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

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ABSTRACT

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. 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 significantly, from 0.1% (1900) to 4% by mid-century (1950), and 19% in 2022 [1,2]. Importantly, global electricity demand keeps rising, and is projected by the International Renewable Energy Agency (IRENA) to double between 2015 and 2050 [3]. While electricity generation doubled between 1990 and 2014 [4], carbon dioxide (CO_2) emissions associated with electricity increased only slightly less, 87%, from 6.28 $GtCO_2$ to 11.76 $GtCO_2$ [5]. To limit end-of-century warming to 1.5 °C [6] whilst meeting UN Sustainable Development Goal #7 (affordable and clean energy) [7], electrification, renewables, and energy efficiency are thought to be essential [3]. Electrification and renewables will mean rapid growth in electricity generation and consumption into the future, but energy efficiency is a complex and nuanced issue, with impacts on economic growth, energy rebound, and aggregate efficiency [8–10].

Electrification of end uses will enable widespread deployment of low-carbon, electricity-producing sources of energy, especially wind and solar. IRENA forecasts that, by 2050, 33% of final energy for transport will be provided by electricity, up from 1% in 2015 [3]. Buildings are also expected to increase their electricity demand by 70% until 2050, from their 2015 value, due to increased cooling demand, electrification of heating, and growing electricity consumption in developing countries [3,11]. Other forecasts propose scenarios which rely on near 100% electrification with renewables to reach climate targets, where demand for electricity is expected to more than double [12–14].

Beyond electrification, emerging end uses will add to future

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electricity demand, especially information and communication technology (ICT). For three specific categories of ICT (communication networks, personal computers, and data centres), Heddeghem et al. [15] found that between 2007 and 2012 electricity consumption from ICT uses 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%. The increase in electricity demand due to electrification and emerging energy uses will be partially controlled by energy efficiency.

1.2. The uncertainty of the impact of energy efficiency on electricity demand

Energy efficiency can be calculated between different stages of the energy conversion chain. Societies use primary energy such as coal in a thermoelectric power plant or wind energy in a wind farm to produce final energy in the form of electricity. Afterwards, electricity is transformed to useful energy such as light in lamps or heat in electric heaters or heat pumps.

The estimation of useful energy is crucial because it is closer to the energy services that people and firms want and therefore more closely tied to economic activity than final energy. As such, it is the appropriate stage at which to measure energy when the goal is understanding trends in the relationship between energy and economic activity, which is an essential step to make scenarios of the future energy transition. One can estimate the energy efficiency of each conversion, that is the ratio of "useful" energy output to "final" energy input. The higher the energy efficiency, the better. However, energy efficiency gives us incomplete information about potential energy savings. For example, the energy efficiency of an electric heater is 100% which suggests that there are no potential energy savings. However, this is not the case because a heat pump can provide the same output using ¼ of the electricity. Here, we address this issue using exergy efficiency which is also the ratio of useful output to input but using exergy to quantify energy. Exergy is a measurement of energy that quantifies the potential of an energy flow to do physical work [16]. For electricity and mechanical work, exergy is equal to the energy content because these types of energy can be completely converted into work. For heat, exergy content is lower than its energy because even an ideal Carnot machine cannot completely convert heat at a temperature T_H into work: it needs to reject some heat at a lower temperature T_C. The fundamental constraint in the conversion of heat into work is associated with the fact that heat carries both energy and entropy. Since entropy cannot be destroyed, the Carnot machine needs to reject heat to get rid of the entropy.

The use of exergy is important not only to estimate an efficiency that provides a meaningful measure of the potential energy savings because the maximum exergy efficiency is 100% but also because exergy efficiency and useful exergy have been empirically linked to economic growth [8]. Economies run on work that (as opposed to heat) shapes materials, assembles machines and products, and transports people, goods, and services throughout the economy. To a lesser extent, economies also consume heat. But heat can (and probably should) be supplied via a heat pump, which consumes work (usually in the form of electricity). Useful exergy is the amount of work (or electricity) needed as input to the economy when all potential energy savings have been accomplished.

Three recent studies illustrate the complexities of energy efficiency. First, Serrenho et al. [17,18] 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. [9] show that an increase in final-to-useful exergy efficiency makes a key contribution to higher GDP for Portugal. Third, Ferguson et al. [19] shows electricity consumption and economic development are strongly correlated for more than 100 countries between 1971 and 1995. Taken together, these three relationships imply increases in final-to-useful efficiency contribute to economic growth and, paradoxically, an increase in the demand of energy, a phenomenon known as energy rebound. Indeed, Ayres et al. [20] 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, depending on the presence of rebound effects [21].

Furthermore, the relationship between electricity efficiency and aggregate final-to-useful efficiency is complex [22]. In Portugal between 1900 and 2009, the aggregated final-to-useful efficiency was always lower than 25% [17], while final-to-useful efficiency for electricity was always above 30% [23]. Also, in Mexico between 1971 and 2009, electricity is the energy carrier with the highest final-to-useful efficiency [24]. The same occurred in the US where Ayres et al. [22] estimated a high stable, average value of 55%, for the final-to-useful US electricity efficiency between 1900 and 2000. Thus, the growing use of electricity increases aggregate final-to-useful exergy efficiency [25].

Regarding, primary-to-useful efficiency, Brockway et al. [26] analyse 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 [26]. In Portugal, the primary-to-useful efficiency of electricity increased between 1900 and 1990 but stagnated afterwards [23] due to increasing share of electricity consumed in less-efficient sectors, mainly residential and commercial.

This emerging picture of the role of useful exergy and efficiency on economic growth and energy consumption (and CO_2 emissions) is illuminating. However, current understanding is based on analyses of single countries [17,22–25,27,28] or a small number of countries (between 2 and 15 countries) [18,26] over short timescales (40–50 years) [18,24,26,28] with little-to-no electricity end-use detail [25,27]. A few studies [17,22,23] 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 [29]. At the world level, there are two studies for a single year [30,31] 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 Refs. [23,32]) and (b) the methods used to estimate efficiencies [29].

