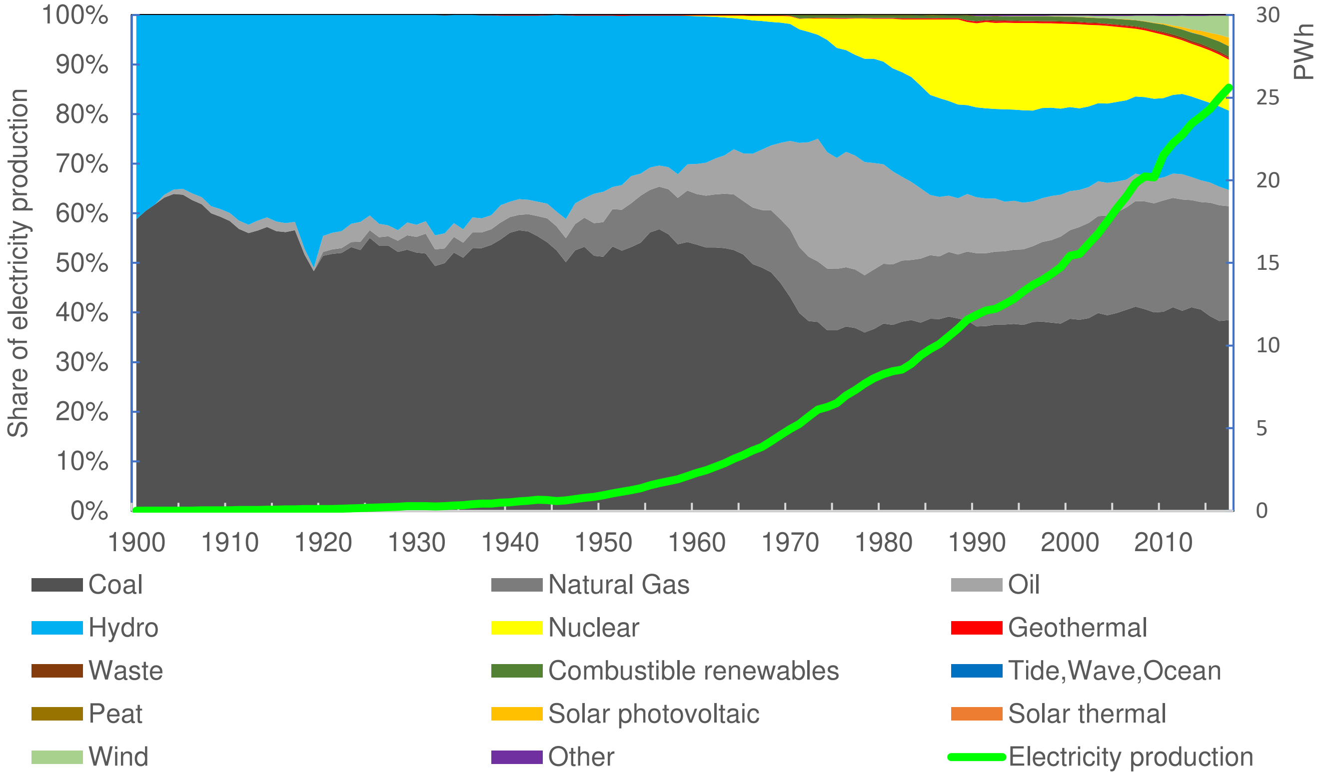

Figure 7: World shares of electricity production per energy source (left axis) and total electricity production (right axis)

3.2. World electricity consumption

3.2.1. Allocation to sector and subsector

Figure 8 shows the allocation of electricity consumption by subsector. The share of electricity consumption in the transport sector decreased significantly from 1900 (27.7%) to 2017 (1.7%). In contrast, consumption by residential and commercial sectors increased from a combined share of 23.5% in 1900 to 48.4% in 2017. The sum of industry subsectors (iron and steel, electrochemistry and electrometallurgy, and other industries) decreased little from 1900 (47.3%) to 2017 (41.9%).

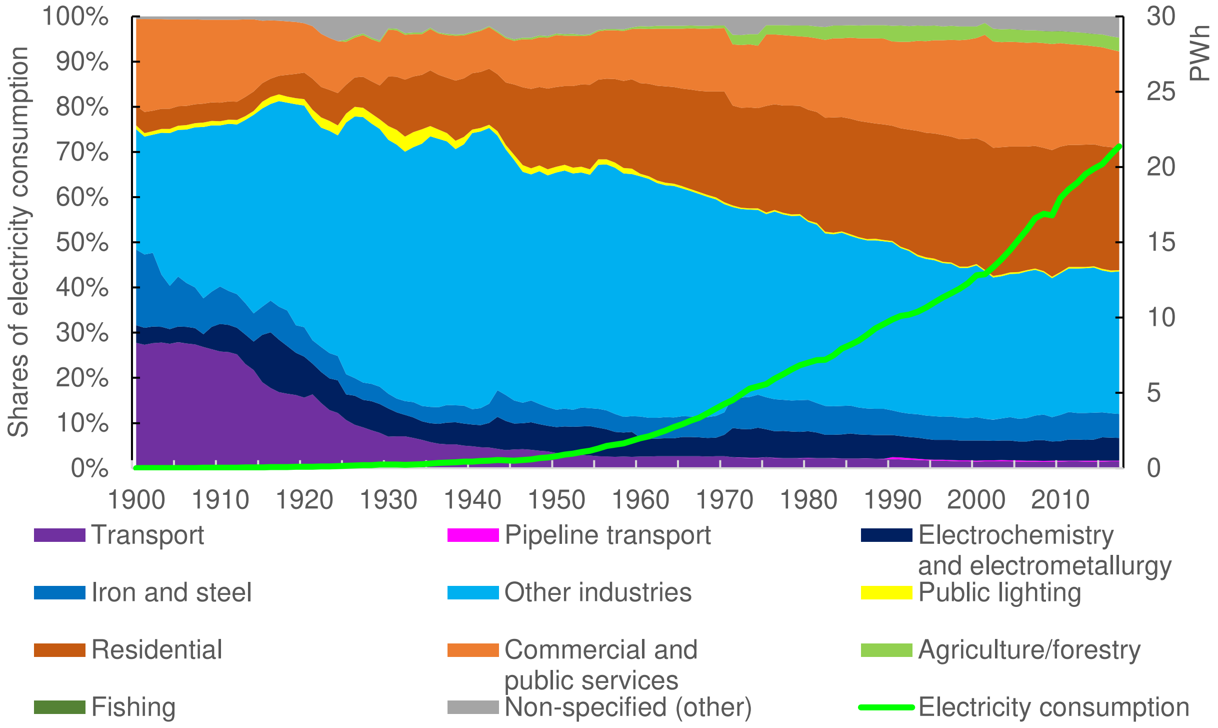

Figure 8: World shares of electricity consumption by sector and subsector (left axis) and total electricity consumption (right axis)

Total electricity consumption in Figure 8 (green line, right axis) shows a similar trend compared to Figure 7 - the differences are Figure 8 includes transmission losses and electricity self-consumed by the energy industry. The average value of transmission losses was 9.1% of electricity produced, while electricity used in the energy industry was on average 8.6% of electricity production, see section 1.2 of the SI A.

The sharp rise in the electrochemistry and electrometallurgy and iron and steel industries at the expense of other industries after 1971 is due to classifications of the IEA data. The IEA data contain a level of detail that enables allocation of a bigger share of other industries to the two subsectors, especially for the USSR.

3.2.2. Allocation to end-uses

Figure 9 shows electricity consumption shares by individual end-uses.

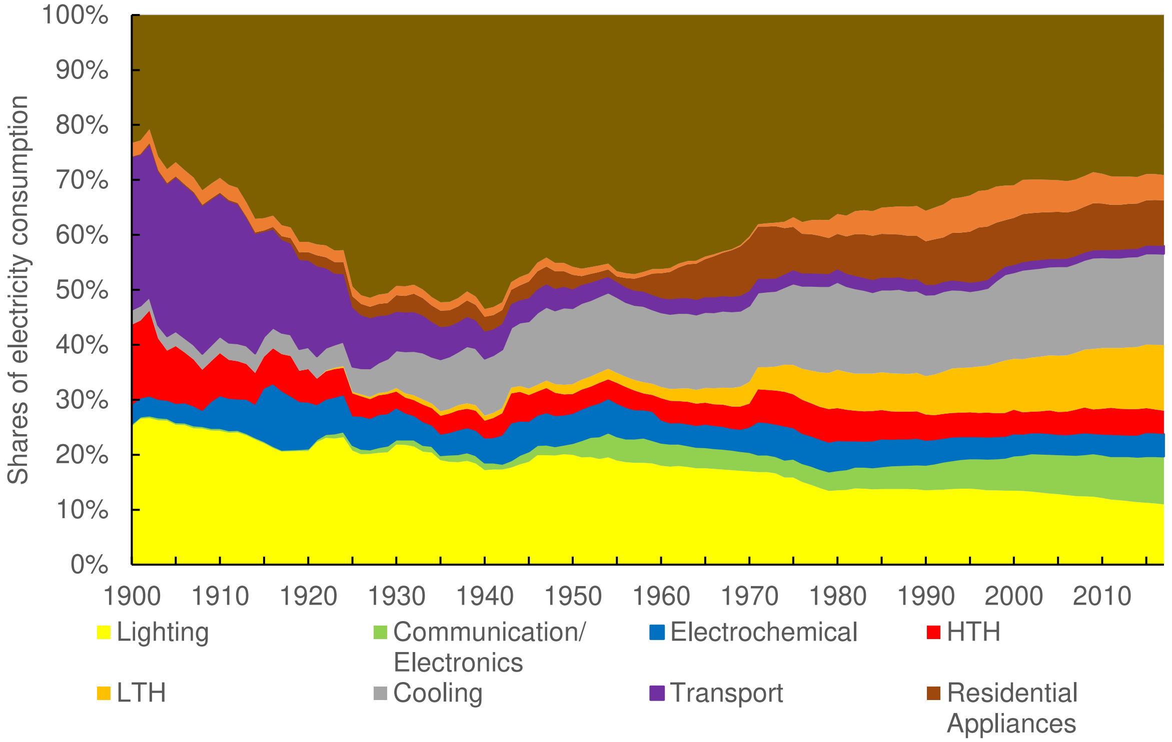

Figure 9: World shares of electricity consumption allocated per end-use.

The share of lighting end-uses decreased throughout the period by more than half. Transport has decreased markedly (1/20th of the 1900 share), because electric trams were replaced by automobiles. By 2017, HTH end-uses were less than one third of their share in 1900. On the other hand, LTH and cooling end-uses have increased significantly, representing over 10% and 15% of total consumption, respectively, in 2017. By comparison in 1900, LTH had no share of electricity consumption and cooling had less than 3% share. Communication and electronics and residential appliances end-uses shares experienced a similar increase from less than 1% to close to 10%. Commercial appliances end-use share almost doubled to 5% in 2017. The share for machine tools and pumps has varied considerably. Looking only at 1900 and 2017, it increased from 23% to 29%. Electrochemical end-uses have remained largely stable over the period (average ~4%).

3.3. Electricity efficiencies

3.3.1. World primary-to-final energy efficiencies for fossil fuels

Figure 10 shows the evolution of primary-to-final energy efficiency for fossil electricity generation. Average efficiency has grown over the last 117 years, mainly due to improvements in electricity generating technology and with a smaller importance the increasing share of higher-efficiency generation. The sudden increase in oil efficiency in 1913 is related to a change in source for Russia while the decrease in 1997 is due to IEA data classifications. The jump in efficiency in 1971 is due to the switch in pre/post IEA datasets.

