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Non-renewable and renewable levelized exergy cost of electricity (LExCOE) with focus on its infrastructure: 1900–2050

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ABSTRACT

This study develops the concept of the levelized exergy cost of electricity (LExCOE), evaluating key global electricity technologies from 1900 to 2050. It distinguishes the origin of the exergy (non-renewable and renewable) with focus on the infrastructure. Using this indicator, we studied the *non-renewable resource use* of these technologies in exergy cost terms. LExCOE decreased from 3.71 to 3.09 MJ/MJ between 1900 and 1960, then further to 2.33 MJ/MJ by 2010 due to the improvements in non-renewable plants performance. Between 2020 and 2050, the International Energy Agency's Net-Zero scenario is followed. Thus, the non-renewable exergy cost of *fuels* would decrease by 98.8 %, leading to a reduction in LExCOE to 1.05 MJ/MJ in 2050. However, the annual non-renewable exergy cost of *infrastructure* would increase by 133–237 %, due to the higher contribution of photovoltaic and wind infrastructure (1.8–0.067 MJ/MJ), compared to fossil technologies (0.032–0.024 MJ/MJ). Thus, the energy transition reduces the overall fossil exergy costs but increases their contribution in the infrastructure since manufacturing industry relies on fossil fuels. Furthermore, this transition will increase the demand for certain metals, which would require a review of its use in society, increase the recycling rates and continuously improve of the material efficiency of renewable energies.

1. Introduction

Electrification is essential for the transition from fossil fuels to renewable energies [1] since electricity is the most easily convertible form of energy from renewable sources, using technologies like hydroelectricity, wind turbines, or photovoltaic (PV) [2]. According to the net-zero emissions (NZE) scenario of the International Energy Agency (IEA), the share of electricity in final energy consumption is expected to increase from 20 % in 2020 to approximately 50 % by 2050 [3]. These technologies alone are expected to account for over 90 % of electricity production in 2050 according to the NZE [3].

Electricity is not a primary energy source, but an energy vector. Consequently, its generation necessitates both means of production (*infrastructure*) and primary energy (*fuels*). Therefore, the environmental impact directly depends on the life cycle of the *infrastructure* and *fuels* used in its generation. Renewable energies avoid the use of fuels, directly harnessing the primary energy of nature and converting it into electricity without direct CO_2 emissions. However, the renewable electricity technologies demand a greater quantity and variety of metals and materials compared to fossil technologies [4,5]. Additionally, mining and metal production continues to be based on fossil fuels [6], and its energy consumption could increase in the future due to (i) lower ore grades, (ii) more complex ores [7,8], and (iii) the decrease of energy return on investment (EROI) of fossil fuels [9]. Thus, most of energy and emissions associated with the renewable electricity production occur during the extraction and processing of metals [10], given the highly energy-intensive nature of metal production [11]. Therefore, if renewable energies depend on fossil fuels during their life cycle, how *renewable* are these technologies?

The present study builds on previous work by the authors [12], where various energy transition scenarios were characterized exergetically, considering the material consumption of the technologies. We found that the dependence on fossil fuels would transform into a multi-dependence on scarce raw materials. Additionally, we identified 13 elements at risk of supply [13]. Furthermore, other authors analyzed these problems from different perspectives. Elshkaki and Graedel [14] and Elshkaki [15] noted potential supply issues with silver in silicon-based technologies. However, silver use in solar panels is declining due to technological advances. Carrara et al. [10] projected a drop from 20 to 1 kg/MW by 2050. Vidal et al. [11] also warned of

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increased demand of materials from industrializing countries. Along these research lines, Elshkaki [16] and Wang et al. [17] studied the materials and metals required for the energy transition in China. These studies highlight the required amount of steel and cement, the high CO_2 emissions of aluminum or the high amounts of rare earths compared to the country's reserves. On the other hand, Pehl et al. [18] studied the life-cycle CO_2 emissions generated by a low-carbon power system until 2050. Capellán-Pérez et al. [19] investigated the evolution of the EROI [9] due to energy transition under a global perspective. Diesendorf et al. [2] employed a similar approach but focused on wind and photovoltaic technologies and the associated storage. Slamersak et al. [20] found that the energy transition can reduce the net energy available and result in substantial CO_2 emissions.

These publications employ the material-energy-emission nexus concept in analyzing electricity production. However, it is possible to unify all these dimensions through exergy [12,21,22]. Exergy is the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment [23]. Nevertheless, while fuels directly serve to provide useful work for productive processes, quantifying the work extractable from materials is not the best property to measure their utility [21]. For this reason, we adopt the *exergy cost* to analyze the *material dimension*, which represent the cumulative exergy consumption to manufacture a product, therefore the materials (kg) are transformed into exergy cost (MJ), through its life-cycle [24]. The exergy cost includes the chemical exergy embodied in the ores, which avoids higher exergy consumption during the metal transformation process, for instance, in sulfide ores. Moreover, we consider the expected decline in ore grade for the seven main metals of the *infrastructure*: iron, aluminum, manganese, copper, zinc, lead and nickel, and two important precious metals: silver and gold.

We define the levelized exergy cost of electricity (LExCOE) as the exergy *invested* (i.e. exergy cost) throughout the lifecycle (including *fuel* and *infrastructure*) to *deliver* a unit of electricity, following the analogy with LCOE (Levelized Cost of Electricity). In essence, LExCOE is the inverse of ExROI [25], which represent the exergy *delivered* per unit of exergy *invested* throughout the lifecycle. Additionally, a distinction is drawn between: (1) the LExCOE of infrastructure, which represents the material dimension, and (2) the LExCOE of fuels, which represents the energy dimension, i.e. the fuels consumed directly in electricity production. The LExCOE is further classified into: (1) non-renewable and (2) renewable [26,27]. From this perspective, the non-renewable LExCOE considers both fuels and infrastructure manufactured with non-renewable exergy to assess the *non-renewability* of electricity production. Thus, we unify the energy-materials-emissions nexus with an exergy approach.