1.3. 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. 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 time span 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

Electricity production data provides the starting point, because it is the energy stage available in yearbooks and books, for construction of the long run database of primary, final, and useful electricity. Electricity production is the electricity that leaves the alternator in a power plant, so it is considered final energy. Fig. 1 and table A9 of the supplementary information A summarize the steps used to calculate primary and useful exergy as well the main sources used to obtain the data necessary to these calculations. The following subsections will go into further details about each stage of the energy conversion chain: primary, final, and useful.

2.1. Final energy stage: electricity production and sources

Our starting point was Etemad et al. "World Energy Production" [33]. Two years were assessed first: 1920 and 1970 Fig. 2. The year 1920 is the first year for which most countries have data available on electricity production in Etemad et al. [33]. 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 Fig. 3. *Large producers* (Canada, Germany, Japan, UK, USA, and USSR) supplied more than 5% of the world electricity in 1920 or 1970. Fig. 4 shows the share of the world total electricity of these countries for the period 1900–1970 (Canada [36], Germany [37–39], Japan [40], UK [41,42], USA [43] and USSR [44–46]).[1] When no other source of data was available, Etemad et al. [33] was used. For years in which no data were available, we interpolated linearly.

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. Fig. 4 shows the share of world electricity production by these countries for the period 1900–1970. The classification of a country as a big, medium or small producer controlled the amount of effort in gathering data for that country between 1900 and 1970. More data were collected for large and medium countries. Fig. 4 shows that the maximum amount of electricity produced by all small producers between 1900 and 1970 is 10%.

Data for thermal and hydroelectricity production for France, Italy, and Spain were found in the statistical yearbooks of each country and for Italy also in Malanima [47–50]. The primary reference for Spain, the statistical yearbook [48] includes only total production values, so hydroelectricity production until 1928 was estimated based on Rodríguez [51]. Missing values for hydroelectricity production in France prior to 1925 [47] were estimated based on Bordes [52]. For France, we determined the share of oil in thermal electricity for 1952 [53] and natural gas share for 1957 and 1958 [47]. Together with data for 1960 from the IEA [34], we interpolated other years. In the case of Italy, for 1925–1960, we identified the share of each fuel in thermal electricity generation based on Castelli [54].

Norway and Sweden data series started with high values of hydroelectricity, indicating that production started before Etemad et al. series [33], 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 [55]. (See supplementary information (SI) A.) For Norway 1930–1960, we estimated thermal electricity sources using statistical yearbooks [56]. For Sweden 1900–1928, we estimated hydroelectricity production using shares of hydro generation available in Kander et al. [57]. South Africa electricity production data was taken from the Bureau of census and statistics [58] between 1917 and 1959 afterwards data was taken from Etemad et al. [33].

Data for total, hydro, geothermal, and nuclear electricity production for other countries was obtained from Etemad et al. [33]. 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. [33], with the exception of hydroelectricity values for Latin America which were obtained from Rubio and Tafunell [59]. 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.

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 largest producers) for 1900–1970, fossil fuel electricity generation efficiencies were calculated directly from available primary energy consumption and electricity production data. For these countries, we had both primary and final energy so there was no need to use efficiencies to estimate primary energy. However, for Canada, Germany, and all medium producers, primary-to-final efficiencies were obtained from Etemad et al. [33] as primary energy data were not available. The same method was used for small producers for 1900–1970, with electricity generation efficiencies for each energy source taken from Etemad et al. [33] assuming that these countries had the lowest efficiency recorded for each year. From 1971 onwards, the IEA [34] has data on 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) [29]. We choose the most commonly used option: 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 [29], with no losses from primary-to-final energy stage.

Last, we convert from primary energy to primary exergy, via multiplication of exergy coefficients, shown in Table 1 [23,60].

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[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.

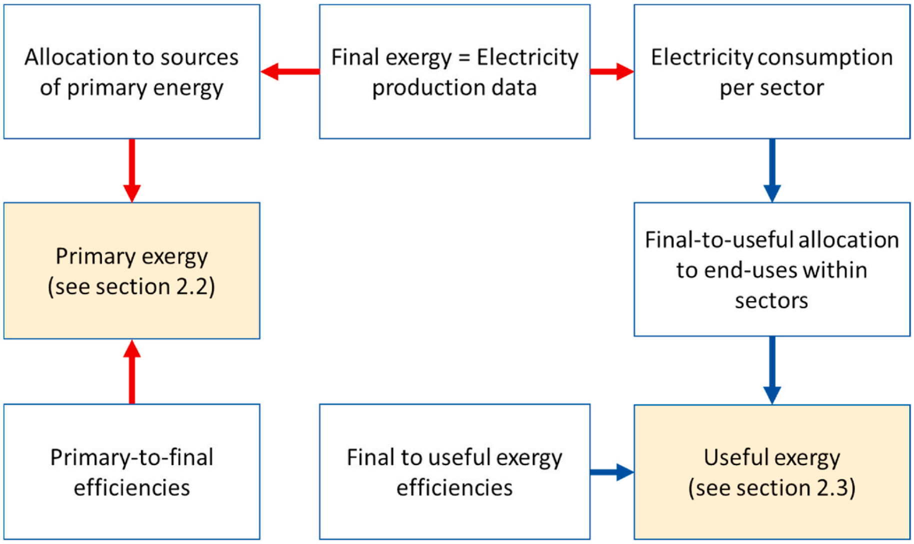

Fig. 1. Flow chart summarizing how primary, final and useful exergy were calculated. Red arrows: used only for pre-1971 calculations. Blue arrows: used for both pre- and post-1971 calculations.