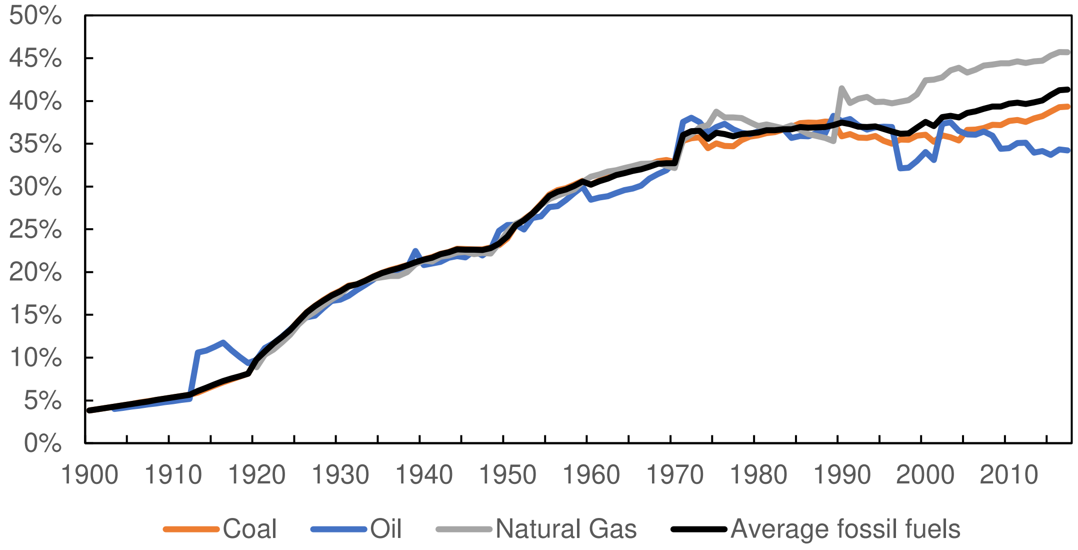

Figure 10: Primary-to-final energy efficiency for fossil fuel electricity production, between 1900 and 2017.

3.3.2. World primary-to-final, final-to-useful and primary-to-useful exergy efficiencies

Figure 11 shows primary-to-final, final-to-useful, and overall exergy efficiencies. The primary-to-final exergy efficiency time series is similar to the average fossil fuel energy efficiency of Figure 10, because electricity production is dominated by fossil fuel sources since 1900.

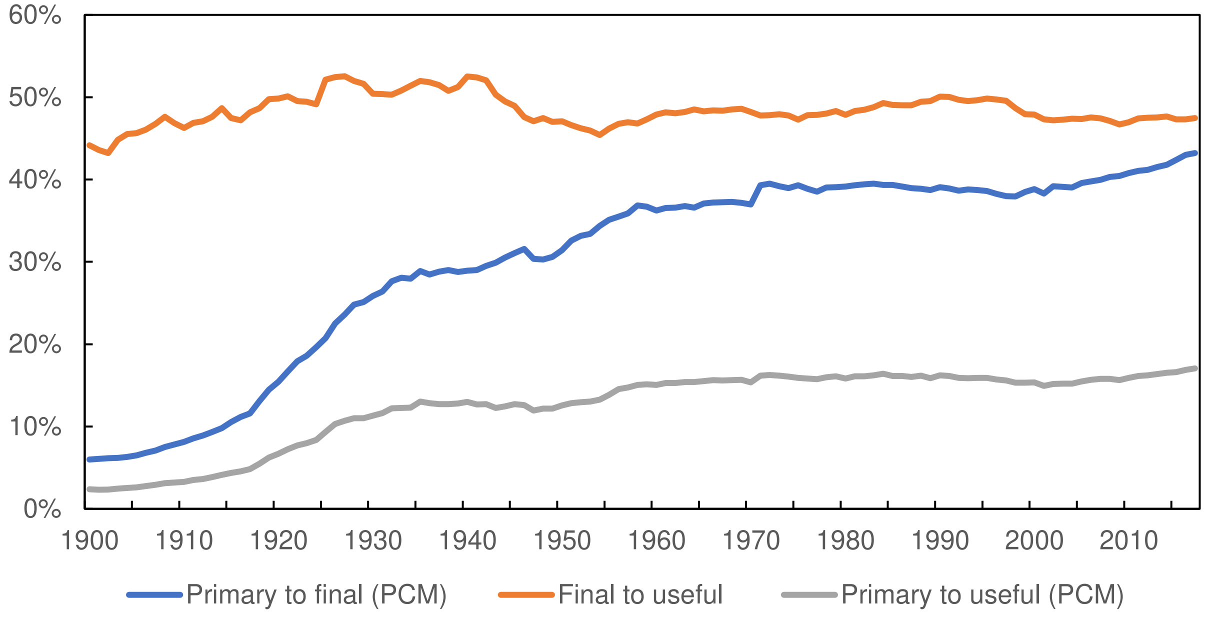

Figure 11: World electricity primary-to-useful, primary-to-final and final-to-useful exergy efficiencies, using the PCM method

Final-to-useful exergy efficiency remains surprisingly stable, within the range 40-50% over the whole period. In 1900, efficiency was 44% and in 2017 it was close to 47%.

In the period 1900-2017, primary-to-useful exergy efficiency grew significantly reaching 17% in 2017.

3.3.3. Final-to-useful exergy efficiencies per end use

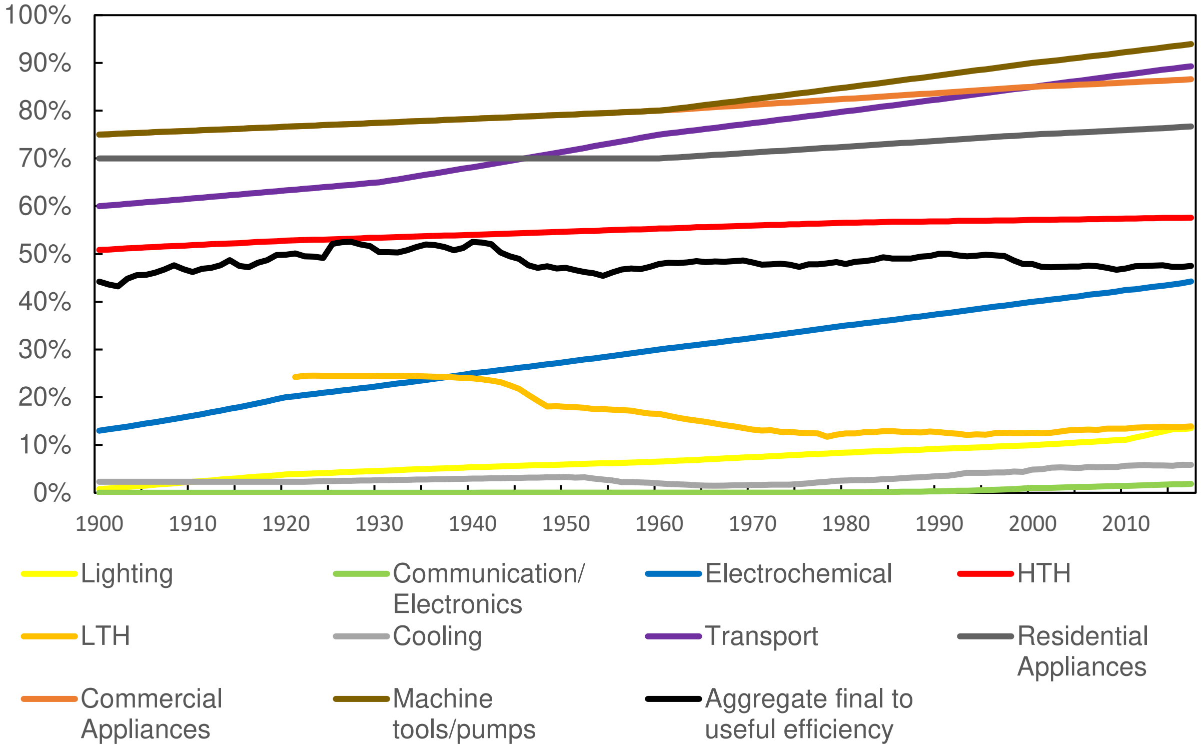

Figure 12: Final-to-useful exergy efficiencies for each electricity end use, during 1900-2017

Figure 12 shows final-to-useful exergy efficiencies for each end use. The LTH line shows a decreasing efficiency trend, until the 1980's, followed by a period of constant efficiency and more recently, after the early 2000's, a slow increasing trend is observed. This pattern is a result of the changing weights of LTH uses. LTH is composed of three different uses: cooking, water heating, and space heating. A decrease in cooking use translated to diminishing share of LTH, whilst space heating and water heating weights increased. Water heating and (especially) space heating are less efficient than cooking, because of the lower temperature of use, causing the decrease in overall LTH exergy efficiency seen until 1980s. The small increase in efficiency observed after the early 2000's is again a result of a change in weights of LTH end-uses, as space heating reduced its importance while water heating increased. The efficiency of cooling end-uses decreases between the mid-1950s and 1970 due to decreases in refrigeration efficiency because of increasing refrigerator and freezer size and new additional features [62].

3.3.4. Final-to-useful exergy efficiencies for each sector

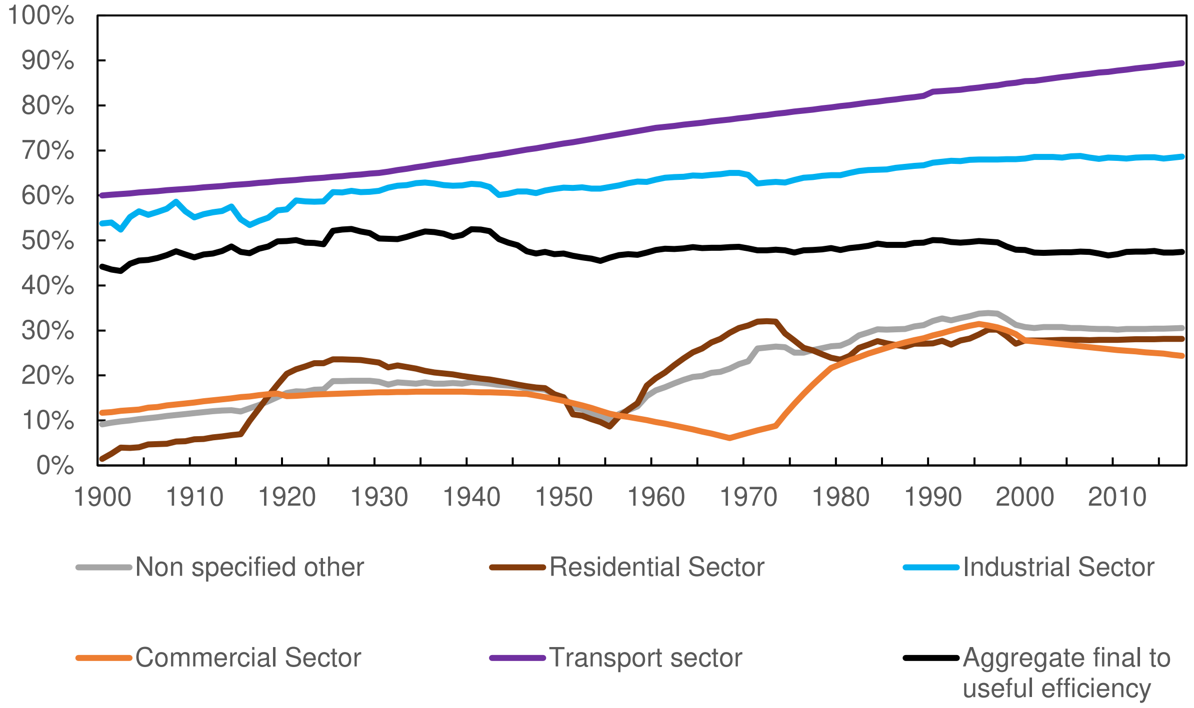

Figure 13: Final-to-useful exergy efficiency of electricity use for different sectors

Figure 13 shows the electricity efficiency for the different sectors and the aggregated final-to-useful efficiency. The industrial and transport sectors have higher efficiencies than the global average. The transport sector has mainly one end-use, transport end-use, which is a highly efficient end use. Industry is mainly composed of HTH use, electrochemical and machine tools and pumps end-uses. High efficiency machine tools and pumps have the largest share, leading to high efficiency for the industrial sector. The residential and commercial sectors had distinct historical differences in terms of efficiency but have since evolved into a similar sectoral final-to-useful efficiency. These two sectors have low efficiencies because of the significant share of low efficiency end uses: lighting, LTH, cooling and communication and electronics.

Figures with allocation per end-use for each sector/subsector are available at section 3.1 of the SI A. The variability in efficiencies of the residential and commercial sectors are associated with fluctuations of individual end-use shares, which are retrieved directly from Ayres et al. [18].

3.4. Carbon intensity and carbon dioxide emissions

Figure 14 (right axis) shows the exponential growth of world CO_2 emissions associated with electricity production for 1900–2017. Figure 14 (left axis) also illustrates how carbon intensity has decreased during this period. Two different metrics are shown: one considers carbon intensity at the final stage of the energy conversion chain (CIF) while the other takes one step forward and calculates carbon intensity at the useful level (CIU). Carbon intensity, both at the useful stage and final stage, has a descending trend for 1900–2017 but both also exhibit stabilization since the 1980s, with slight decrease of carbon intensity in the last 5 years. Looking at the whole period 1900-2017, CIF dropped from 5.23 to 0.49 kg CO_2/kWh while the CIU decreased from 13.18 to 1.24 kg CO_2/kWh.