LExCOE calculation is challenging because the *infrastructure* relies itself on electricity for manufacturing the materials. In other words, the past LExCOE influences the present LExCOE, given the dynamic and reproductive nature of the manufacturing processes of the means of production of the electricity. Therefore, it is crucial to trace back in time as far as possible (we found data up to 1900 [28]) to determine the current LExCOE and project the future cost in the framework of the energy transition [3].

2. Data and methodology

The calculation begins with Section 2.1 (exergy consumed as *fuel*), and Section 2.2 (exergy invested in *infrastructure* with the electricity). Then, the first year of LExCOE (Section 2.3) and the exergy invested in the *infrastructure* with primary exergy (Section 2.4) are estimated. Finally, the annual LExCOE is obtained (section 2.5). We used MATLAB software for the calculations.

2.1. Exergy consumed as fuel

Fuel represents the exergy cost (denoted as B^*) directly consumed each year for producing electricity without considering the *infrastructure* exergy cost. Thus, *fuel* for each technology (B_F^*, we use uppercase letters to express magnitudes in absolute terms) in MJ/year, is calculated from the yearly electricity generation of each technology (EL) in MJ/year, the efficiency (η) in MJ/MJ and the exergy conversion factors considering the fossil fuels degradation with the historical EROIs (C) in MJ/MJ of Table 1, using Equation (1).

$$B_F^* = \frac{EL}{\eta} \cdot C \tag{1}$$

Equation (1) is applied to the eight technologies studied: coal plants (*COAL*), hydropower (*HYD*), oil (*OIL*), natural gas (*NG*), nuclear (*NUC*), bioenergy (*BIO*), wind turbines (*WIND*), photovoltaic (PV), and batteries (BAT).

We obtained the electricity generation (*EL*) from Pinto et al. [28] up to 2017 and from the NZE of the IEA [3] up to 2050. Therefore, we considered a future scenario that contemplates a strong penetration of renewables while maintaining economic growth. Efficiency data were based on the IEA [3], but considering efficiency improvements throughout history. Thus, we estimated the efficiency of coal plants at 20 % in 1900, progressed to 25 % by 1950, reached 30 % by 2000 and maintained at 35 % thereafter. Natural gas had the same efficiency as coal until 1995, as it was predominantly consumed in similar power plants. However, by 2005, with the adoption of combined cycles, its efficiency surged to 45 %, and we assumed an increase to 55 % by 2050. Oil plants have the same efficiency as coal, but with a maximum of 30 %. We considered linear progress between the years.

2.2. Exergy invested in infrastructure with electricity

Infrastructure represents the exergy cost of the materials required to build the infrastructure. We considered 34 different materials and metals: Ag, Al, Au, B, Cd, Co, Cr, Cu, Dy, Fe, In, Li, Mg, Mn, Mo, Nb, Nd, Ni, Pb, Pr, Si, Sn, Ta, Tb, Ti, Zn, steel (unalloyed, low-alloyed, and stainless), concrete, plastic, glass and solar glass. We obtained the material intensity of the infrastructure (M) from several references [10,30–33]. M is measured in kg/MW, except for batteries (kg/MWh) and the values are shown in the Supplementary Materials. We assumed that 4 MWh of batteries are required per MW supplied, based on the power of real plants [34]. Thus, we calculate M in kg/MW for batteries.

We obtained the exergy cost of the 34 materials (b_M^*, we use lowercase letter to express magnitudes in specific terms, such as in MJ/kg), from the reference [35] or following the same methodology using the Ecoinvent Database 2022 [36]. The exergy cost includes the energy footprint [35], multiplied by the factor of Table 1, and the chemical exergy present in the minerals, calculated with the Szargut methodology [23,37].We considered the decline in ore grades for copper, zinc, lead, nickel, silver and gold since these metals show a long-term declining trend [8,38]. We estimate future ore grades with a power regression of past ore grades [38] and the increase of energy requirements from references [8,38]. b_M^* values are shown in the Supplementary Materials.

Equation (2) show the calculation of the exergy cost of the infrastructure (b_I^*), expressed in MJ/MW. This parameter is differentiated among natural gas, diesel, coal and electricity, according to the methodology of reference [35].

Table 1
Exergy conversion factors (C) MJ_{exergy}/MJ_{energy} of each source [25]. Fossil fuels are based on their decreasing EROI [9,29].

Year	Nat. gas [9]	Oil [9]	Coal [9]	Hydro	Nuclear	Bioenergy	Wind	PV	Electricity
1900	1.01	1.01	1.01	1	1	1.11	1	1	1
2020	1.06	1.07	1.04	1	1	1.11	1	1	1
2050	1.10	1.14	1.07	1	1	1.11	1	1	1

$$b_I^* = \sum_{j=1}^{34} M_j \cdot b_{M_j}^* \tag{2}$$

After determining b_I^*, we required the annual power installation ($P_{install}$) in MW/year to calculate the yearly exergy cost of the infrastructure (in MJ/year). First, we obtained the total power required (P_{req}) from NZE scenario of the IEA [3] between 2018 and 2050, and we calculated it between 1900 and 2017 using Equation (3), through EL and capacity factors (CF) in hours/year [3]. We obtained CF from NZE scenario of the IEA [3] and the values are shown in the Supplementary Materials.

$$P_{req} = \frac{EL}{CF \cdot 3600} \tag{3}$$

$$LExCOE_{1900} = \left(\frac{B_F^*(HYD) + B_{I-EL(FF)}^*(HYD)}{EL_{HYD}}\right)_{1900} \cdot D_{HYD\,1900} + \left(\frac{B_F^*(COAL) + B_{I-EL(FF)}^*(COAL)}{EL_{COAL}}\right)_{1900} \cdot D_{COAL\,1900} \tag{7}$$

Second, we considered the power that needs to be installed to replace the old infrastructure. Therefore, we calculated the annual installed power ($P_{install}$) using Equations (4) and (5), through P_{req}, the probability of dismantling a technology each year (L_i) and the decommissioned power each year (P_{decom}), where i represents a given year. L remains constant between the minimum and maximum year of the technology's lifespan (Fig. 1). We obtained these data from references [30,32].

$$P_{install_i} = P_{req\,(i)} - P_{req\,(i-1)} + P_{decom\,(i)} \tag{4}$$

$$P_{decom} = L \; x \; P_{install} \tag{5}$$

Next, we calculated the exergy invested each year in infrastructure with electricity (B_{I-EL}^*) by means of $P_{install}$ (MW/year) and b_I^* (MJ/MW), through Equation (6).

$$B_{I-EL}^* = P_{install} \cdot b_I^* \tag{6}$$

Finally, we separated B_{I-EL}^* into two components: one involving fossil fuels, i.e., natural gas, oil and coal ($B_{I-EL(FF)}^*$) and the other involving the electricity ($B_{I-EL(EL)}^*$), which cost is calculated in the following sections.