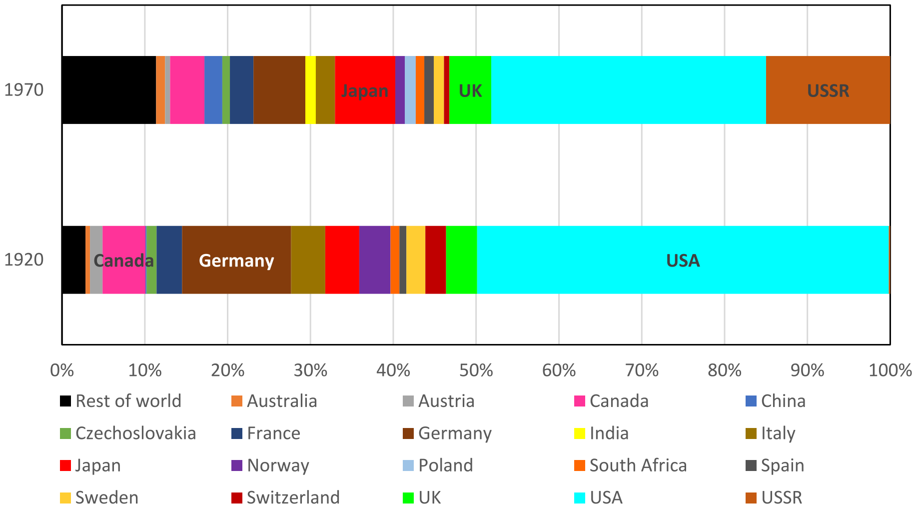

Fig. 2. Large and medium producers share of the world electricity production in 1920 and 1970, large producers' countries that generate more than 5% of world electricity production, in 1920 or 1970, while medium producers are the countries that generate more than 1%.

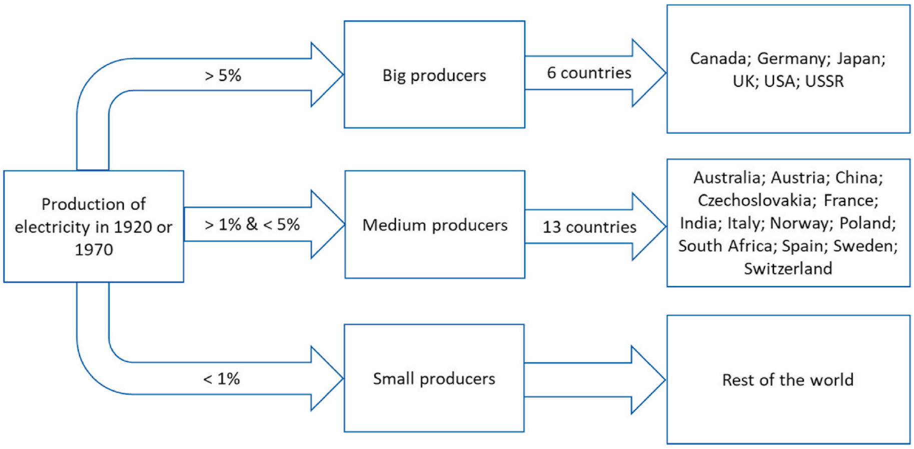

Fig. 3. Flow chart summarizing the countries which were allocated to three different groups, based on size of production share.

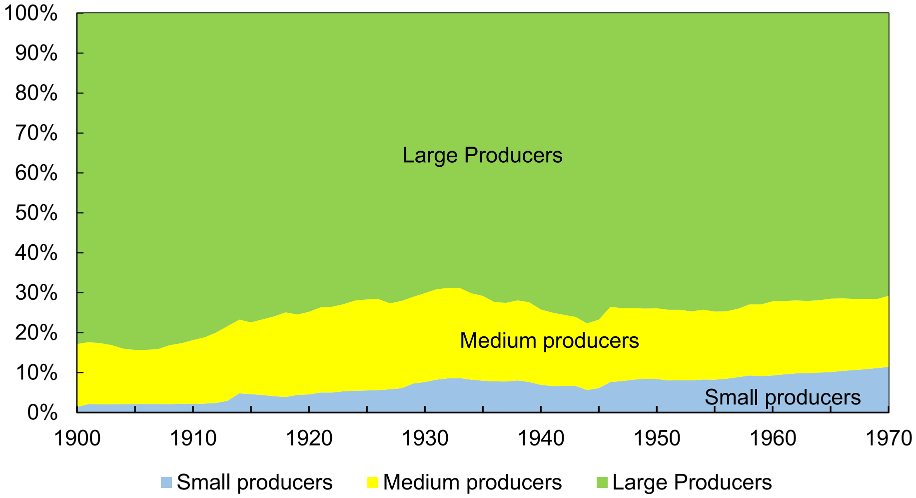

Fig. 4. Share of world electricity production for 1900–1970 for large, medium, and small producers.

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-to-useful exergy

To move from final exergy 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" [17, 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 [22,23,37–40,42,44,47,48,50,56,58,61–65]. Detailed descriptions of country-level references are given in Table A1 of SI A. After 1971, sectoral electricity consumption is available from the IEA [34]. Refer to Sections A2.1 and A2.2 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 10 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 [22,23]. Electricity consumption in residential and commercial sectors for the remaining countries was allocated to end-uses using Ayres et al. [22] 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. [22]. A more detailed description is available in section A2.3 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 [22,35]. 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 Performance (COP) 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 cooler at 5 °C, following Palma [32]. 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. [22] 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 A2.4 of the SI A as well as more details about real COP values [73].

2.4. Carbon intensity

To estimate CO_2 emissions, we used Intergovernmental Panel on Climate Change (IPCC) emission factors [66], which do not include the life cycle emissions for each electricity production technology. Thus, renewable technologies have emission factors equal to zero. Due to lack

Table 2
Cooling and heating exergy efficiencies (all formulas use temperature in Kelvin (K)). T_0 - environment temperature; T_1 - end-use temperature; T_c – Desired temperature of the freezer/cooler; η - energy efficiency. Ideal COPs for the freezer, cooler and their combined average are 6.7, 18.5 and 14.6, respectively.