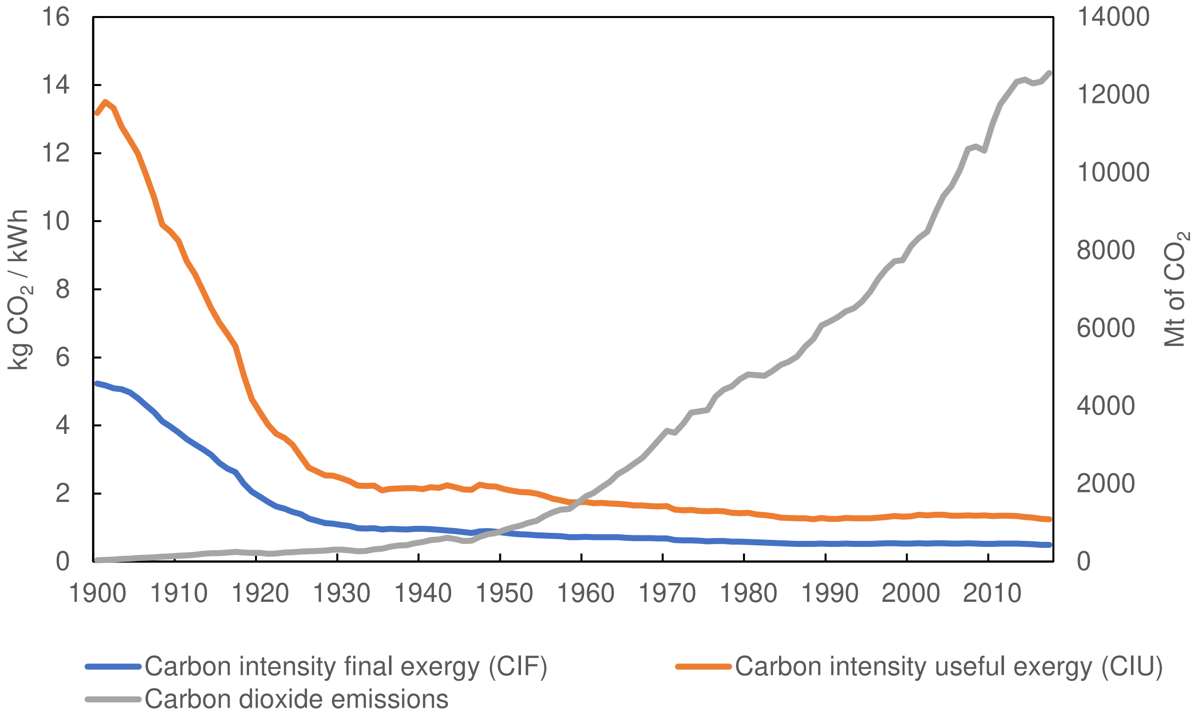

Figure 14: CO_2 emissions from electricity generation in grey (right axis), carbon intensity of final exergy in blue and useful exergy in orange (left axis), during the period 1900 to 2017.

3.5. Annual growth rates

Figure 15 shows that there has never been a period when primary-to-useful exergy efficiency growth has led to CO_2 emissions decline, since CO_2 growth rate was never negative. Figure 15 also shows the lack of correlation between primary-to-useful exergy efficiency and CO_2 emissions, especially after 1940. The result holds for primary-to-final and final-to-useful exergy efficiencies, as shown in Figures A7 and A8.

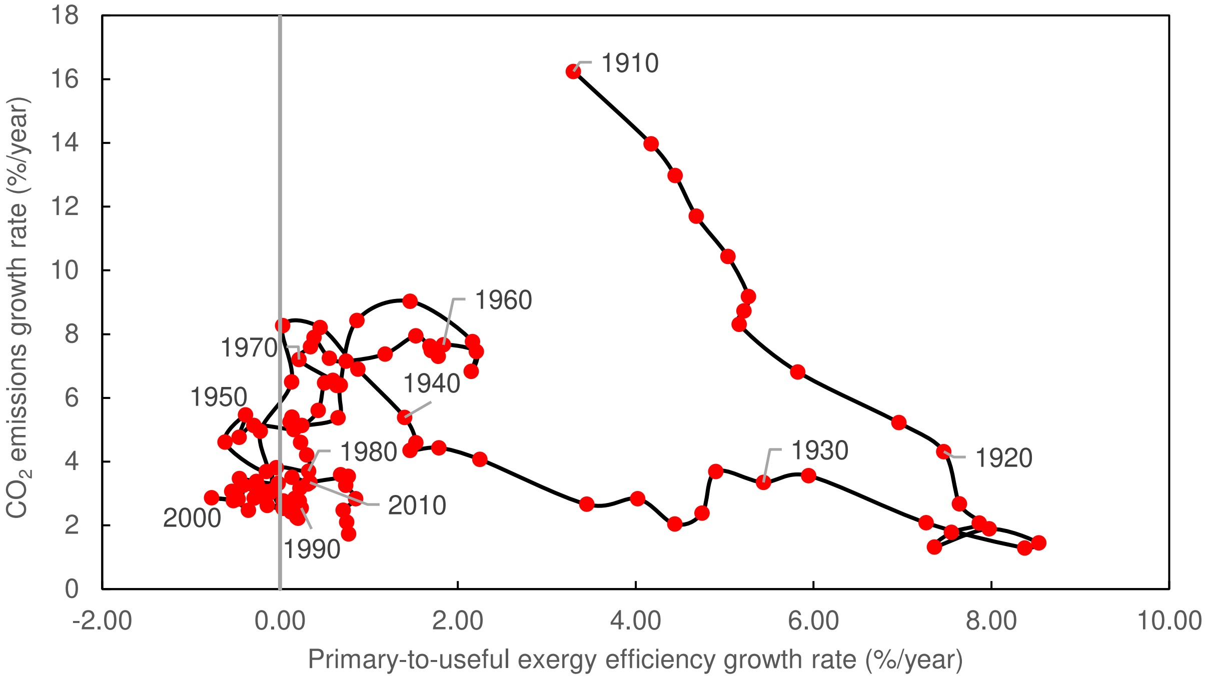

Figure 15: Annual growth rates of CO_2 emissions and primary-to-useful exergy efficiency shown as 10-year moving averages (1910 represents the average annual growth rate between 1901 and 1910).

Figure 16 shows three distinct periods. In 1910–1927, CO_2 growth rates are considerably lower than electricity production growth rates. For 1936–1996, CO_2 growth rates are very similar, although smaller, to electricity production growth rates. In the third period (1996–2005), CO_2 growth rates are slightly higher than electricity production growth rates because of negative growth rates in primary-to-useful exergy efficiency and a decrease in the share of electricity production with no CO_2 emissions.

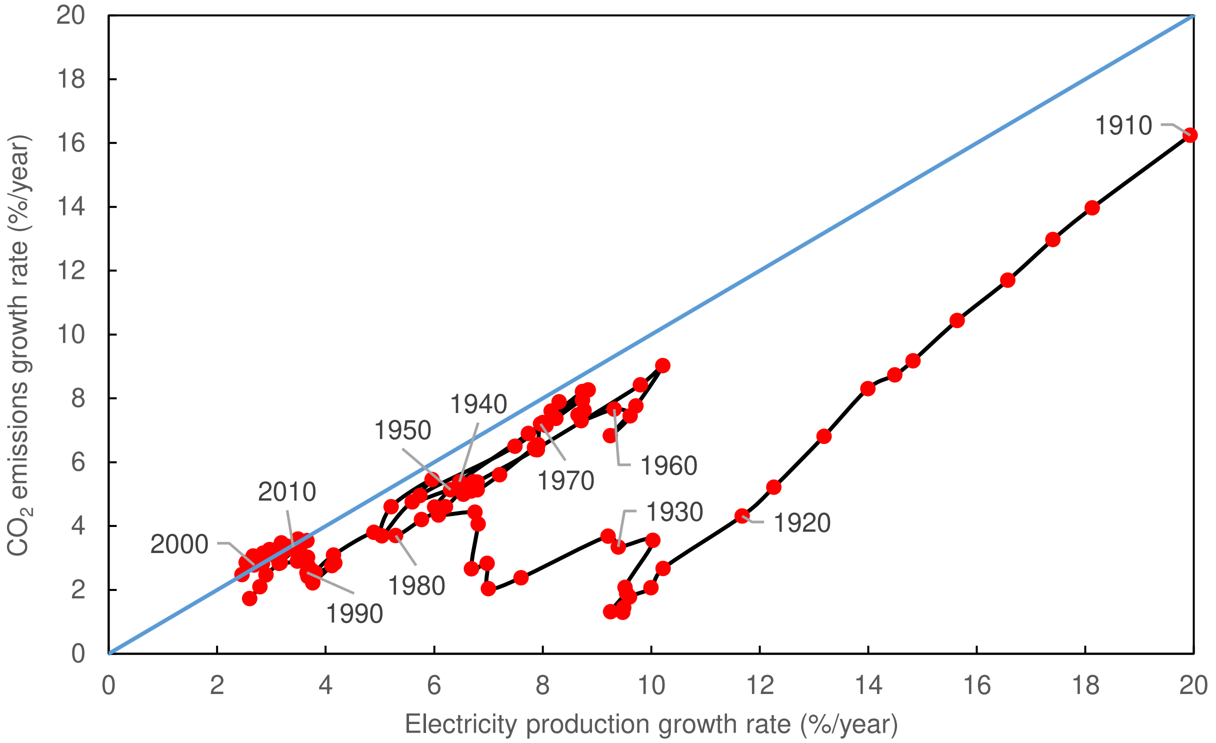

Figure 16: Annual growth rates of CO_2 emissions and electricity production shown as 10-year moving averages. The blue line shows equal growth rates.

4. Discussion

4.1. Historical perspective

The construction of the world long-run electricity production and consumption database enables consideration of the evolution of electricity production, consumption, and efficiency since the beginning of the 20th century. We see two distinct periods: 1900–1950 and 1950–2017.

Between 1900 and 1950, over 85% of the world electricity was produced from coal and hydro sources, with approximately constant shares (Figure 7). From 1900 to 1950 primary-to-final exergy efficiency increased significantly, from 6% to 31%, caused by efficiency improvements in thermal power plants (blue line Figure 11). During this period, the industrial sector increased its share of electricity consumption at the expense of the transport sector. Within the industrial sector, iron and steel decreased its share more than 10% (Figure 8). These sectoral changes influence end-uses, with significant increases in the share of machine tools and pumps and cooling end-uses, while end-uses for transport and HTH decreased their share significantly (Figure 9). Final-to-useful exergy efficiency only slightly increased from 1900 (44%) to 1950 (47%) (orange line Figure 11), due to efficiency dilution effects. Final-to-useful exergy efficiency reached a peak in 1940 and declined thereafter (orange line Figure 11). Primary-to-useful exergy efficiency, the product of both efficiencies, increased sharply, mostly due to the increase of primary-to-final exergy efficiency (grey line Figure 11). Carbon intensity decreased to 0.85 $kgCO_2/kWh$ (CIF) and 2.13 $kgCO_2/kWh$ (CIU) respectively by 1950, less than 1/5th of their 1900 values, mainly because of primary-to-final efficiency improvements (orange and blue lines Figure 14). Nonetheless, CO_2 emissions increased 24-fold during this period due to the near 150-fold increase in electricity production (grey line Figure 14 and green line Figure 7).

In the second period (1950–2017), electricity production from nuclear, oil, and (more recently) natural gas sources rose in prominence. Whilst in the last decade (2007–2017) solar and wind have become more important, their combined share remains less than 10% (Figure 7). Primary-to-final exergy efficiency increased significantly in the 1950-1960 decade, due to efficiency improvements in thermal power plants, and stabilized until 1970 (blue line Figure 11). After an increase in the early 1970s, primary-to-final exergy efficiency stalled during the following 40 years, rising slightly after 2005 (blue line Figure 11) because of increasing (a) fossil fuel thermal powerplant efficiency and (b) share of solar/wind based electricity – which via the PCM method assumes 100% primary-to-final efficiency. Comparative results using PSM and RCM methods show similar results and can be seen in section 3.2 of the SI A.