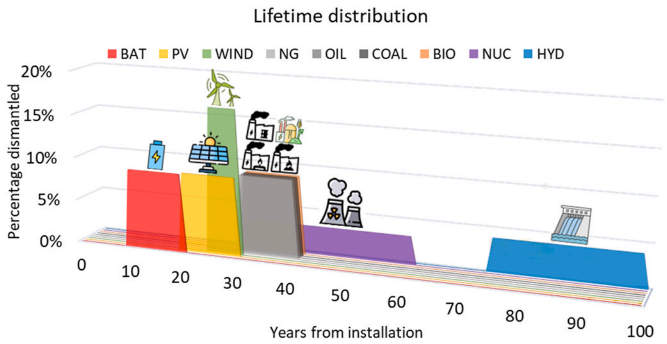

Fig. 1. Lifetime distribution of the technologies studied. Percentage indicates the probability of dismantling a power plant in a certain year from the year of installation.

2.3. LExCOE for the first year (1900)

Only hydropower and coal were utilized to generate electricity in 1900 [28]. Furthermore, we assumed that no electricity was used to build the infrastructure in 1900 and that the plants were already operating at full capacity in that year. Therefore, the primary exergy cost invested in infrastructure (B_I^*) was replaced in Equation (7) by $B_{I-EL(FF)}^*$, which was calculated in Section 2.2. We calculated LExCOE (MJ/MJ) in 1900 ($LExCOE_{1900}$) through Equation (7), where $D_{HYD1900}$ and $D_{COAL1900}$ (in MJ/MJ) represent the respective share of electricity produced by hydropower and coal plants during that year.

2.4. Exergy invested in infrastructure

Once $LExCOE_{1900}$ was estimated, we calculated the exergy invested in infrastructure for the subsequent year $B_{I_i}^*$ from $B_{I-EL(FF)_i}^*$ and $B_{I-EL(EL)_i}^*$ (calculated in section 2.2., equation (6)) through Equation (8). The term $B_{I-EL(EL)_i}^*$ was transformed into primary exergy multiplying it by the previous year's LExCOE ($LExCOE_{i-1}$). Then, we added $B_{I-EL(FF)_i}^*$ to obtain the annual primary exergy invested in infrastructure ($B_{I_i}^*$) for each technology.

$$B_{I_i}^* = B_{I-EL(FF)_i}^* + \left(B_{I-EL(EL)_i}^* \cdot LExCOE_{i-1}\right) \tag{8}$$

2.5. Evolution of the levelized exergy cost of electricity

The first iteration of Equation (8) allows to calculate $B_{I_{1901}}^*$ since $LExCOE_{1900}$ was known, from Section 2.3. Then, using $B_{I_{1901}}^*$, we calculated $LExCOE_{1901}$ through Equation (9). This equation is similar to Equation (7), but considering also the electricity invested in the infrastructure ($B_{I-EL(FF)}^*$) where the parameter $B_{I_i}^*$ is implicit (see Equation (8)) and the eight technologies studied (Fig. 1, except batteries). We embedded the primary exergy cost invested in batteries ($B_{I(BAT)_i}^*$) into $B_{I(WIND)_i}^*$ and $B_{I(PV)_i}^*$ proportionally to the electricity generation of wind and photovoltaics, since storage requirements primarily arise from the intermittency of these technologies.

$$LExCOE_i = \sum_{TEC=1}^{8} \frac{B_{F(TEC)_i}^* + B_{I(TEC)_i}^*}{EL_{TEC\,i}} \cdot \left(D_{TEC\,i}\right) \tag{9}$$

Summarizing, starting with $LExCOE_{1900}$ (Equation (7)), we first calculated $B_{I_{1901}}^*$ (Equation (8)), which allowed us to calculate $LExCOE_{1901}$ (Equation (9)). We then calculated $B_{I_{1902}}^*$, and subsequently obtaining $LExCOE_i$ and $B_{I_i}^*$ up to 2050 for each technology.

Finally, we calculated the annual LExCOE for each technology

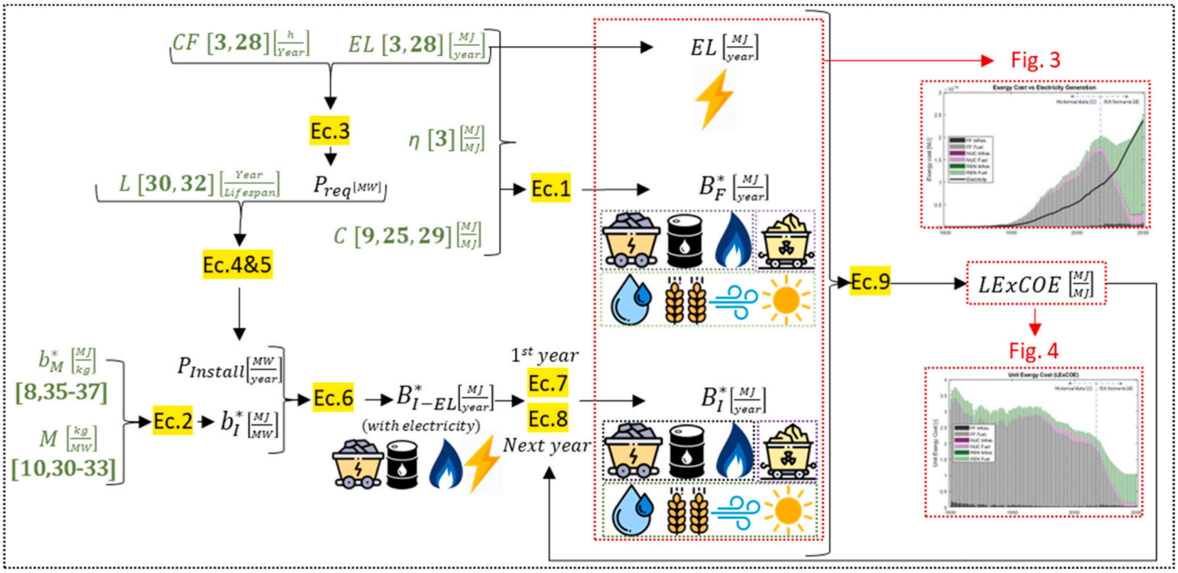

Fig. 2. Simplified scheme of the model.