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

of data, we do not take into account upstream emissions from fossil fuels. In 2000, these emissions represented between 10% and 25% of the direct emissions of a power plant, depending on the fuel and country considered [67,68]. Thus, carbon intensity is the ratio of direct emissions/exergy, calculated at both the final stage (CIF) and the useful stage (CIU) [23].

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

Fig. 5 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 to 2017. Renewables, especially wind, have increased their share in the last decade. The fuel sources for electricity production have become more varied through time.

3.2. World electricity consumption

3.2.1. Allocation to sector and subsector

Fig. 6 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%).

Total electricity consumption in Fig. 6 (green line, right axis) shows a similar trend compared to Fig. 5, where total electricity production is shown - the differences are Fig. 6 excludes 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 A1.2 of the SI A. Both electricity production and consumption are part of the final energy stage of the energy conversion chain.

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 larger share of other industries to the two subsectors, especially for the USSR.

3.2.2. Allocation to end-uses

Fig. 7 shows electricity consumption shares by individual end-uses.

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 exergy efficiencies for fossil fuels

Fig. 8 shows the evolution of primary-to-final exergy 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.

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

Fig. 9 shows primary-to-final, final-to-useful, and overall exergy efficiencies. As electricity production has been dominated by fossil fuel sources since 1900, primary-to-final exergy efficiency follows a similar pattern to average fossil fuel exergy efficiency, Fig. 8.

Final-to-useful exergy efficiency remains surprisingly stable, within

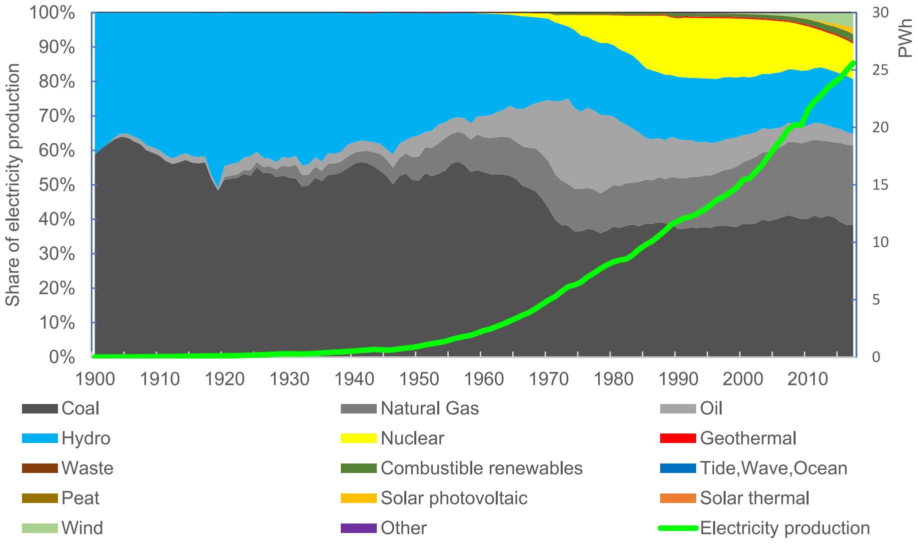

Fig. 5. World shares of electricity production per energy source (left axis) and total electricity production (right axis) (1 PWh = 10^{12} kWh = 3.6 EJ).

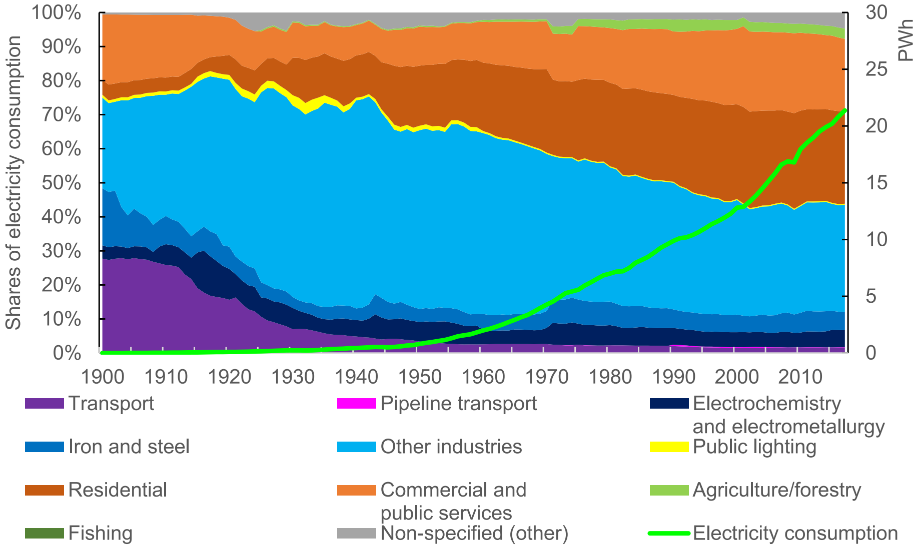

Fig. 6. World shares of electricity consumption by sector and subsector (left axis) and total electricity consumption (right axis) (1 PWh = 10^{12} kWh = 3.6 EJ).