Throughout 1950–2017, residential and commercial sectors increased their shares of electricity consumption, at the expense of industrial sector (Figure 8). These sectoral changes have impacted end-uses as seen in the significant increase of the LTH end-use associated with the increase of the residential and commercial sectors (Figure 9). On the other hand, the share of the machine tools and pumps end uses decreased sharply due to the decrease in share of the industrial sector (Figure 9). Between 1950 and 2017, cooling end-use share grew only 3% but experienced a change in relative importance of its two constituents: the relative weight of refrigeration reduced, while space cooling grew. Final-to-useful exergy efficiency varied between 46% and 50% during this period but remained overall stable (orange line Figure 11). Primary-to-useful exergy efficiency increased until 1960, caused by the increase in primary-to-final exergy efficiency and stabilized afterwards (grey line Figure 11). In 2017, carbon intensity was almost half the 1950 value (orange and blue lines Figure 14). CIF declined continuously until 1985. From 1950–1970, the decline is caused by growing primary-to-final efficiency. From 1971–1985, carbon intensity improvements are explained by an increase in the share of electricity production with no CO_2 emissions, mostly nuclear power. Although carbon intensity stabilized between 1985 and 2014 (orange and blue lines Figure 14), electricity production was not flat (green line in Figure 7). In fact, electricity production more than doubled and therefore total electricity-based CO_2 emissions also more than doubled, between 1985 and 2014. The most recent decline in carbon intensity (2014–2017) is caused by growth in wind and solar electricity.

4.2. Electricity efficiency

Efficiency, at the final-to-useful stage, is thought to be a key driver of decarbonisation [2], but our results show that despite 117 years of technological evolution, efficiency gains have not decreased CO_2 emissions (Figure 15). With the exception of the commercial sector, all sectoral and aggregate efficiencies grew throughout 1990–2017 (Figure 13).

Two different stories have unfolded: primary-to-final exergy efficiency increased by a factor of 7, mainly in the period 1900-1960, and staying quite stable thereafter. Final-to-useful exergy efficiency increased only slightly during the whole period from 44% (1900) to 47% (2017). This near stagnation was due to efficiency dilution, where less efficient end uses (LTH and cooling) in residential and commercial sectors offset efficiency gains of end-use devices.

To our knowledge, this study is the first to estimate world electricity production and consumption efficiency over a long period. Other studies have looked to specific countries for shorter time periods. The results obtained for final-to-useful exergy efficiency for the USA in Ayres et al.[18] also show that final-to-useful exergy efficiency remained approximately constant during 1900–2000, due to the increase in LTH end uses. Felício et al.[19] show Portugal's final-to-useful efficiencies are similar in 1900 and 2014, between those two years there is variation but in the beginning (1900) and in the end (2014) of the period final-to-useful efficiencies are both close to 30% . However, while world final-to-useful exergy efficiency has remained constant since 2000, Portugal's show a continuous decrease, due to the growth of the residential sector share. Our world results do not show a decrease in primary-to-final exergy efficiency as did the long-term study for Japan [21], because hydro was not as significant at the world level as in Japan. Regarding primary-to-useful exergy efficiency, we estimate an increase of 1% for 1960–2010, in line with the result for China [24], USA, and UK [22].

Electricity consumption is expected to rise from 19 % in 2022 to more than 40% of total final energy consumption by 2050 [2,63]. The increase of electrification will contribute to an increase in the aggregate final-to-useful exergy efficiency, because electricity end-uses typically have higher final-to-useful exergy efficiencies compared to other end uses. Additionally, the mix of end-uses provided by electricity will change significantly.

4.3. Transitions

The time series of world electricity production and consumption shows historical energy transitions and provides insight into future energy transitions, in particular electrification, renewables, and efficiency as potential drivers of decarbonization. In the future, electrification of end-uses will create structural changes to electricity consumption, with an increase in the share of electricity consumption for the transport sector. Indeed, the transport sector share is expected to reach over 20% of total electricity consumption by 2050, while commercial and residential sectors are expected to decrease their share [63]. Under those assumptions, aggregate world final-to-useful exergy efficiency will increase because the transport sector is expected to remain more efficient than the commercial and residential sectors (Figure 13).

Electrification of end-uses (combined with a switch to renewables-based sources) is key to decarbonization as a result electricity production is forecast to double between 2020 and 2050 [63]. The past rate of increase in electricity production was in line with these figures, electricity generation doubled between 1990 and 2017.

But will electrification and efficiency be enough to meet decarbonization needed? Figure 15 shows efficiency alone has never been sufficient to decrease CO_2 emissions, with no observed historical correlation between rising primary-to-useful exergy efficiency and CO_2 emissions decline (Figure 15). Our results suggest electrification and efficiency must be linked with a deep renewables transition if decarbonization is to occur.

We know that electrification of end uses and the transition to renewables must happen quickly (10–20 years) to meet Paris climate objectives. However, Figure 7 shows that transition has been slow and, too small to reduce electricity-related CO_2 emissions, which have increased almost every year. On average across 1900–2017, 60% of electricity was produced using fossil fuels (Figure 7). There has been slowly increasing share of oil-based electricity in the 1960s and early 1970s, nuclear electricity in the 1970s and

1980s, and natural gas based electricity in the 1990s until 2010. Recently, there is a small increase in the share of renewables. Whilst moving through coal-oil-nuclear-gas and now to renewables are positive steps, past transitions have not been sufficiently large to reduce electricity-related CO_2 emissions, which have increased almost every year (grey line Figure 14).

Carbon intensity is an insufficient metric to assess transitions, if the goal is reducing CO_2 emissions. During 1900–2017, world carbon intensity dropped by around 90% (orange and blue lines Figure 14), a result similar to Felício et al. [19] results for Portugal. Ang and Su [64] found similar results at the world level 1990–2013. However, carbon emissions increased 380-fold since 1900, as electricity production had a much larger (4000-fold) increase since 1900. Historically, rising demand for electricity (driven by economic growth and electrification of end-uses) has always outstripped the capability of efficiency to reduce CO_2 emissions.

In 2017, carbon intensity of electricity production was 0.49 $kgCO_2/kWh$. Using the IRENA scenario for 2050 [2] a carbon intensity of 0.10 $kgCO_2/kWh$ is required, implying a further reduction of 0.39 $kgCO_2/kWh$ - a fifth of its current value, in less than 40 years. When we compare to the decrease of 0.12 $kgCO_2/kWh$ between 1977 and 2017, the tremendous challenge ahead is obvious. The necessary speed of decrease of carbon intensity to meet Paris objectives is unprecedented.

4.4. Limitations

There are several limitations to note. Information regarding end-uses was scarce, leading to necessary approximations to complete this study. The impacts of the missing information on final-to-useful exergy efficiency are discussed below.

Final-to-useful exergy efficiency depends on the allocation to sectors, and it also depends on the allocation to end-uses within the sectors. Regarding allocation to sector, IEA data was available after 1971 [47], while before 1971 information for various countries was collected as described in sections 2.3 of this manuscript and 2.1 of SI A. Considering allocation to end-uses within each sector and subsector, we assumed the USA as a proxy, except for the industrial sector where we used the allocation to subsectors that were country-specific. For the residential and commercial sectors, we used USA data to allocate sectoral consumption to end-uses. Although the USA is unlikely to be representative of the sectoral electricity consumption patterns in every country, errors associated with this assumption are minimized at the world level, because the USA consumes a large share (36%) of world electricity production on average over the time period of this study.

To check the sensitivity of our results to the allocation to end-uses within the residential sector, we replaced allocations for every country except the US with allocations for Portugal [19]. The results obtained were only modestly different. For example, using Portugal's allocations yielded average final-to-useful exergy efficiency of 47.1% compared to 48.4% using US allocations. The differences between the two final-to-useful exergy efficiency curves can be seen in section 3.4 of the SI A.

5. Conclusions

We believe this study is the first to estimate world long-term time series for electricity consumption and production, exergy efficiency, and carbon intensity of electricity. The most striking finding is that overall primary-to-useful exergy efficiency has stalled, rising dramatically from 2% in 1900 to 15% in 1960, and remaining stable for the last 50 years, only reaching 17% by 2017. The rapid efficiency gain in the 1900-1960 period was due to the rise in primary-to-final electricity efficiency (mainly due to improvements in power station efficiency), as final-to-useful exergy efficiency was stable, with an average of 48%, over 1900–2017. In the last 50 years, the stagnation of both electricity generation (primary-to-final) exergy efficiency and end use (final-to-useful) exergy efficiency means that the overall (primary-to-useful) electricity efficiency has remained stable (15–17%) since 1960. The cause of the final-to-useful exergy efficiency stagnation is efficiency dilution caused by structural and end-use change. For example, increasing share of low temperature heating (at low efficiency) caused by increasing share of overall electricity consumption in the residential and commercial sectors. Carbon intensities decreased significantly, mainly due to increases in power station (primary-to-final) energy conversion efficiency, being at the final and useful energy stages less than 10% of their 1900 values. However, to reach climate goals, a significant decrease in carbon intensity to 20% of current values is necessary up to 2050.

Finally, there are three key implications of our results for decarbonisation. First, the rate of increase in electricity production in the past decades, 2.9%/year between 1990 and 2017, is higher than the rate that is needed for the electrification of the world energy system to meet Paris objectives, 1.8%/year. However, secondly, the rate of change in electricity generation mix (to modern renewable electricity, e.g. solar and wind) necessary to reach climate goals is unprecedented. Third, final-to-useful electricity efficiency has been quite stable since 1900, suggesting that anticipated gains via electrification may be offset by continued end-use dilution, unless there is also a change to lower intensity energy services. However, gains in primary-to-useful exergy efficiency in the past did not lead to a reduction of CO_2 emissions associated with electricity consumption and production, casting doubt on the reliance upon efficiency to reduce CO_2 emissions.

Lastly, our results raise crucial questions for future energy transitions. It is known that the key drivers of previous transitions have been demand-sided, especially cheaper and/or better energy services [65]. (e.g., electricity-altered production processes allowed radical reconfigurations of the factory floor [65]). It seems fair to ask whether electrification of transport and heating end uses could be similarly driven at sufficient speed by a demand-side clamour for improved transportation and heating services. If so, will climate policies be sufficient to effect a supply-side transition to renewable sources for electricity generation at sufficient speed to keep pace with demand-side electrification? Both electrification of end uses and a transition to renewables are required to meet Paris targets. The results presented above show that doing both at sufficient speed will be unprecedented.

Acknowledgments

The authors are grateful to Zeke Marshall for the help with cooling data and efficiency; to Roger Fouquet for the help with UK data; and to Laura Felício and Tiago Domingos for their insightful suggestions.

Ricardo Pinto’s work was supported by Fundação para a Ciência e Tecnologia through the individual research grant SFRH/BD/146923/2019. Paul Brockway's time was funded by the UK Research and Innovation (UKRI) Council, supported under EPSRC Fellowship award EP/R024254/1. Sofia Henriques acknowledges the generous support of Handelsbanken and Crafoord foundation for the projects “Energy use and economic growth: a long-run European study 1870-2013”.

Supplementary information

The supplementary information is divided in two documents. The first is a *word* document entitled “SI A Methodology and supplementary results” were details about the methodology and some additional results are presented. The second is an *excel* document entitled “SI B data” and contains the data used to build the graphs displayed in this manuscript. It is available at link TBD

6. References

[1] De Stercke S. Dynamics of Energy Systems: a Useful Perspective. IIASA Interim Report,IIASA: 2014.

[2] International Renewable Energy Agency (IRENA). Global Energy Transformation: A roadmap to 2050. 2018.

[3] IEA (International Energy Agency). World Energy Outlook 2018. 2018.

[4] Goh T, Ang BW, Su B, Wang H. Drivers of stagnating global carbon intensity of electricity and the way forward. Energy Policy 2018;113:149–56. https://doi.org/10.1016/j.enpol.2017.10.058.

[5] Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V, et al. Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nat Clim Chang 2015;5:519–27. https://doi.org/10.1038/nclimate2572.

[6] IEA, International Renewable Energy Agency (IRENA), UNSD, World Bank, WHO. Tracking SDG 7: The Energy Progress Report 2020. Washington DC: 2020.

[7] Brockway PE, Sorrell S, Semieniuk G, Heun MK, Court V. Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. Renew Sustain Energy Rev 2021;141:110781. https://doi.org/10.1016/j.rser.2021.110781.

[8] Santos J, Domingos T, Sousa T, St. Aubyn M. Useful Exergy Is Key in Obtaining Plausible Aggregate Production Functions and Recognizing the Role of Energy in Economic Growth: Portugal 1960–2009. Ecol Econ 2018;148:103–20. https://doi.org/10.1016/j.ecolecon.2018.01.008.