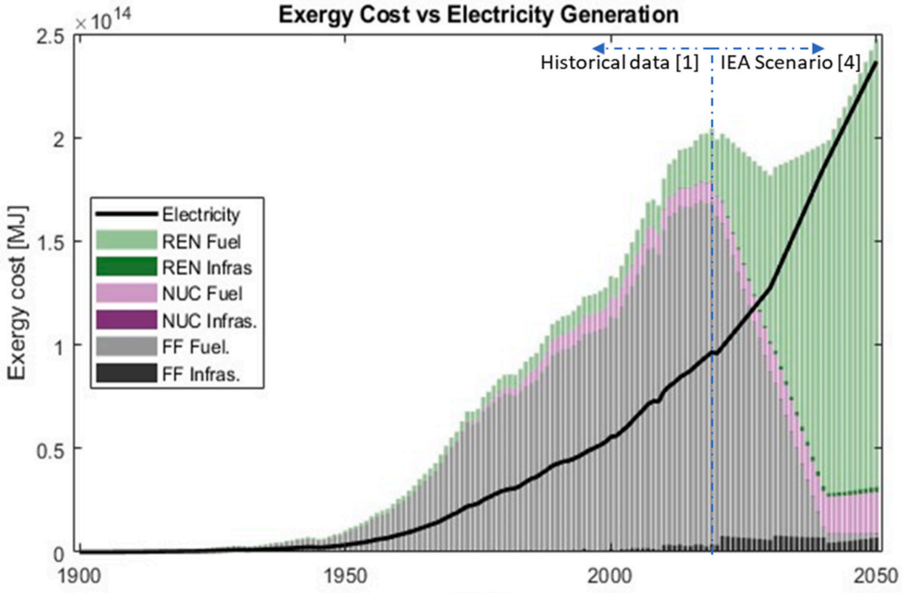

Fig. 3. Exergy as fuel (B^*_F) and exergy cost of infrastructure (B^*_I) with respect to electricity generation *EL* between 1900 and 2050. Values are shown in Supplementary Materials.

($LExCOE_{TEC}$) through Equation (10), using $B^*_{F(TEC)}$ and $B^*_{I(TEC)}$ and the percentage of power installed each year i of each technology ($\%P_{install_i}$).

$$LExCOE_{TEC_i} = \sum_{i=1}^{150} \frac{B^*_{F(TEC)_i} + B^*_{I(TEC)_i}}{EL_{TECi}} \cdot \left(\%P_{install(TEC)_i}\right) \tag{10}$$

Fig. 2 shows all the model inputs (green), indicating the references from which we obtained the data. The equations (yellow) indicate the variables to obtain the outputs (red). Thus, we calculate $P_{install}$ through *EL*, *C* and *L*, and with b^*_M and *M*, we calculate B^*_I for the first year. B^*_F is calculated with *EL*, η and *C*. Hence, with B^*_F, B^*_I and *EL*, we calculate LExCOE for the first year and B^*_I for the subsequent year (equation (8)) and successively up to 2050. Once the calculation of LExCOE and B^*_I for all years has been completed, Figs. 3 and 4 can be represented.

3. Results and discussion

First, we present the results of the levelized exergy cost of electricity (*LExCOE*). Second, the levelized exergy cost of electricity for each specific technology ($LExCOE_{TEC}$) is shown. Finally, limitations and some considerations on material utilization are discussed.

3.1. Levelized exergy cost of electric generation

Fig. 3 shows the evolution of the annual global exergy cost of *fuels* (B^*_F) and *infrastructure* (B^*_I) compared to electricity generation (*EL*). The term (B^*_F) represent the direct exergy consumption of fuels to generate electricity and it is grouped by its origin: fossil fuels *fuel* ("FF fuel"), nuclear *fuel* ("NUC fuel"), and renewable *fuel* ("REN fuel"). Infrastructure (B^*_I) represent the exergy invested in infrastructure and is grouped by its origin similarly to *fuels*.

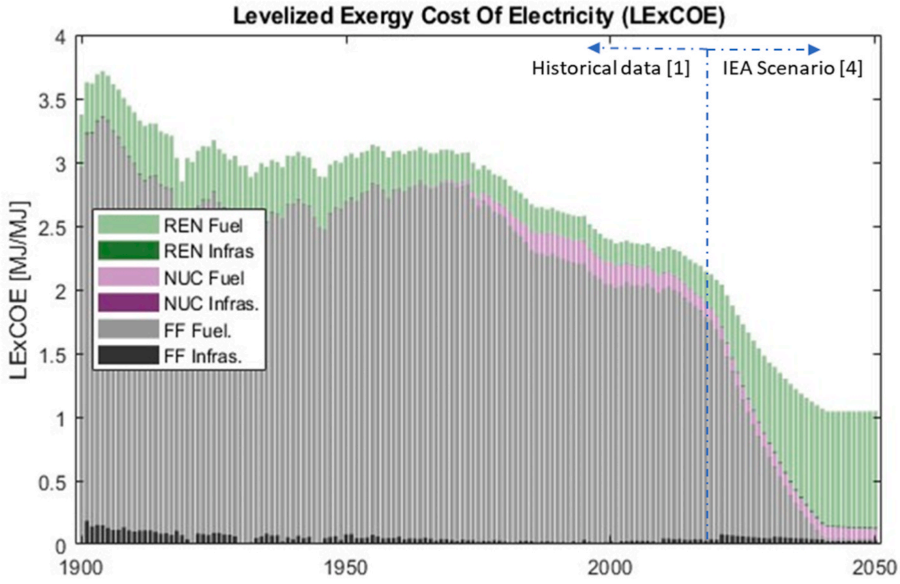

Fig. 4. LExCOE divided into fuel, infrastructure and three exergy sources: fossil fuels, nuclear and renewables. Values are shown in Supplementary Materials.