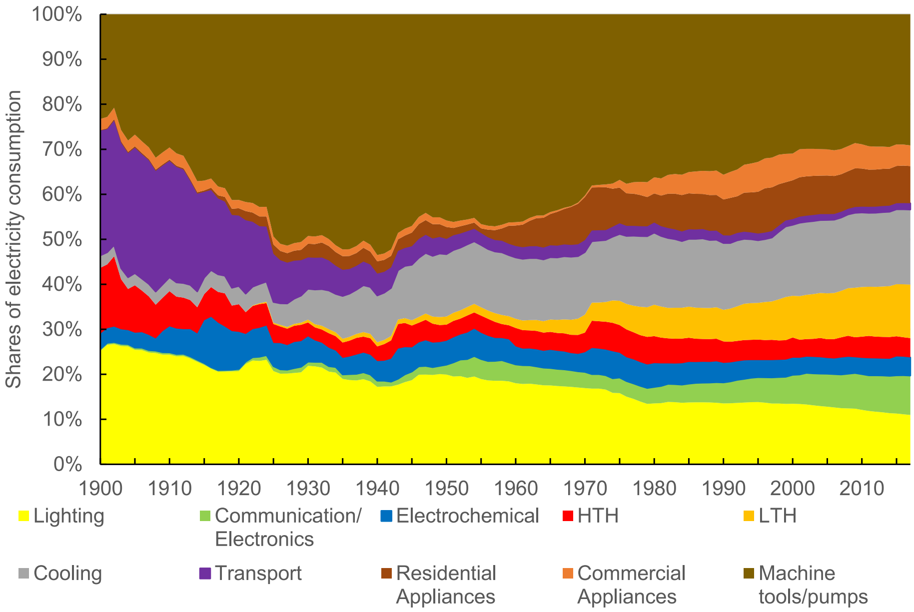

Fig. 7. World shares of electricity consumption allocated per end-use.

the range 40–50% over the whole period. In 1900, efficiency was 44% and in 2017 it was approximately 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*

Fig. 10 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 variable shares of the different 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 the 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 decreased between the mid-1950s and 1970 due to decreases in refrigeration efficiency because of increasing refrigerator and freezer size and new additional features [69].

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

Fig. 11 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

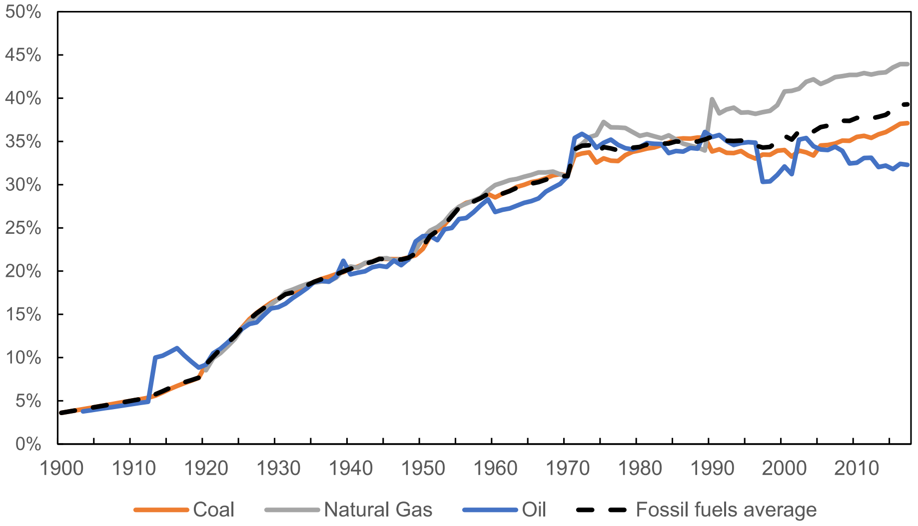

Fig. 8. Primary-to-final exergy efficiency for fossil fuel electricity production, between 1900 and 2017.

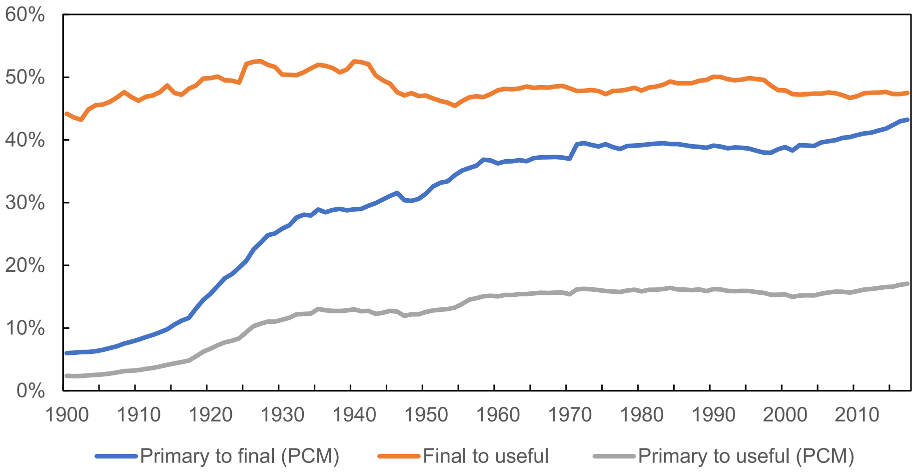

Fig. 9. World electricity primary-to-useful, primary-to-final and final-to-useful exergy efficiencies, using the PCM method.

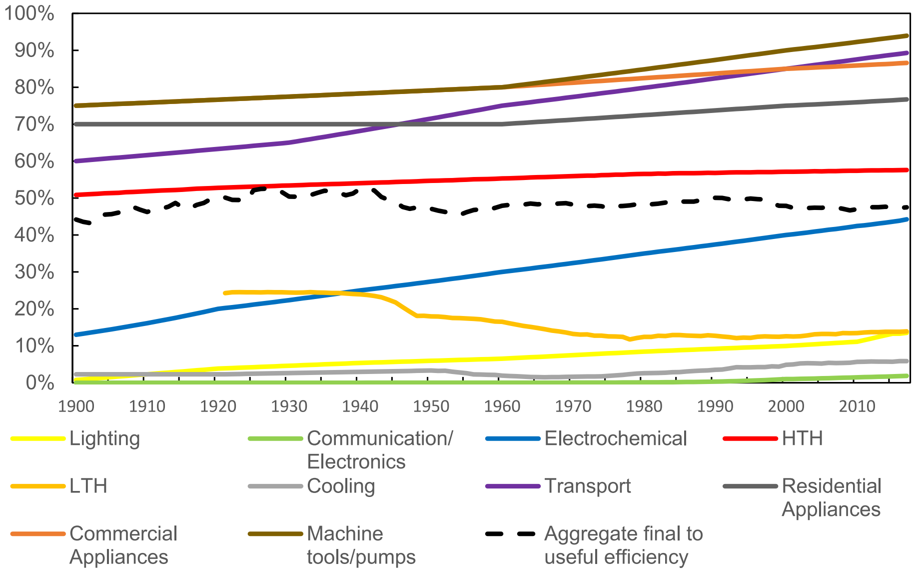

Fig. 10. Final-to-useful exergy efficiencies for each electricity end-use, during 1900–2017.