[9] Herring H. Energy efficiency - A critical view. Energy 2006;31:10–20. https://doi.org/10.1016/j.energy.2004.04.055.

[10] Waite M, Cohen E, Torbey H, Piccirilli M, Tian Y, Modi V. Global trends in urban electricity demands for cooling and heating. Energy 2017;127:786–802. https://doi.org/10.1016/j.energy.2017.03.095.

[11] Van Heddeghem W, Lambert S, Lannoo B, Colle D, Pickavet M, Demeester P. Trends in worldwide ICT electricity consumption from 2007 to 2012. Comput Commun 2014;50:64–76. https://doi.org/10.1016/j.comcom.2014.02.008.

[12] Sousa T, Brockway PE, Cullen JM, Miller J, Cabrera A, Domingos T. The Need for Robust, Consistent Methods in Societal Exergy Accounting. Ecol Econ 2017;141:11–21. https://doi.org/10.1016/j.ecolecon.2017.05.020.

[13] Serrenho AC, Warr B, Sousa T, Ayres RU, Domingos T. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. Struct Chang Econ Dyn 2016;36:1–21. https://doi.org/10.1016/j.strueco.2015.10.004.

[14] Serrenho AC, Sousa T, Warr B, Ayres RU, Domingos T. Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009. Energy 2014;76:704–15. https://doi.org/10.1016/j.energy.2014.08.068.

[15] Ferguson R, Wilkinson W, Hill R. Electricity use and economic development. Energy Policy 2000;28:923–34. https://doi.org/10.1016/S0301-4215(00)00081-1.

[16] Ayres RU, Ayres LW, Warr B. Exergy, power and work in the US economy, 1900 – 1998. Energy 2003;28:219–73. https://doi.org/10.1016/S0360-5442(02)00089-0.

[17] Heun MK, Brockway PE. Meeting 2030 primary energy and economic growth goals: Mission impossible? Appl Energy 2019;251:112697. https://doi.org/10.1016/j.apenergy.2019.01.255.

[18] Ayres RU, Ayres LW, Pokrovsky V. On the efficiency of US electricity usage since 1900. Energy 2005;30:1092–145. https://doi.org/10.1016/j.energy.2004.07.012.

[19] Felício L, Henriques ST, Domingos T, Serrenho AC, Sousa T. Insights from Past Trends in Exergy Efficiency and Carbon Intensity of Electricity: Portugal, 1900–2014. Energies 2019. https://doi.org/10.3390/en12030534.

[20] Guevara Z, Sousa T, Domingos T. Insights on energy transitions in Mexico from the analysis of useful exergy 1971–2009. Energies 2016;9. https://doi.org/10.3390/en9070488.

[21] Williams E, Warr B, Ayres RU. Efficiency dilution: Long-term exergy conversion trends in Japan. Environ Sci Technol 2008;42:4964–70. https://doi.org/10.1021/es0716756.

[22] Brockway PE, Barrett JR, Foxon TJ, Steinberger JK. Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010. Environ Sci Technol 2014;48:9874–81. https://doi.org/10.1021/es501217t.

[23] Eisenmenger N, Warr B, Magerl A. Trends in Austrian Resource Efficiency: An Exergy and Useful Work Analysis in Comparison to Material Use, CO 2 Emissions, and Land Use. J Ind Ecol 2017;21:1250–61. https://doi.org/10.1111/jiec.12474.

[24] Brockway PE, Steinberger JK, Barrett JR, Foxon TJ. Understanding China's past and future energy demand: An exergy efficiency and decomposition analysis. Appl Energy 2015;155:892–903. https://doi.org/10.1016/j.apenergy.2015.05.082.

[25] Cullen JM, Allwood JM. The efficient use of energy: Tracing the global flow of energy from fuel to service. Energy Policy 2010;38:75–81. https://doi.org/10.1016/j.enpol.2009.08.054.

[26] Nakićenović N, Gilli PV, Kurz R. Regional and global exergy and energy efficiencies. Energy 1996;21:223–37. https://doi.org/10.1016/0360-5442(96)00001-1.

[27] Palma M, Sousa T, Guevara Z. How much detail should we use to compute societal aggregated exergy efficiencies? Energies 2016;9. https://doi.org/10.3390/en9050364.

[28] Etemad B, Luciani J, Bairoch P, Toutain J-C. World Energy Production. Switzerland: DROZ; 1991.

[29] Dominion Bureau of Statistics. The Canada Year Book. 1925-1977: 1925.

[30] Statistischen reichsamt. Statistisches Jahrbuch für das Deutsche Reich. 1928-1941: 1928.

[31] Staatlichen zentralverwaltung für statistik. Statistisches Jahrbuch der Deutschen Demokratischen Republik. 1955-1971: 1955.

[32] Statistisches bundesamt. Statistisches Jahrbuch für die Bundesrepublik Deutschland. 1953-1972: 1953.

[33] Japan Statistics Association. Historical Statistics of Japan, 1868-1984 2001. https://warp.da.ndl.go.jp/info:ndljp/pid/11423429/www.stat.go.jp/english/data/chouki/10.html (accessed February 17, 2020).

[34] Mitchell BR. European Historical Statistics 1750–2010. MacMillan. London: 2013.

[35] Department of Energy & Climate Change (DECC). Historical electricity data: 1920 to 2019 2013. https://www.gov.uk/government/statistical-data-sets/historical-electricity-data (accessed January 22, 2020).

[36] United States Bureau of the Census. Historical statistics of the United States, colonial times to 1970. Bicentennial Ed. Washington, DC: United States Government Printing Office: 1975.

[37] U.S.S.R Commitee for International Scientific and Technical Conferences. Electrical power development in the USSR. INBA publishing society; 1936.

[38] National Foreign Assessment Center. USSR: Development of the Gas Industry. A research paper. The center; 1978.

[39] Wilson D. The demand for energy in soviet union. Rowman & Allanheld; 1983.

[40] Institut national de la statistique et des Études Économiques. Annuaire statistique de la France 1966.

[41] Instituto Nacional Estadistica. Anuario estadistico de España. 1930-1961: 1930.

[42] Malanima P. Energy Consumption in Italy in the 19th and 20th Centuries: A Statistical Outline. 2006.

[43] Italian National Institute of Statistics. Gross electricity production and final electricity consumption in Italy - Years 1883-2014 2015. http://seriestoriche.istat.it/index.php?id=1&no_cache=1&L=1&no_cache=1&tx_usercento_centofe%5Bcategoria%5D=31&tx_usercento_centofe%5Baction%5D=show&tx_usercento_centofe%5Bcontroller%5D=Categoria&cHash=579686ba1e4b0850cf494bfb15f55d77 (accessed March 14, 2020).

[44] Isabel Bartolomé Rodríguez. La Industria Eléctrica en España (1890- 1936). Estud Hist Económica - Banco España 2007;50:165.

[45] Bordes J. Les barrages en France du XVIII è à la fin du XX è siècle Histoire , évolution technique et transmission du savoir 1994:70–120.

[46] Organisation for European Economic Co-operation (OEEC). The Electricity Supply Industry in Europe. 1955.

[47] International Energy Agency (IEA). Extended world energy balances. IEA World Energy Stat Balanc 2018. https://doi.org/https://doi.org/https://doi.org/10.1787/data-00513-en.

[48] Castelli F. Developments in the use of fuels for thermal power generation in Italy. Sixth world Power Conf., 1962.

[49] Norwegian Water Resources and Energy Directorate. Utbygd vannkraft i Norge. Oslo: Norges Vassdrags- Og Elektrisitetsforening: 1946.

[50] Statistisk Sentralbyra. Statistisk årbok for Norge. 1940-1970: 1940.

[51] Kander A, Malanima P, Warde P. Power to the People: Energy in Europe over the Last Five Centuries. 2013. https://doi.org/10.1017/S0022050715001011.

[52] Rubio MDM, Tafunell X. Latin American hydropower: A century of uneven evolution. Renew Sustain Energy Rev 2014;38:323–34. https://doi.org/10.1016/j.rser.2014.05.068.

[53] Ertesvåg IS, Mielnik M. Exergy analysis of the Norwegian society. Energy 2000;25:957–73. https://doi.org/10.1016/S0360-5442(00)00025-6.

[54] Bureau of census and statistics. Union Statistics for fifty years. Pretoria: 1960.

[55] World Power Conference. Statistical Year Book of the World Power Conference No.8. 1956.

[56] World Power Conference. Statistical Year Book of the World Power Conference No. 9. 1960.

[57] Urquhart MC, Buckley KAH. Historical statistics canada.pdf 1965.

[58] Statistiska centralbyrån. Statistisk årsbok för Sverige. Stockholm; 1925.

[59] Union Internationale des Producteurs et Distributeurs D'Énergie Électrique (UNIPEDE). Statistiques. (Several Issues) Years between 1937 and 1952: 1937.

[60] Heun MK, Marshall Z, Aramendia E, Brockway PE. The energy and exergy of light with application to societal exergy analysis. Energies 2020;13:1–24. https://doi.org/10.3390/en13205489.

[61] Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K. IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy. Japan: Institute for Global Environmental Strategies; 2006.

[62] Dahmus JB. Can Efficiency Improvements Reduce Resource Consumption?: A Historical Analysis of Ten Activities Dahmus Can Efficiency Improvements Reduce Resource Consumption? J Ind Ecol 2014;18:883–97. https://doi.org/10.1111/jiec.12110.

[63] IEA (International Energy Agency). Net Zero by 2050. Paris: 2021.

[64] Ang BW, Su B. Carbon emission intensity in electricity production: A global analysis. Energy Policy 2016;94:56–63. https://doi.org/10.1016/j.enpol.2016.03.038.

[65] Fouquet R. The slow search for solutions: Lessons from historical energy transitions by sector and service. Energy Policy 2010;38:6586–96. https://doi.org/10.1016/j.enpol.2010.06.029.

The rise and stall of world electricity efficiency:1900-2017

Ricardo Pinto[a,*], Sofia T. Henriques[b], Paul E. Brockway[c], Matthew Kuperus Heun[d] and Tânia Sousa[a]

[a] MARETEC—Marine, Environment and Technology Center, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, 1, Lisboa 1049-001, Portugal
[b] CEFUP, Faculdade de Economia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-464, Porto, Portugal
[c] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom
[d] Engineering Department, Calvin University, 3201 Burton St. SE, Grand Rapids, MI 49546, USA

Supplementary Information A

In this SI, we present the following information:

Section 1: Methodology details about final energy stage

Section 2: Methodology details about useful energy stage

Section 3: Supplementary results

1. Final energy stage: Electricity production

1.1. Norway hydroelectricity

An estimate of hydroelectricity production, for the period between 1900 and 1936, was made using [1] a report with the installed capacity of all hydropower plants in use in 1943. Electricity production was estimated using the following equation:

$$Elec\ prod = W * 24 * 365 * Cf \qquad \text{A1}$$

Where W is the installed capacity and Cf is the capacity factor. The capacity factor was assumed to be equal to the current capacity factor if the hydropower plant is still in production otherwise the capacity factor was assumed to be 0.4 below modern average. Hydroelectricity production was also assumed to be at most 99% of total production, this value is the average of the first 10 years with data.