Electricity generation has exponentially increased by 4.4 % annually since 1950. Until 2000 the exergy invested in infrastructure ("FF Infras.", "NUC Infras." and "REN Infras." in Fig. 3) was relatively low, driven by: (i) lower electricity generation and (ii) the prevalence of fossil energy sources, which generally require fewer materials compared to renewable energy infrastructures [12,26]. However, since 2010, this trend started to change due to the growing investment in renewable energies. Therefore, between 2010 and 2020, the non-renewable (fossil and nuclear) fuel only increased 4 % (from 161.6 EJ to 168.2 EJ), but the non-renewable exergy cost in infrastructure increased three-fold (from 1.1 EJ to 3.5 EJ). Thus, from 1900 to 2010, fossil fuels were consumed directly to generate electricity. However, starting around 2010 with the onset of the energy transition, fossil fuels have been increasingly utilized in the production of materials for renewable infrastructure. Consequently, the peak in fossil fuel consumption, including both *infrastructure* and direct *fuel*, occurred during 2016–2020, totaling around 169 EJ. Investing fossil fuels in renewable infrastructure is preferable than direct consumption, since the non-renewable exergy consumption of renewables through its life-cycle is smaller compared to fossil fuels technologies. Due to this reason, there is no sharp increase in the fossil fuels consumption during the energy transition. On the contrary, as soon as the investment in renewable energies begins, the total use of fossil fuels decreases despite its strong increase in fossil fuel infrastructure ("FF Infras.", in Fig. 3. This conclusion is supported by other studies such as [20]. Therefore, a rapid transition is preferable.

The installation of renewable infrastructure accelerates between 2020 and 2050, increasing again the non-renewable exergy cost of infrastructure, annually 4.65–8.26 EJ, i.e., between 133 and 237 % more compared to 2020. However, at the same time, fossil exergy cost of fuel decreases from 158 EJ in 2020 to 2 EJ in 2050, i.e. by 98.8 %. Therefore, we observe a decrease in the total fossil fuel exergy cost, despite the decrease in the EROI of fossil fuels and the decrease in ore grade, even though it implies significant increases in the exergy cost for individual metals (8 % for copper, 12 % for nickel, 22 % for lead, 13 % for zinc, 7 % for silver or 102 % for gold). These findings are also supported by other studies regarding the fossil fuels' EROI [39] and ore grade decline [40].

The primary contributors to the exergy cost of the infrastructure are steel and iron (45 %), followed by silicon (29 %), and concrete (7.8 %). Secondary contributors are aluminum, copper, chromium, plastics, and solar glass, which range 2-5%. These nine materials together account for 96.5 % of infrastructure exergy costs. Therefore, any variation in their production costs would proportionally affect the overall infrastructure exergy cost. Further detailed data is available in supplementary materials.

The results obtained regarding the exergy cost required for the energy transition are comparable to those presented by Elshkaki [16]. Elshkaki reported that the energy invested in infrastructure for China ranged from 5.70E+11 and 1.76E+12 MJ between 2015 and 2050. Considering that China contributed 28 % of global electricity production in 2022 [41], and extrapolating these values globally, the results ranged between 2.04E+12 and 6.29E+12 MJ. Our study reports similar annual requirements (7.61E+12 MJ) on average from 2015 to 2050.

Fig. 4 shows *LExCOE* disaggregated between its contributors: (i) FF Infras., (ii) NUC Infras., and (iii) REN Infras., which represents the exergy cost invested in the infrastructure; and (iv) FF fuel, (v) NUC fuel, and (vi) Ren fuel, which represents the exergy cost consumed as fuel.

Fig. 4 shows that the LExCOE ranged from 3.71 to 3.09 MJ/MJ between 1900 and 1960. This means that 3.71 to 3.09 units of exergy were needed to produce one unit of electricity, being 82–90 % of fossil origin. However, between 1960 and 2010, the LExCOE, decreased from 3.09 MJ/MJ to 2.33 MJ/MJ. This resulted from the growing adoption of nuclear technology since the 1960s and combined cycle technology since the 2000s, both offering higher energy efficiency compared to other fossil-based technologies. The energy efficiency of nuclear power was higher since we applied the physical content method (PCM), wherein primary energy is defined as the first commercially available form of energy [28]. This approach is the most appropriate when a study focuses on the energy sector [42]. The next significant decrease occurred from 2010, driven by the energy transition and the extensive investments in renewable infrastructure, significantly lowering the LExCOE from 2.33 to 1.05 MJ/MJ. Thus, from 2010, the share of renewable exergy in electricity generation rises from 8.4 % to 88.3 % by 2050. Despite this decrease, a residual fossil footprint persists (6.0 % in 2040 and 3.6 % in 2050), primarily due to the fossil fuel contribution to infrastructure, accounting for 60 % and 80 % of the total fossil exergy in 2040 and 2050, respectively. This highlights again that the exergy invested in infrastructure is considerably lower compared to the exergy directly consumed from fuels [20,26]. Therefore, as renewable installations increase, the exergy cost progressively shifts from direct fossil fuels consumption to the minor indirect fossil fuel consumption to manufacture the materials used in the renewable infrastructure, leading to an overall reduction in the LExCOE. This statement aligns with our previous findings [12].