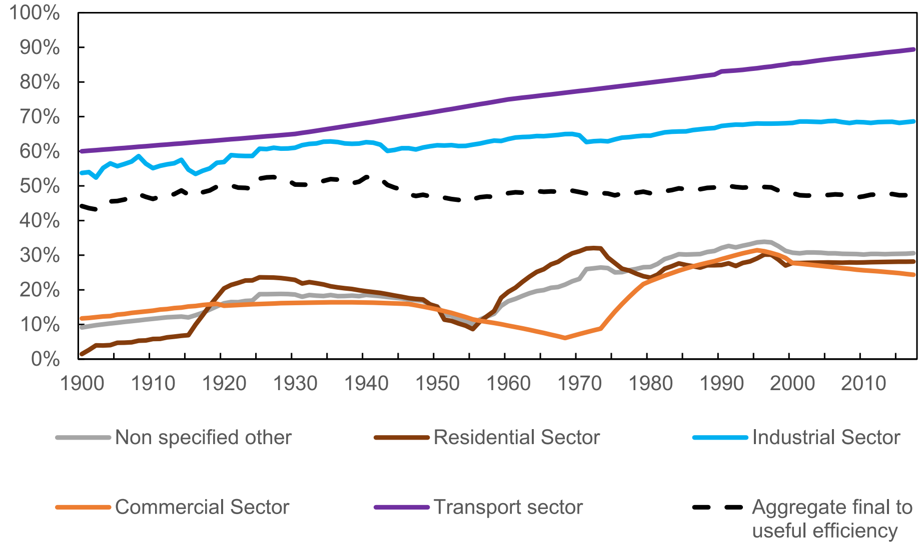

Fig. 11. Final-to-useful exergy efficiency of electricity use for different sectors.

efficiency end-uses: lighting, LTH, cooling and communication and electronics.

Figures with allocation per end-use for each sector/subsector are available at section A4.1 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. [22].

3.4. *Carbon intensity and carbon dioxide emissions*

Fig. 12 (right axis) shows the exponential growth of world CO_2 emissions associated with electricity production for 1900–2017. Fig. 12 (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.

3.5. *Annual growth rates*

Fig. 13 shows that there has never been a period when primary-to-useful exergy efficiency growth has led to CO_2 emissions decline, since the CO_2 growth rate has never been negative. Fig. 13 also shows the lack of correlation between primary-to-useful exergy efficiency and CO_2 emissions, especially after 1940. Primary-to-useful exergy efficiency growth rate was close to zero, less than 0.5%/year, in the 1940s and between 1970 and 2010. The result holds for primary-to-final and final-to-useful exergy efficiencies, as shown in Figures A7 and A8 of SI A.

4. Discussion

In this section we will look in detail at the results shown above and will go through them using a historical perspective first and then zooming in to electricity efficiency and transitions. We will also discuss some limitations associated with this work.

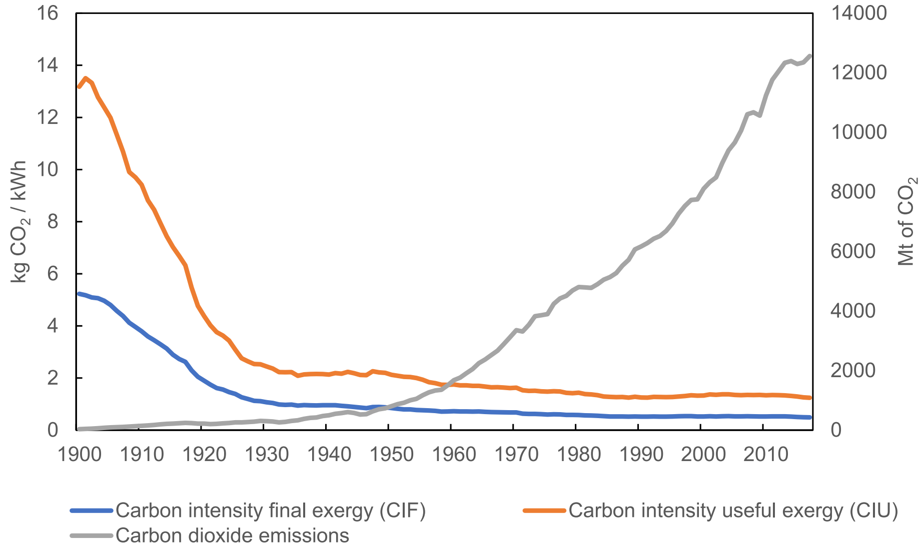

Fig. 12. CO_2 emissions from electricity generation in grey (right axis), carbon intensity of final exergy in blue and useful exergy in orange (left axis), during the period 1900 to 2017.

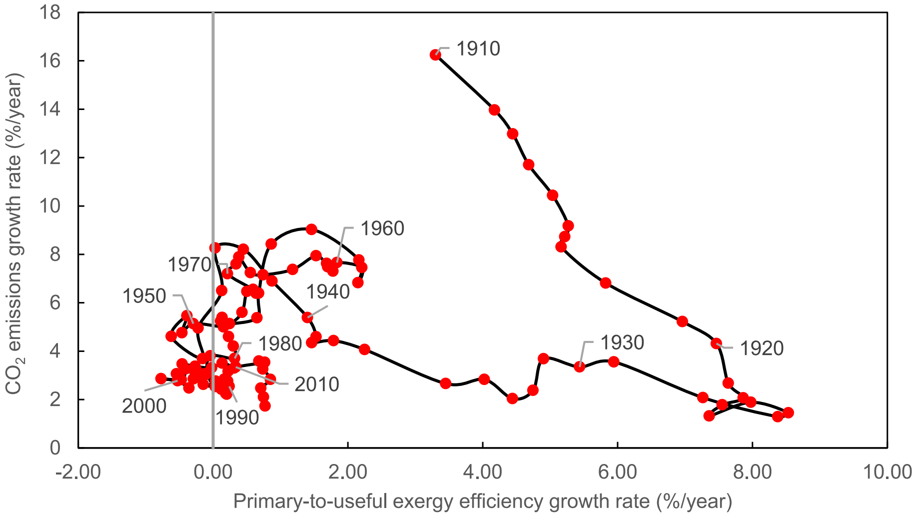

Fig. 13. Annual electricity production based growth rates of CO_2 emissions and primary-to-useful exergy efficiency of electricity shown as 10-year moving averages (1910 represents the average annual growth rate between 1901 and 1910).