1.2. Transmission losses and energy industry own use

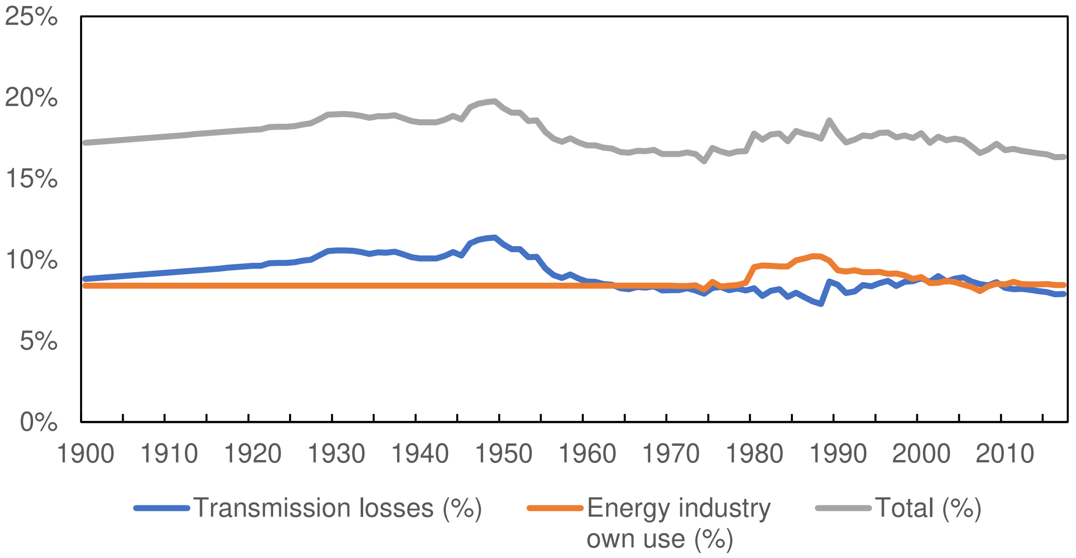

Figure A1: World average transmission losses and energy industry own use, as a percentage of energy production

2. Useful energy stage: Final exergy to useful exergy

Table A1: Date and sources of allocation per sectors/subsectors, for big and medium producers of electricity

	Sector/Subsector allocation			
	Data available prior to 1970	Start date/period	Source prior to 1960/1971	Source after 1960/1971
Australia	Yes	1948-1957	UNIPEDE [2]/ WPC [3,4]	IEA [5]
Austria	Yes	1937-1957	UNIPEDE [2]/ WPC [3,4]	IEA [5]
Canada	Yes	1930	Historical Statistics of Canada [6]	IEA[5]
China	No	-	-	IEA [5]
Czechoslovakia	No	-	-	IEA [5]
France	Yes	1926	France statistical yearbook [7]	IEA [5]
Germany	Yes	1925,1930 & 1933-1939	Germany statistical yearbook [8]	IEA [5]
Federal Republic of Germany (FRG)	Yes	1947-1959	FRG statistical yearbook [9]	IEA [5] until 1970
German Democratic Republic (GDR)	Yes	1956-1970	GDR statistical yearbook [10]	Included in data from IEA for FRG
India	Yes	1948-1957	UNIPEDE [2] / WPC [3,4] [2–4]	IEA [5]
Italy	Yes	1931-1959	Italy statistical Institute [11]	IEA [5]
Japan	Yes	1930-1959	Japan Historical Statistics [12]	IEA [5]
Norway	Yes	1915-1930 & 1932-1959	Norway statistical yearbook [13]	IEA [5]
Poland	Yes	1950-1957	UNIPEDE [2] / WPC [3,4]	IEA [5]
Portugal*	Yes	1900	Felício et al.[14]	Felício et al. [14]
South Africa	Yes	1917-1959	Union Statistics [15]	IEA [5]
Spain	Yes	1901-1959	Spain statistical yearbook[16]	IEA [5]
Sweden	Yes	1900-1959	Sweden official statistics [17]	IEA [5]
Switzerland	Yes	1937-1957	UNIPEDE [2]/ WPC [3,4]	IEA [5]
UK	Yes	1900-1913 / 1920-1959	Foquet / DECC [18]	IEA [5]
USA	Yes		Ayres 2005 [19]	IEA [5]
USSR	Yes	1926,1928,1930,1932, 1934 & 1935/ 1952-1957	Electric power development in the USSR [20] / WPC [3,4]	IEA [5]

*Although it is not a big or medium producer data for sectoral allocation was available and was used.

2.1. Allocation of electricity consumption to sectors and subsectors before 1971

Data was gathered from the various sources referenced on Table A1. This data was typically divided in sectors, depending on the sectoral division we assigned the electricity consumption to our corresponding subsector. We had 11 subsectors. In the transport sector we had 2 subsectors pipeline transport (used only after 1971) and transport A summary of this allocation is available at Table A2. In the industrial sector we had 3 subsector iron and steel, electrochemistry and electrometallurgy and other industries. In the "other" sector we had 6 subsectors residential, commercial and public services, public lighting, fishing, agriculture and forestry and non-specified other.

Regarding the industrial sector when no information about the separation was available, we allocated the consumption to other industries. In the "other" sector the data for residential and commercial subsectors was sometimes combined so in that case we assumed that the shares of commercial and residential was equal to the average of the countries were separated data was available. When data given was allocated to the non-specified other subsector, we assumed that it was distributed by all the subsectors of the "other" sector, and we allocated it based on the weight of each individual subsector within the "other" sector. A summary of this allocation is available at Table A3.

The last step necessary to obtain a world allocation by sector was to allocate: the countries that were small producers; countries with no information from the big and medium producers (China, Czechoslovakia) and years with no data for countries from the big and medium producers. The following method was used to do this allocation:

- Calculated the percentage of world transmission losses and energy industry own consumption (EIOC) for the first 5 years with IEA data (1971-1975);
- Calculated the average percentage of those 5 years and assumed that for 1970 the transmission losses and EIOC percentages were equal to that average;
- Used the USA evolution of transmission losses, obtained from [21], as a proxy to estimate the losses in the remaining years from 1900 to 1969, in other words, we assumed that the transmission losses in the world evolved (increased/decreased) at the same rate as the USA transmission losses;
- EIOC was always equal to the average of the first 5 years with (1971-1975);
- Multiplied the final electricity (final electricity from Etemad et al. and other sources as described in section 2.1 of the paper) by (1- (losses + EIOC)) to obtain the final electricity (available for consumers);
- Calculated the weighted shares of each subsector allocation, using the countries with allocation data;
- Multiplied the final electricity by the share of each subsector to obtain electricity consumed in each subsector.

Table A2: Allocation of the transport sector subsectors to the two subsectors considered.

Transport	Vehicle Transport	Pipeline Transport
Road	**X**	
Rail	**X**	
Pipeline transport		**X**
Non-specified (transport)	**X**	

Table A3: Allocation of the industrial sector to the three subsectors considered

Industry	Iron and Steel	Electrochemistry and electrometallurgy	Other industries
Iron and steel	**X**		
Chemical and petrochemical			**X**
Non-ferrous metals		**X**	
Non-metallic minerals			**X**
Transport equipment			**X**
Machinery			**X**
Mining and quarrying			**X**
Food and tobacco			**X**
Paper, pulp and print			**X**
Wood and wood products			**X**
Construction			**X**
Textile and leather			**X**
Non-specified (industry)			**X**

2.2. Allocation of electricity consumption to sectors and subsectors after 1971

Data from the IEA [5] was used to directly allocate electricity consumption to the 11 subsector mentioned above, in this period direct allocation by name to the individual subsectors was done. The only exception was the allocation of the non-ferrous metals to the electrochemistry and electrometallurgy subsector. Since IEA does not have public lighting consumption discriminated it was assumed that public lighting was one-eighth of the residential lighting consumption.

2.3. Allocation of electricity consumption to end-uses

After the allocation of electricity consumption to individual subsector it was necessary to allocate within each sector to end-uses. We considered the following 11 end uses: lighting, communication and electronics, electrochemical, high temperature heat (HTH), low temperature heat (LTH), cooling (including ventilation), transport, residential appliances, commercial appliances, and machine tools and pumps. USA and Portugal allocation within each sector had to be extend through 2017 this was done with the trend function available in *Microsoft office excel*.

Regarding the remaining countries the transport subsector was allocated to the transport end-use. The pipeline transport subsector was allocated to the machine tools and pumps end-use. Public lighting subsector was allocated to the lighting end-use. Both the agriculture and forestry and the fishing subsector were allocated to the machine tools and pumps end-use.

The industrial subsectors were allocated assuming a different main end-use: HTH for the iron and steel subsector, electrochemical for the electrochemistry and electrometallurgy and machine tools and pumps for the other industries and three other end-uses lighting, communication and electronics and cooling. These last three end-uses had shares equal to their share in the industrial sector of Ayres et al. [19], for that same year, and their shares were equal in all three subsectors, while the main end-use was the remaining share. In other words, all industrial subsectors had, in on specific year, the same share attributed to cooling, lighting, communication and electronics and each main end-use but these shares change on a yearly basis.

Concerning the residential and commercial subsectors, the share of each end-use within these subsectors was equal to the shares of individual end-uses within the same subsectors in Ayres et al. [19]. As stated, before when data for the residential and commercial subsectors was combined a weighted average using the countries with split data was used to allocate the combined data to the individual subsectors and afterwards the allocation to end-use was made assuming the same criteria as the remaining subsector. The non-specified subsector was allocated to the different subsectors inside the "other" sector, using a weighted average, and then the allocation to end-uses was made with the same conditions as the rest of the consumption in each of those subsectors.

A summary of the allocation to end-uses within each sector and subsector is shown in the following Tables A4-A6.

Table A4: Allocation to end uses within the transport subsectors.

TRANSPORT	Transport	Machine tools and Pumps
Pipeline transport	**-**	**X**
Vehicle Transport	**X**	**-**

Table A5: Allocation to end uses within the industrial subsectors.

INDUSTRIAL	Lighting	Communication and electronics	Electro- -chemical	HTH	Cooling	Machine tools and Pumps
Iron and Steel	**X**	**X**	**-**	**X**	**X**	**-**
Electrochemistry and electrometallurgy	**X**	**X**	**X**	**-**	**X**	**-**
Other industries	**X**	**X**	**-**	**-**	**X**	**X**

Table A6: Allocation to end uses within the other subsectors.

OTHER	Lighting	Communication and electronics	LTH	Cooling	Residential Appliances	Commercial Appliances	Machine tools and Pumps
Public lighting	X	-	-	-	-	-	-
Residential	X	X	X	X	X	-	-
Commercial and public services	X	X	X	X	-	X	-
Agriculture and Forestry	-	-	-	-	-	-	X
Fishing	-	-	-	-	-	-	X

2.4. Final-to-useful exergy efficiencies per end-use

Table A7: References of the efficiencies per end use

	References
Lighting	[22]
Communication and electronics	[19]
Electrochemical	[19]
HTH (high temperature heat)	Calculated (see section 2.3 of the main paper and text below)
LTH (low temperature heat)	
Cooling	
Transport	[19]
Residential Appliances	[19]
Commercial Appliances	[19]
Machine tools and Pumps	[19]

Regarding cooling exergy efficiencies, real COP values were taken from [23].

3. Supplementary results

3.1. Electricity consumption allocation within sectors/subsectors

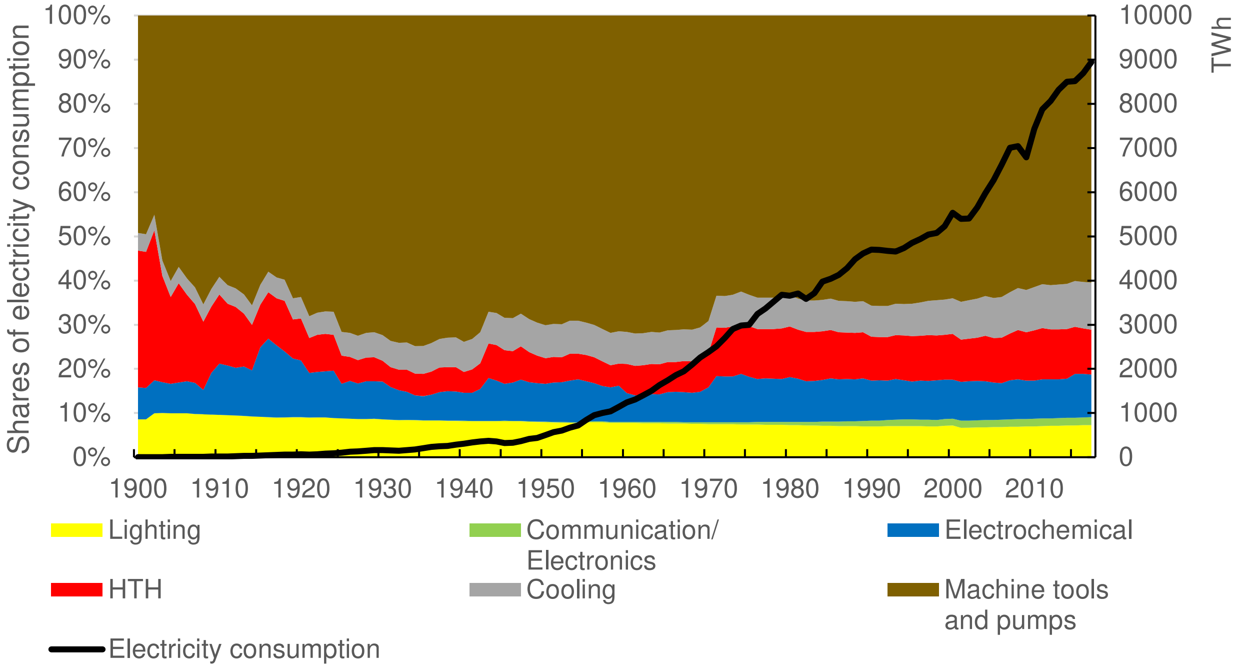

Figure A2: Shares of electricity consumption for the industrial sector per end use (left axis) and electricity consumption (right axis), between 1900-2017