Another interesting aspect is the diminishing reliance on fossil fuels

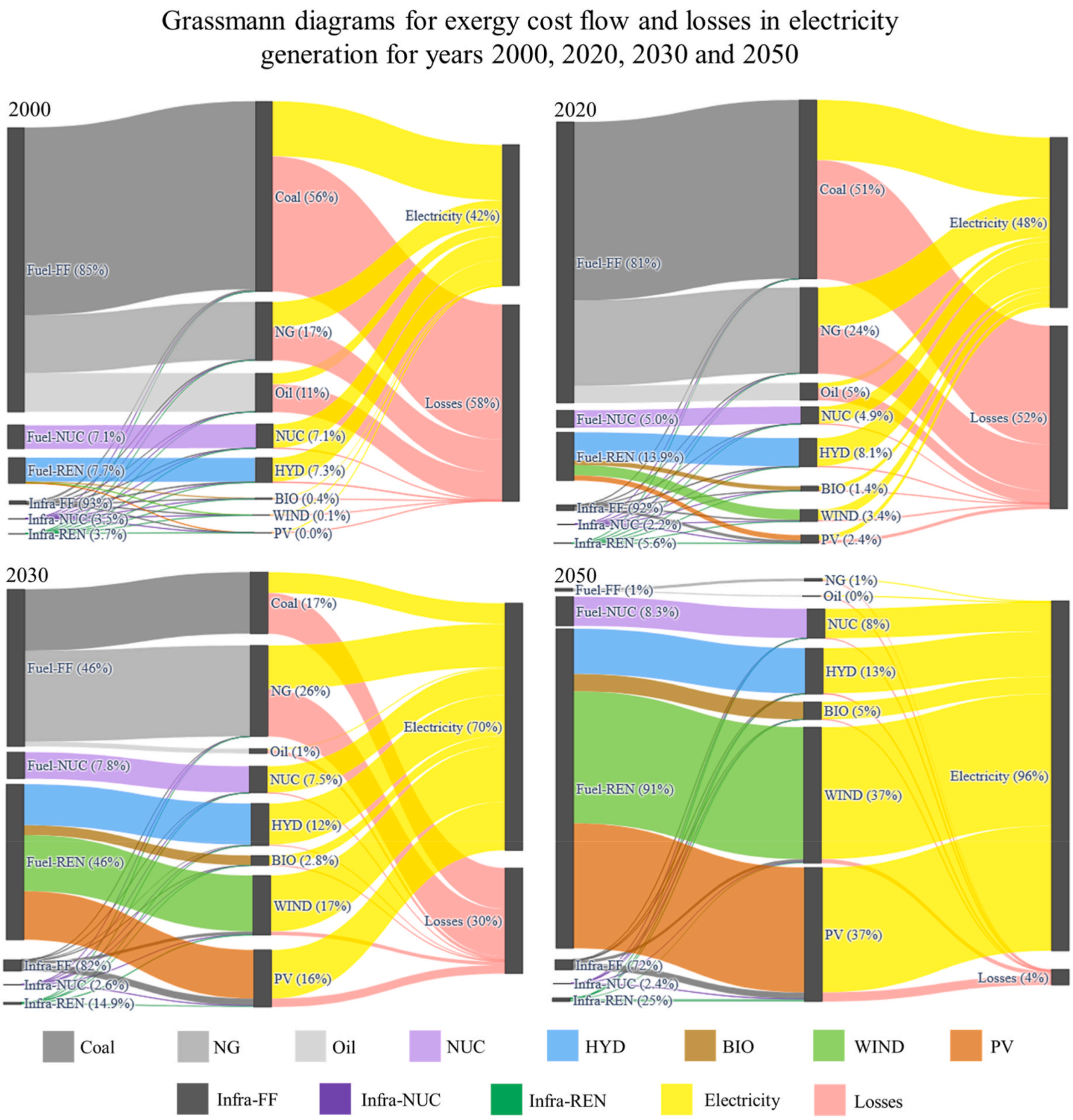

Fig. 5. Grassmann diagram of electricity generation for the years 2000, 2020, 2030 and 2050. Data is available in Supplementary Materials.

for infrastructure construction since the electricity for manufacturing materials is more renewable. This dynamic process is illustrated in Fig. 5. In the year 2000, only 3.7 % of the infrastructure was built with renewable exergy, reflecting the predominance of fossil fuels. In contrast, by 2050, 25 % of the infrastructure incorporates renewable exergy. This change occurs due to the dynamic feedback from the manufacturing processes of electricity infrastructure: with each installation of renewable infrastructure, the succeeding generation incorporates a greater amount of renewable electricity into its materials, thereby diminishing the reliance of infrastructure on fossil fuels. However, this decline is limited, as only a portion of the exergy required to manufacture the infrastructure is electricity. The fossil footprint from

Table 2
Non-Renewable (Fossil and Nuclear) LExCOE for each technology. Complete results are shown in Supplementary Materials.

MJ/MJ	1950		2010		2020		2030		2050	
	Fuel	*Infras.*	*Fuel*	*Infras.*	*Fuel*	*Infras.*	*Fuel*	*Infras.*	*Fuel*	*Infras.*
Hydro	0	0.106	0	0.060	0	0.054	0	0.048	0	0.038
Coal	4.3	0.055	3.5	0.032	3.5	0.029	3.5	0.029	–	–
Oil	4.2	0.065	3.7	0.032	3.6	0.032	3.6	0.032	3.6	0.032
Nat. gas	4.2	0.046	2.8	0.031	2.7	0.027	2.6	0.024	2.6	0.024
Nuclear	–	–	1.0	0.030	1.0	0.026	1.0	0.021	1.0	0.016
Bioenergy	–	–	0	0.073	0	0.051	0	0.036	0	0.021
Wind	–	–	0	0.247	0	0.178	0	0.131	0	0.067
PV	–	–	0	6.730	0	1.752	0	0.586	0	0.226

the past persists, but with an increasing use of renewable exergy, successive generations of infrastructure will gradually decarbonize over time.