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, on average, over 95% of the world electricity was produced from coal and hydro sources, with approximately constant shares (coal representing 55% and hydro 40%) (Fig. 5). 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 Fig. 9). During this period, the industrial sector increased its share of electricity consumption at the expense of the transport sector (Fig. 6). Within the industrial sector, iron and steel decreased its share more than 10% (Fig. 6). 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 (Fig. 7). Final-to-useful exergy efficiency increased only slightly from 1900 (44%) to 1950 (47%) (orange line Fig. 9), due to efficiency dilution effects. Final-to-useful exergy efficiency reached a peak in 1940 and declined thereafter (orange line Fig. 9), this peak is associated with a peak in the share of the end-use machine tools and pumps. Primary-to-useful exergy efficiency, the product of both efficiencies, increased sharply (grey line Fig. 9), mostly due to the increase of primary-to-final exergy efficiency. 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 (orange and blue lines Fig. 12), mainly because of primary-to-final efficiency improvements. Nonetheless, CO_2 emissions increased 24-fold during this period due to the near 150-fold increase in electricity production (grey line Fig. 12 and green line Fig. 5).

In the second period (1950–2017), electricity production from nuclear, oil, and (more recently) natural gas sources rose in prominence (Fig. 5). Whilst in the last decade (2007–2017) solar and wind have become more important, their combined share remains less than 10% (Fig. 5). 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 Fig. 9). After an increase in the early 1970s, primary-to-final exergy efficiency stalled during the following 40 years, rising slightly after 2005 (blue line Fig. 9) 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 A4.2 of the SI A.

Throughout 1950–2017, residential and commercial sectors increased their shares of electricity consumption, at the expense of the industrial sector (Fig. 6). 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 (Fig. 7). 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 (Fig. 7). 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 Fig. 9), due to efficiency dilution effects. Primary-to-useful exergy efficiency increased until 1960, caused by the increase in primary-to-final exergy efficiency and stabilized afterwards (grey line Fig. 9). In 2017, carbon intensity was almost half the 1950 value (orange and blue lines Fig. 12). CIF declined continuously until 1985. From 1950 to 1970, the decline in CIF is caused by growing primary-to-final efficiency while from 1971 to 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, CIF and CIU, stabilized between 1985 and 2014 (orange and blue lines Fig. 12), electricity production was not flat (green line in Fig. 5). 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

End-use efficiency (i.e. more energy efficient cars, lights, heating etc.) is commonly assumed to be a key driver of (primary and final) energy reductions (and associated carbon emissions) in future scenarios [2,3,13]. In contrast, our results show that: (1) individual exergy efficiencies grew throughout 1900–2017 (with the exception of LTH and cooling) due to technological evolution, but aggregate primary-to-useful exergy efficiency gains were significant only until mid 1930s (primary-to-useful exergy efficiency grew 10% from 1900 until 1935 and only 4% in the period 1935–2017) and (2) there is no obvious correlation between aggregate primary-to-useful exergy efficiency, electricity consumption and CO_2 emissions (Fig. 13).

Two different stories have unfolded: primary-to-final exergy efficiency increased by a factor of 7, mainly in the period 1900–1960, and stayed 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 growing demand for 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. [22] 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. [23] 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 found in the the long-term study for Japan [25], 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 [28], USA, and UK [26].

Global electricity consumption is expected to rise from 19% in 2022 to more than 40% of total final energy consumption by 2050 [2,3]. The increase of electrification may 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 which might push the electricity final-to-useful efficiency upwards if the increase in the electrification of transport dominates the transition.

4.3. Transitions

The time series of world electricity production and consumption 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 [2]. Under those assumptions, aggregate world final-to-useful exergy efficiency would increase because the transport sector is expected to remain more efficient than the commercial and residential sectors (Fig. 11).

The IEA forecasts predict that electricity production will double between 2020 and 2050 [2]. The past increase in electricity production, which doubled between 1990 and 2017 suggests that the IEA scenario is feasible. In contrast, Jacobson et al. [13] states that if we transition totally to electricity by 2050, electrify all end-uses currently using fossil fuels, we will reduce final energy demand by more than 50%, compared to a business-*as*-usual scenario but tripling electricity consumption between 2020 and 2050 would require an increase in electricity production higher than observed in the past.

But will electrification and efficiency be enough to meet decarbonization needed? Fig. 13 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 (Fig. 13). Our results suggest electrification and efficiency must be linked with a deep renewables transition if decarbonization is to occur.

We know that a large-scale transition to renewables must happen quickly (10–20 years) to meet Paris climate objectives. However, Fig. 5 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 (Fig. 5). 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 decreasing carbon intensities of fuels (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 Fig. 12).

Carbon intensity of electricity 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 Fig. 12), a result similar to Felício et al. [23] results for Portugal. Ang and Su [70] found similar results at the world level 1990–2013 for carbon intensity at the final stage. 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 [3] 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

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 sectors, IEA data were available after 1971 [34], while before 1971 information for various countries was collected as described in sections 2.3 of this paper and A2.1 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.