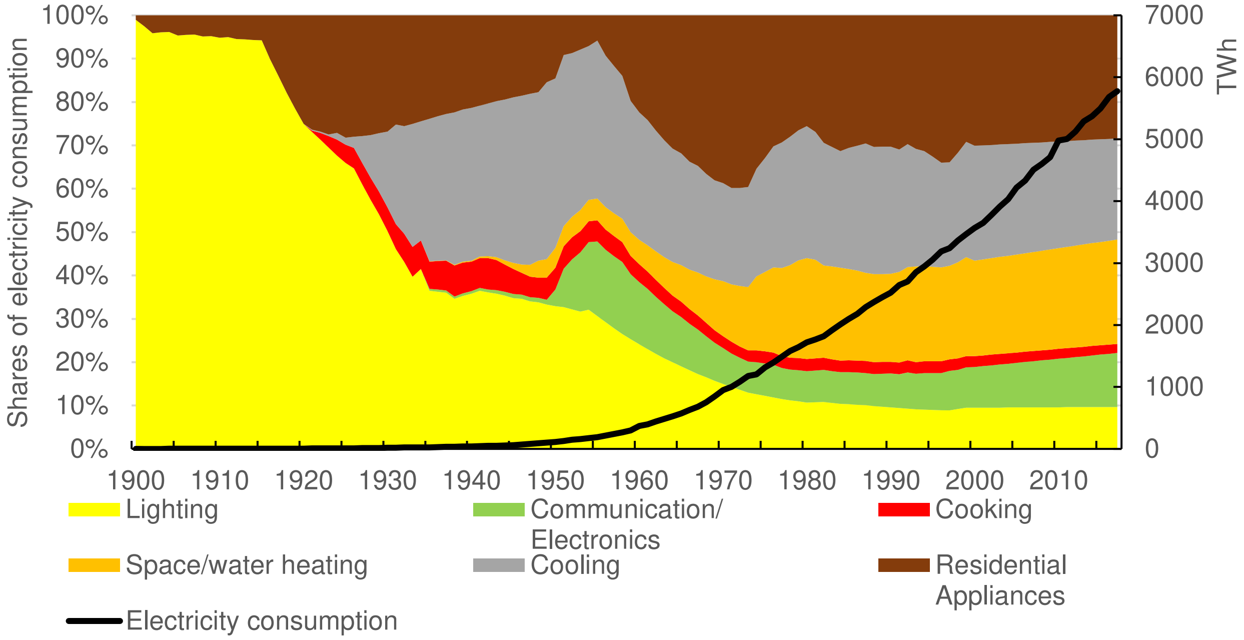

Figure A3: Shares of electricity consumption for the residential subsector per end use (left axis) and electricity consumption (right axis), between 1900-2017.

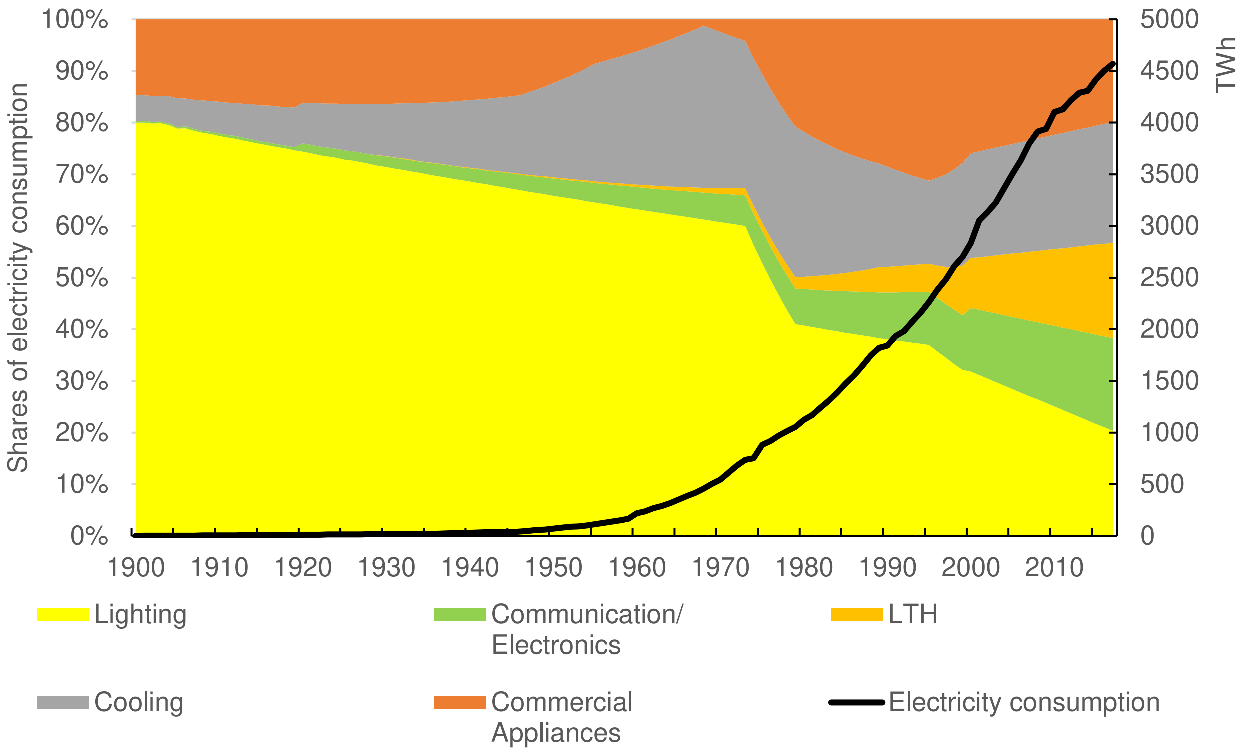

Figure A4: Shares of electricity consumption for the commercial subsector per end use (left axis) and electricity consumption (right axis), between 1900-2017

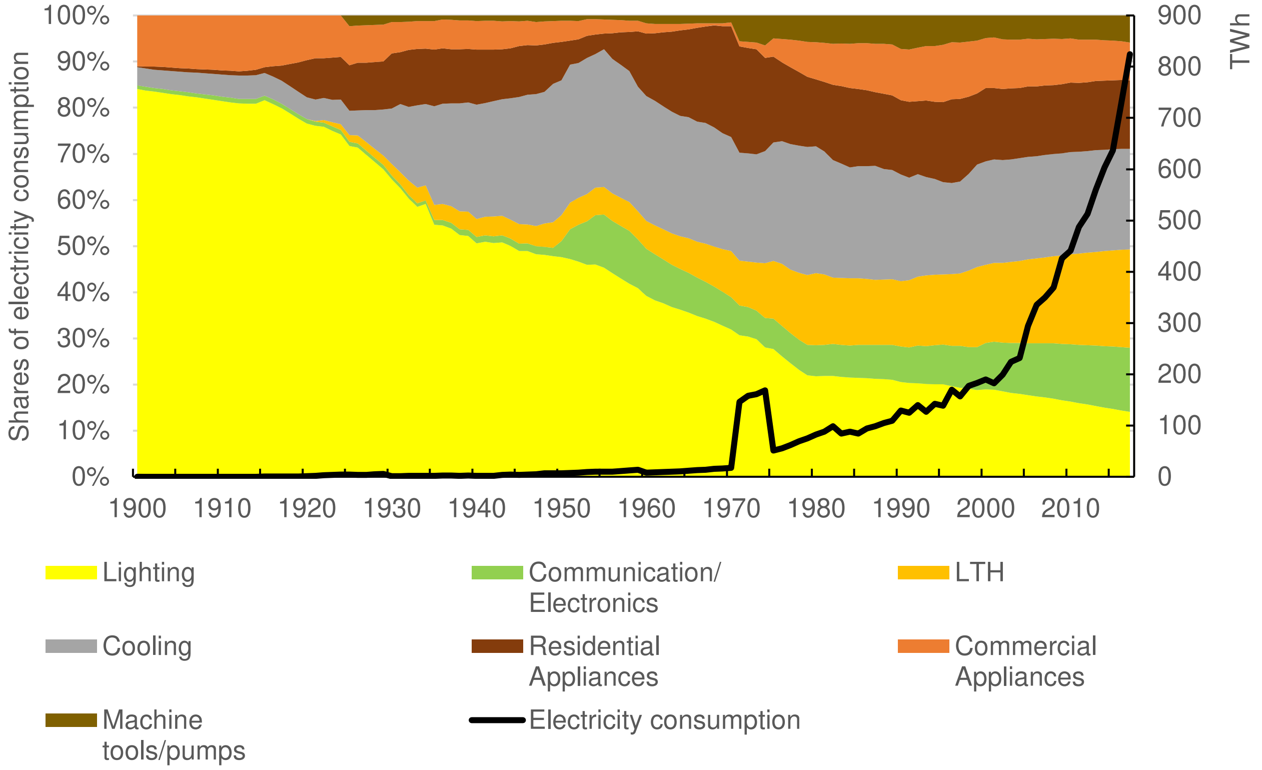

Figure A5: Shares of electricity consumption for the non-specified other subsector per end use (left axis) and electricity consumption (right axis), between 1900-2017

3.2. Primary-to-final exergy efficiency using different methods

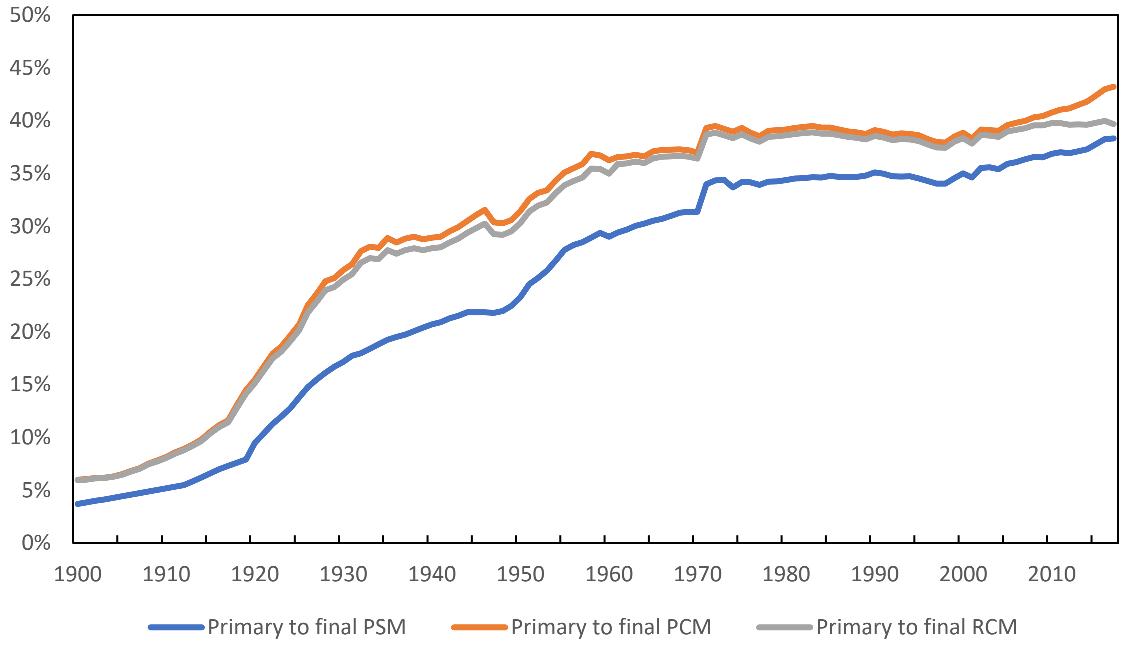

Figure A6: Primary to final efficiency using 3 different methods, PCM, RCM and PSM

Table A8: Primary to final efficiencies for the different methods

	Efficiencies primary to final		
	RCM	PCM	PSM
Coal and Coal products	Average of all countries until 1971, afterwards primary energy of fossil fuels is available from IEA		
Oil and Oil products			
Natural gas			
Combustible Renewables	estimated/IEA prim *		
Hydro	0.75/0.85 **	1	Aggregate thermoelectric efficiency
Wind	0.4	1	
Solar photovoltaic	0.15	1	
Solar thermal	0.1	1	
Wave	0.07	1	
Geothermal	0.15	0.15	0.15
Nuclear	0.33	0.33	0.33