3.2. Non-renewable LExCOE of technologies

The non-renewable LExCOE represents all non-renewable exergy cost to produce one MJ of electricity from any technology, including the fuels to manufacture the infrastructure. Table 2 shows the non-renewable $LExCOE_{TEC}$ for each technology across various reference years. The column “Infras” represents the sum of “FF Infra” and “NUC Infra” and the column “Fuel” the sum of “FF Fuel” and “NUC Fuel” of Fig. 4. The renewable exergy costs are omitted from this table. All the technologies exhibit a similar pattern in terms of time-evolution, starting with a high initial infrastructure cost that gradually declines. This occurs because the installation of infrastructure involves a substantial exergy investment without immediate electricity generation [19]. As a result, $LExCOE_{TEC}$ increases in the first year of installation (see Equation (8)), and then the infrastructures are *amortized* over time. Notably, renewable energies like wind or PV demonstrate this trend more prominent due to their higher exergy cost investment in the infrastructure compared to other technologies (see Table 3). For instance, PV’s non-renewable LExCOE decreases from 6.7 MJ/MJ to 1.8 MJ/MJ between 2010 and 2020, compared to coal’s decline from 0.032 MJ/MJ to 0.029 MJ/MJ over the same period. Regarding the evolution of Fuel over time, there is also a decreasing trend in fossil fuel technologies (coal, oil and natural gas) due to the increase in the energy efficiency. For example, the exergy cost of coal plants decreased from 4.3 MJ/MJ to 3.5 MJ/MJ between 1950 and 2030, even considering a decrease in the EROI of coal in that period (see Table 1). In the case of nuclear energy, the fuel cost remains constant at 1, as the PCM method was applied, maintaining 100 % energy efficiency.

The non-renewable $LExCOE_{TEC}$ from fossil fuels technologies (coal, oil and natural gas) is the highest, ranging between 4.3 and 2.6 MJ/MJ due to the unavoidable burning of fossil fuels (represented in column “Fuel”). The only renewable technology with a non-renewable exergy cost higher than fossil fuels technologies is PV, which in 2010, had a cost of 6.7 MJ/MJ compared to 4.3–2.6 MJ/MJ. In other words, around 2010, a PV plant was more polluting than conventional power plants. However, by 2020 the non-renewable $LExCOE_{PV}$ already dropped to 1.8 MJ/MJ (i.e., half of natural gas $LExCOE_{NG}$, 2.6 MJ/MJ) and by 2050, it reached 0.226 MJ/MJ. This significant reduction, observed across all infrastructures due to their *amortization*, is particularly pronounced in PV due to reducing the materials required for the infrastructure (see Table 3). This enormous decrease (between 8.2 and 143 TJ/MW) highlights the influence of our assumptions, especially given the substantial contribution of PV to the electricity mix in 2050, accounting for 35.7 %. Despite the sharp decline in material intensity, PV exhibit the highest non-renewable $LExCOE_{PV}$ (0.226 MJ/MJ in 2050) among renewables, due to the high exergy cost of its infrastructure (Table 3) and short lifetime (Fig. 1). Fig. 6 shows the $LExCOE_{PV}$ evolution comparing renewable and non-renewable contributions. Following $LExCOE_{PV}$ are $LExCOE_{WIND}$ (0.067 MJ/MJ for 2050) and $LExCOE_{HYDRO}$ (0.038 MJ/MJ).

Table 3
Exergy cost of one MW of infrastructure for each technology studied. Complete results are shown in Supplementary Materials.

TJ/MW	Exergy Cost (b_I^*)	Ashby et al. [30]	Ludin et al. [44]
Hydro	10.5	7.2–15	
Coal	5.6	3.5–9.5	
Oil	2.8	–	
Natural gas	2.8	1.7–2.7	
Nuclear	4.6	2–4.3	
Bioenergy	4.1	5–19.8	
Wind	6.9	3.5–10	
Photovoltaic	8.2–143	20–40	15.5–40.9

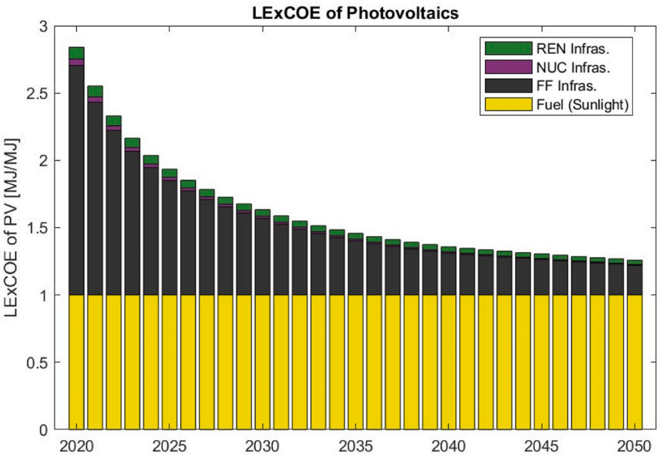

Fig. 6. $LExCOE_{PV}$ between 2020 and 2050.

Although Hydro technology exhibit a higher exergy cost for the infrastructure compared to PV or Wind (10.5 TJ/MW compared to 8.2 and 6.5 TJ/MW, see Table 3), its LExCOE is lower due to its significantly longer lifespan (75–100 years compared to 20–30 years for PV or 25–30 years for wind). $LExCOE_{BIO}$ shows the lowest non-renewable exergy cost for renewables with 0.021 MJ/MJ. However, we did not consider the exergy cost associated with biomass production, potentially resulting in a higher exergy cost. Furthermore, the large-scale adoption of biomass may lead to environmental and social problems, related to the significant area demanded [30] and if cropland is used for electricity production [43]. Finally, nuclear energy presents the lowest non-renewable $LExCOE_{TEC}$ in infrastructure (0.016), but still needs non-renewable fuel (i.e., nuclear fuel), which rise the total non-renewable cost to 1.016. In addition, we did not consider the exergy cost of radioactive waste treatment due to data limitations, which would increase $LExCOE_{NUC}$.

Table 3 compares b_I^* results (Equation (2)) in TJ/MW with the energy footprint from other studies [30,44] to validate our results. These values do not include the exergy cost of electricity or ore grade declining to improve comparability. Our values are slightly higher, as we consider the quality of the energy through exergy, but still align with the range observed in other studies.