One way to estimate the uncertainty of our results is to undertake a full sensitivity analysis, as for example done by Paoli et al. [71] but the necessary data are not available, as in the past the uncertainty estimates were not provided with statistics. Paoli et al. [71] state that "the main source of uncertainty is found in the allocation to end-use applications". Therefore, to provide a check on the sensitivity of our results regarding the allocation to end-uses within the residential sector, we replaced allocations for every country except the US with allocations for Portugal [23]. The results obtained were not significantly different: an average final-to-useful exergy efficiency of 47.1% compared to 48.4% and a similar trend. The differences between the two final-to-useful exergy efficiency curves can be seen in section A4.4 of the SI A.

Other possible sources of uncertainty are the final-to-useful individual exergy efficiencies. To evaluate the sensitivity of our study, we changed the efficiency of the end-use with the largest share (see Fig. 7), machine tools and pumps. We changed the efficiency of machine tool and pumps by 10% (for example in 1900 the efficiency went from 75% to 82.5%) and obtained an average aggregate final-to-useful exergy efficiency of 48.4% ± 2.8%. Additionally, this change did not affect the overall trend of stagnation, see section A4.5 of the SI A for the comparison.

This paper is only focused on electricity which means that our results do not quantify the evolution of overall efficiency (efficiency considering all final energy sources including oil, coal, etc.) and are insufficient to evaluate the impact of switching from other fuels to electricity.

5. Conclusions

This work produced a novel long-run 1900–2017 global electricity dataset that relates primary energy sources to final and useful energy flows. We presented new figures for electricity production and consumption at a sectoral level, primary to final and final to useful exergy efficiencies and final and useful carbon intensities of electricity. The most striking finding is that world electricity energy efficiency (measured as overall primary-to-useful exergy efficiency) has stalled, rising dramatically from 2% in 1900 to 15% in 1960, and remaining nearly stable for the last 50 years, only reaching 17% by 2017. The rapid efficiency gain in the 1900–1960 period was due to the 6-fold rise (from 6% to 36%) 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. Carbon intensities decreased significantly until 1960, mainly due to increases in power station (primary-to-final) energy conversion efficiency. In 2017, carbon intensities at the final and useful energy stages were less than 10% their 1900 values. However, to reach climate goals, a further decrease in carbon intensity to 20% of current values (2% of 1900 values) is necessary before 2050.

The cause of the final-to-useful exergy efficiency stagnation in the past is efficiency dilution caused by structural transitions and end-use changes, such as the increasing share of low-temperature heating caused by the increasing share of overall electricity consumption in the residential and commercial sectors and the decreasing importance of static mechanical work associated with the decrease in the share of the industrial sector. The empirical result shows that final-to-useful efficiency has stalled because it has been significantly dependent on the type of end-uses that were electrified, suggesting that future energy efficiency may be mostly dictated by the mix of end-uses. The result emphasizes that technological developments alone will not be the only factor in changing aggregated electricity efficiency. Instead, shares of key electrified technologies (transport, low-temperature heat and ICT) in electricity consumption will have significant impacts on changing aggregate electricity efficiencies upwards or downwards. Whether overall efficiency increases or decreases will depend on technological and policy choices and development patterns. For example, a crucial question is whether developing and emerging economies will follow the path of their forerunners. If developing economies become more service based and expansion of household low-temperature heat and cooling applications continue, we may expect end-use efficiencies to drop. On the other hand, if developing economies leapfrog to electric cars and avoid pollution intensive modes of transportation, end-use efficiencies may increase and a brighter future might emerge. Our results show that there is a need for a deeper investigation of the full impact of electrification on world energy efficiency. A follow-on study that includes the remaining energy carriers (coal, oil, natural gas and biomass) will enable comparisons among electricity and other energy carriers' efficiencies by end-uses and forecasts of the full impact of electrification on overall efficiency due to the forthcoming energy transition.

Overall, our study raises crucial questions for future renewable electricity transitions. It is known that the key drivers of previous transitions have been cheaper and/or better energy services [72]. (E.g., electricity-altered production processes allowed radical reconfigurations of the factory floor [72].) It seems fair to ask whether electrification of transport and heating end uses could be driven similarly at sufficient speed by a demand-side clamour for improved transportation and heating services. If so, will climate policies be sufficient to drive a supply-side transition to renewable sources for electricity generation at sufficient speed to keep pace with demand-side electrification? Our results show that the rate of increase in electricity production between 1900 and 2017 was 7.4%/year. However, between 1990 and 2017 the rate of increase in electricity production was 2.9%/year which is higher than the rate needed for the electrification of the world energy system under IEA net zero emission scenario [2], 1.8%/year, but lower than the rate of increase of electricity production necessary to reach nearly total electrification as described in Jacobson et al. [13], which is 3.4%/year, and much lower than the rate of increase outlined in Ram et al. [12], 5.2%/year. Additionally, the fastest transitions in the electricity generation mix were the increase in fossil fuel share in the 1950s and 1960s and the increase in nuclear share in the 1960s and the 1970s, none of which exceeded 1%/year. The transition to non-hydro renewables has been significant after the mid-2000s, rising from 0.6% to more than 6% of total electricity production, however the increases in share have not exceeded 1%/year, highlighting the need for a massive investment in renewables and a significant decrease in new fossil fuel generation. Both the electrification of end-uses and the transition to renewables are required to meet Paris targets. The results presented above show that doing both at sufficient speed will be unprecedented.

Credit author statement

Ricardo Pinto: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. Sofia T. Henriques: Conceptualization, Methodology, Investigation, Writing – review & editing. Paul E. Brockway: Conceptualization, Methodology, Writing – review & editing, Supervision. Matthew Kuperus Heun: Conceptualization, Methodology, Writing – review & editing. Tânia Sousa: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

SI B contains the data used to build the graphs displayed in this paper. Any need for more detailed data will be made available on request.

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Appendix A. Supplementary data

The supplementary information is divided in two documents. The first is a *word* document entitled "SI A Methodology and supplementary results" where 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 paper.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.126775.

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