*before 1989 efficiency equal to average efficiency of combustible renewables between 1989-1993, afterwards primary taken from IEA

**before 1960 efficiency equal to 0.75 afterwards equal to 0.85

Cells highlighted in yellow from Brockway et al. [24]

Cells highlighted in green from Felício et al. [14]

3.3. Annual growth rates

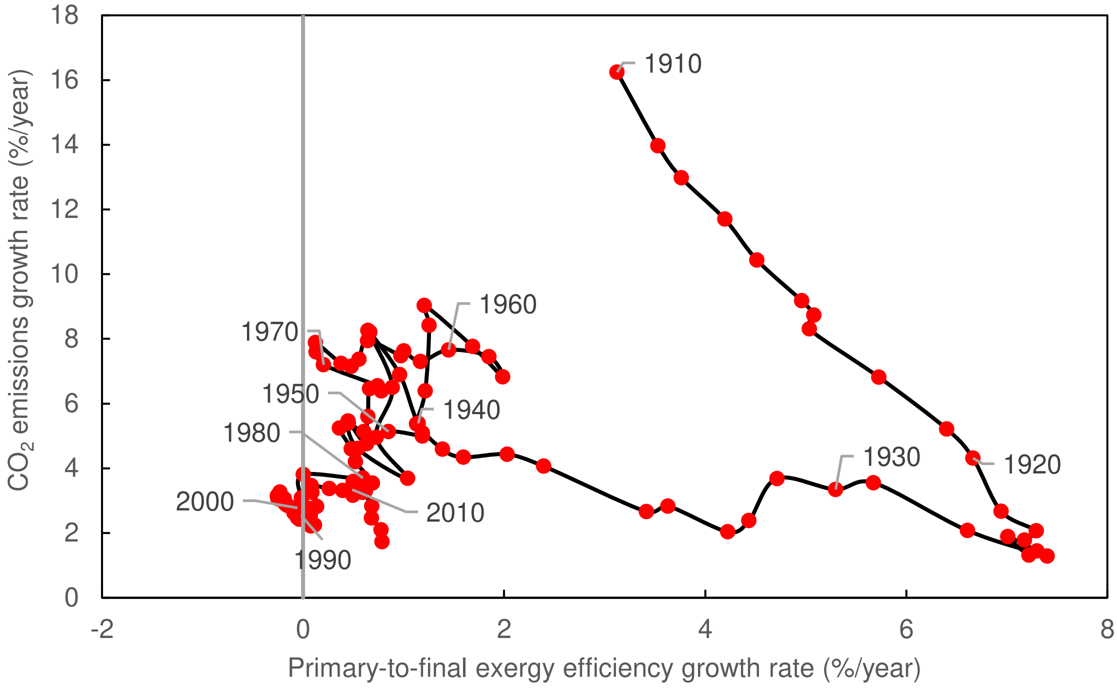

Figure A7: Annual growth rates of CO2 emissions and primary-to-final exergy efficiency shown as 10-year moving averages

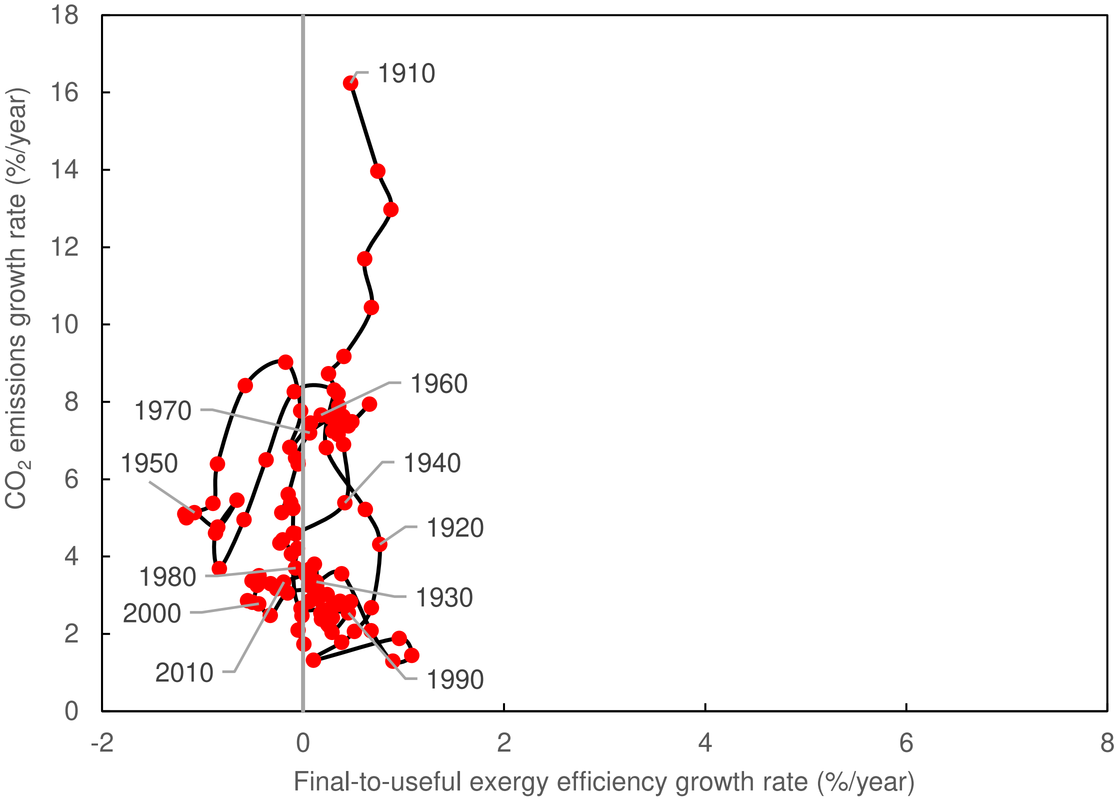

Figure A8: Annual growth rates of CO2 emissions and final-to-useful exergy efficiency shown as 10-year moving averages

3.4. World final to useful exergy efficiency using Portugal and USA residential allocation

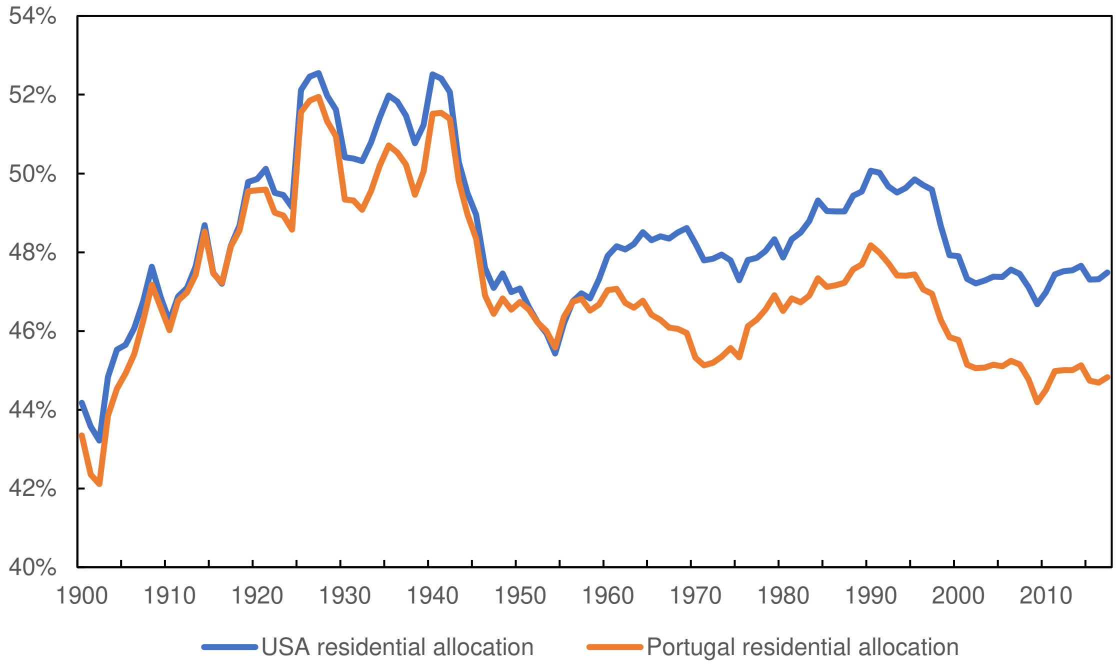

Figure A9: Comparison of world final to useful exergy efficiency using Portugal and USA residential allocation

References

[1] Norwegian Water Resources and Energy Directorate. Utbygd vannkraft i Norge. Oslo: Norges Vassdrags- Og Elektrisitetsforening: 1946.

[2] Union Internationale des Producteurs et Distributeurs D'Énergie Électrique (UNIPEDE). Statistiques. (Several Issues) Years between 1937 and 1952: 1937.

[3] World Power Conference. Statistical Year Book of the World Power Conference No. 9. 1960.

[4] World Power Conference. Statistical Year Book of the World Power Conference No.8. 1956.

[5] International Energy Agency (IEA). Extended world energy balances. IEA World Energy Stat Balanc 2018. https://doi.org/https://doi.org/https://doi.org/10.1787/data-00513-en.

[6] Urquhart MC, Buckley KAH. Historical statistics canada.pdf 1965.

[7] Institut national de la statistique et des Études Économiques. Annuaire statistique de la France 1966.

[8] Statistischen reichsamt. Statistisches Jahrbuch für das Deutsche Reich. 1928-1941: 1928.

[9] Statistisches bundesamt. Statistisches Jahrbuch für die Bundesrepublik Deutschland. 1953-1972: 1953.

[10] Staatlichen zentralverwaltung für statistik. Statistisches Jahrbuch der Deutschen Demokratischen Republik. 1955-1971: 1955.

[11] Italian National Institute of Statistics. Gross electricity production and final electricity consumption in Italy n.d. http://seriestoriche.istat.it/index.php?id=1&no_cache=1&L=1&tx_usercento_centofe%5Bcategoria%5D=31&tx_usercento_centofe%5Baction%5D=show&tx_usercento_centofe%5Bcontroller%5D=Categoria&cHash=579686ba1e4b0850cf494bfb15f55d77 (accessed January 14, 2020).

[12] Japan Statistics Association. Historical Statistics of Japan, 1868-1984 2001. https://warp.da.ndl.go.jp/info:ndljp/pid/11423429/www.stat.go.jp/english/data/chouki/10.html (accessed February 17, 2020).

[13] Statistisk Sentralbyra. Statistisk årbok for Norge. 1940-1970: 1940.

[14] Felício L, Henriques ST, Domingos T, Serrenho AC, Sousa T. Insights from Past Trends in Exergy Efficiency and Carbon Intensity of Electricity: Portugal, 1900–2014. Energies 2019. https://doi.org/10.3390/en12030534.

[15] Bureau of census and statistics. Union Statistics for fifty years. Pretoria: 1960.

[16] Instituto Nacional Estadistica. Anuario estadistico de España. 1930-1961: 1930.

[17] Statistiska centralbyrån. Statistisk årsbok för Sverige. Stockholm; 1925.

[18] Department of Energy & Climate Change (DECC). Historical electricity data: 1920 to 2019 2013. https://www.gov.uk/government/statistical-data-sets/historical-electricity-data (accessed January 22, 2020).

[19] Ayres RU, Ayres LW, Pokrovsky V. On the efficiency of US electricity usage since 1900. Energy 2005;30:1092–145. https://doi.org/10.1016/j.energy.2004.07.012.

[20] U.S.S.R Commitee for International Scientific and Technical Conferences. Electrical power development in the USSR. INBA publishing society; 1936.

[21] United States Bureau of the Census. Historical statistics of the United States, colonial times to 1970. Bicentennial Ed. Washington, DC: United States Government Printing Office: 1975.

[22] Heun MK, Marshall Z, Aramendia E, Brockway PE. The energy and exergy of light with application to societal exergy analysis. Energies 2020;13:1–24. https://doi.org/10.3390/en13205489.

[23] Marshall, Zeke, Heun M, Aramendia E, Brockway P, Franzius JI, Kim J, Phelps T, et al. A Multi-Regional Primary-Final-Useful (MR-PFU) energy and exergy database v1, 1960-2019. 2021.

[24] Brockway PE, Barrett JR, Foxon TJ, Steinberger JK. Divergence of trends in US and UK aggregate exergy efficiencies 1960-2010. Environ Sci Technol 2014;48:9874–81. https://doi.org/10.1021/es501217t.