Table 3 shows that renewable energies (hydro, wind and photovoltaic) exhibit higher exergy costs for manufacturing (143–6.9 TJ/MW), compared to other sources (5.6–2.8 TJ/MW), except for bioenergy (4.1 TJ/MW). These patterns align with findings in other studies [20,26]. We assumed constant material intensity for infrastructure over time, except for photovoltaics since silicon and silver intensity has significantly decreased over the past decades. Silicon consumption decreased from 16 t/MW in 2004 to 4 t/MW in 2018, and it is expected to fall between 3 and 2 t/MW in 2028, and silver usage from 25 t/GW in 2016 to 5-1 t/GW by 2050 [10]. Our results and other studies [22,45] confirm this trend, since reduced material usage and enhanced performance caused the average EROI for PV to surge from 2008 onwards, reaching an average of 14.4 compared to 7 before 2008 [45].

3.3. Discussion: limitations and material considerations

This study establishes a methodology for the historical-dynamic calculation of the LExCOE, however, presents some limitations. We considered the IEA NZE scenario, a decreasing material intensity of infrastructure of PV, and an increasing exergy cost of the most extracted metals as ore grades decrease. However, future studies could explore other scenarios, such as slower renewable deployment or degrowth scenarios. Additionally, the life-cycle exergy cost of metals may be influenced by the production from different ores or the recycling from old infrastructure. Other factors such as the grid components, the exergy cost of transporting materials, infrastructure maintenance and decommissioning can also be considered. Consequently, future statistical studies could contemplate all these variables. For instance, conductors may represent up to 26 % and 15 % of the global copper and aluminum stocks, respectively [46]. Recycling is identified as a potential factor to decrease energy requirements in infrastructure [17], and it also helps in avoiding primary extraction [11]. However, the short-term availability of these resources is severely limited [17], particularly the crucial metals for the energy and digital transition [33].

Finally, it should be stated that some metals could be at risk of supply. This study estimates that the copper cumulated demand is expected to increase from 15 million tons (between 1900 and 2020) to 127 million tons (between 2020 and 2050), i.e., multiplied by eight compared to the past 120 years only considering the infrastructures of this study. Therefore, when considering other sectors (80–85 % of the copper demand [47]), the copper cumulated demand could reach 850 million tons, almost matching the current reserves of 880 million tons [48]. Regarding battery metals, such as lithium, cobalt or nickel, its cumulated demand multiplies by 210, 80, and 8, respectively, due to storage deployment between 2020 and 2050 with respect to 1900–2020 (further information is available in Supplementary Materials). However, the demand for these metals would increase significantly more due to electric mobility [33], which is not considered in this study. Hence, the maximum size of a complete renewable infrastructure could be limited by mineral reserves and declining ore grades of some metals. Therefore, a review of the use of metals in society, considering degrowth scenarios, increase recycling rates and improve material efficiency of renewable energies are imperative to successfully achieve the goals of the energy transition.

4. Conclusions

Exergy enables a comprehensive evaluation of global electricity decarbonization addressing the energy, material, and emissions dimensions by means of energy units. We divided exergy according to its origin: renewable and non-renewable to capture the dimension of carbon emissions, and we considered the material dimension through the concept of exergy cost applied to the infrastructure. Following these ideas, we obtained the levelized exergy cost of electricity (LExCOE) from 1900 to 2050. We employed historical electricity mix data until 2017, accounting for the eight most important technologies, to consider the dynamic variation of the LExCOE over the years, which affects the exergy cost of materials produced the subsequent years. Our projection until 2050 was based on the rapid transition to renewable energies proposed by the NZE scenario of the IEA. This approach allows to identify the *non-renewable* exergy cost of the infrastructure over time.

The results indicate that there is no sharp increase in non-renewable exergy cost when rapidly investing exergy in materials for renewable infrastructure, despite the shift of fossil exergy from direct use as *fuels* to indirect use in *infrastructure*. This outcome stem from the low non-renewable LExCOE of renewable energies compared to fossil fuel technologies. Between 2020 and 2050, the non-renewable exergy cost as *fuel* decreases (by 98.8 %), but the non-renewable exergy cost in *infrastructure* increases (between 133 and 237 %). This results in a decline in the LExCOE from 2.33 MJ/MJ in 2010 to 1.05 MJ/MJ in 2050. However, in 2050, 3.6 % of the LExCOE still originates from fossil fuels, being the 80 % embedded in the infrastructure. To achieve further decarbonization, new technologies should be incorporated into the production processes, such as green hydrogen, which were not considered in this study.

Fossil fuel technologies exhibited the higher non-renewable LExCOE (4.3 - 2.6 MJ/MJ), due to the direct consumption of fossil fuels. On the other hand, by 2050, the non-renewable LExCOE of renewable energies decreases to 0.226 MJ/MJ for PV, 0.067 MJ/MJ for wind, 0.038 MJ/MJ hydro and 0.021 MJ/MJ bioenergy. Nuclear energy shows a non-renewable LExCOE of 1.016, primarily attributed to the nuclear fuel. However, these latter two technologies face significant constraints, such as ensuring sustainable biomass production or addressing nuclear waste. Notably, in 2010, the *non-renewable* exergy cost of PV was 6.7 MJ/MJ, 50 % more compared to a coal plant. The rapid decrease in *non-renewable* exergy cost of PV is attributed to reduced silicon and silver usage, resulting in an energy intensity variation from 143 TJ/MW to 8.2 TJ/MW. Another aspect which could jeopardize the energy transition is the amount of metals required compared to reserves. For instance, considering the use of copper in other sectors, the cumulative demand between 2020 and 2050 (850 million tons) could almost reach current reserves (880 million tons).

In conclusion, this study offers valuable insights for future exergy analyses of any production process involving the use of electricity. Regarding the energy system, there is a paradigm shift: from fossil fuel combustion and GHGs generation to infrastructure-dominated environmental impacts. This fact, while decreasing gaseous emissions, results in an increase in solid waste. Thus, the large amount of metals required by the infrastructures' energy sector calls for a review of the use of metals in society, increase recycling rates for reducing the solid waste and improve material efficiency of renewable energies to successfully achieve the goals of the energy transition.

CRediT authorship contribution statement

Jorge Torrubia: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antonio Valero:** Writing – review & editing, Supervision. **Alicia Valero:** Writing – review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.133987.

Data availability

Data will be made available on request.

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