Energy 304 (2024) 131961

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Renewable exergy return on investment (RExROI) in energy systems. The case of silicon photovoltaic panels

Jorge Torrubia *, Alicia Valero, Antonio Valero

Reseach Institute for Energy and Resource Efficiency of Aragón (Energaia) - University of Zaragoza, Campus Río Ebro, Mariano Esquillor Gómez, 15, 50018, Zaragoza, Spain

A R T I C L E   I N F O

Keywords:
Renewable exergy return on investment (RExROI)
Exergy cost
carbon footprint
Renewable energy
Photovoltaic panels
Energy transition
Renewation index

A B S T R A C T

The ongoing energy transition towards renewable sources faces reliance on fossil fuels throughout their life cycle, primarily due to mining and material production for infrastructure. This study proposes the Renewable Exergy Return on Investment (RExROI) metric, which quantifies the renewable exergy obtained from each unit of non-renewable exergy invested in energy systems. It can be seen as a *Renewation* Index, applicable to any energy production system, indicating the degree of renewability of such technologies. Focused on silicon photovoltaic panels, the study explores five material intensities, nine scenarios based on the capacity factor and lifespan, and two alternatives for electricity used in the manufacture. Results show that material intensity increases RExROI from −0.6 MJ/MJ (non-renewable exergy is higher than electricity produced) to 5.7 MJ/MJ, increasing until 19 MJ/MJ with the best location and lifespan, and reaching 34 MJ/MJ if renewable electricity is used in manufacturing. Thus, carbon intensity can range from 734 to 7 gCO_2eq/kWh. Furthermore, some strategies to enhance RExROI are discussed based on the (i) energy sources, (ii) materials, and (iii) production stages of photovoltaic panels. Thus, this study demonstrates the usefulness of RExROI in evaluating the energy-material-emission nexus of energy systems through exergy in the context of energy transition.

1. Introduction

The climate crisis is increasing the urgency of accelerating the energy transition and minimizing dependence on fossil fuels [1]. In this context, electricity generation serves as the cornerstone of this transition, as numerous emerging energy applications, such as electric vehicles or the production of green hydrogen and other e-fuels, rely on it. Therefore, the share of electricity in final energy consumption is expected to surge from 20 % in 2020 to approximately 50 % by 2050 [1]. Furthermore, renewable energy sources would provide 90 % of electricity production in 2050, according to the Net Zero Scenario of the International Energy Agency [1]. However, these technologies necessitate several metals with specific functions [2]. Besides the diversity, the quantity of metals required for renewable energy is higher than the existing fossil fuel-based facilities [3].

This diversity and quantity of metals places mining and metal production at the center of the energy transition [4]. However, these activities remain heavily reliant on fossil fuels, with coal and coal products constituting about 19 % of total global energy usage, followed by 5 % for gas, and 2 % for oil [5]. Consequently, the majority of energy consumption and emissions associated with renewable electricity production occur during the extraction and processing of metals [4]. Given this reliance on fossil fuels throughout their life cycle, the question arises: To what extent are these technologies renewable?

Several authors studied this problem from different perspectives. For instance, research has delved into the material-energy-emissions nexus considering the energy transition [6,7], industrialization [3] or through specific studies for the case of PV technologies [8,9]. Another approach involves the use of life cycle assessment (LCA), which accounts for the energy consumption and emissions generated throughout the manufacturing and commissioning of an energy system. This methodology was widely applied to evaluate the environmental impact of energy technologies, including PV technologies [10,11]. The Energy Return on Investment (EROI) [12] was also employed to assess the energy produced relative to the energy required to extract, process, produce, convert and deliver that energy. Some studies have specifically concentrated on PV panels [13,14]. However, these three approaches primarily focus on energy use and overlook the aspect of energy quality addressed by exergy.

This study employs exergy, which is the maximum theoretical useful

* Corresponding author.
E-mail address: jtorrubia@unizar.es (J. Torrubia).

https://doi.org/10.1016/j.energy.2024.131961
Received 13 November 2023; Received in revised form 5 April 2024; Accepted 5 June 2024
Available online 14 June 2024

work obtained if a system is brought into thermodynamic equilibrium with the environment [15], to integrate the material-energy-emission nexus. However, while fuels clearly reflect their function of providing energy for productive processes, for materials quantifying the work that can be extracted from them may not be the best measure to capture their utility [16]. For this reason, the *exergy cost*, which represents the cumulative exergy consumption needed to manufacture a product [17], is used to evaluate the material dimension.

One of the novelties is to incorporate the chemical exergy present in the minerals for metal production, which is non-renewable. Other studies used exergy to analyze renewable energies, but without considering this material aspect [18,19]. The origin of exergy cost determines its classification as either renewable or non-renewable [20]. On the other hand, the exergy return on investment (ExROI) represents the EROI but using exergy instead of energy. The ExROI was employed to analyze other technologies such as biodiesel [20] or oil [21], but without specifically focusing on the material exergy cost, which is essential in renewable energies. Therefore, the aim of this research is to apply the concept of Renewable Exergy Return on Investment (RExROI), which quantifies the renewable exergy obtained from natural sources when one unit of non-renewable exergy is invested in the infrastructure of energy systems. Additionally, the study utilizes the example of PV panels to examine (i) energy sources, (ii) materials, and (iii) production processes. Consequently, five material intensities, nine scenarios, and two alternatives based on the origin of the electricity used to manufacture PV panels are investigated.

2. Data and methodology

First, the data for calculating the exergy cost of one MW of PV panels, considering the five material intensity cases, is presented. Second, the calculation of the exergy cost, RExROI, and carbon intensity of the electricity is explained by establishing the nine scenarios and the two alternatives of the origin of electricity for manufacturing. All calculations were done with MATLAB.

2.1. Exergy cost of infrastructure per MW of PV panels

Table 1 shows the material intensity in kilograms per megawatt (kg/MW) of the main materials composing a silicon PV panel. Five material intensity cases were defined, each approximately corresponding to different production years: 2000, 2010, 2020, 2030 and 2050. These cases show a reduction in material intensity attributable the technological advancements. Material intensity data for the 2000 and 2010 cases were obtained from Ref. [22], while data for the 2020, 2030 and 2050 cases from Ref. [4]. The years mentioned serve as approximate reference to the manufacturing year and should be interpreted with flexibility. This study did not distinguish between single-crystalline or multi-crystalline wafer PV since the material intensity of both is grouped in Table 1. This technology accounted for 95.4 % of the PV panel market in 2019 and is expected to remain dominant in the near future [4].

Steel is defined as low-alloy steel [23] so, besides iron, it contains other metals such as chromium, manganese or niobium. Most of the metals in Table 1 are classified as *host metals*, i.e., the main metals in a mine. On the other hand, there are *companion metals*, also known as secondary metals, which are co-products of the host metals [24]. Silver is the only companion metal in Table 1, being a co-product of lead-zinc, copper, and gold mines [25]. Co-products are a common phenomenon in mining, posing a challenge when calculating the energy consumption, carbon footprint, or environmental impact of individual metals. This challenge arises from the necessity to allocate these impacts to each of the metals produced simultaneously [26]. Various allocation methods exist, such as economic or mass allocation. However, the chosen method is a physical allocation method, which relies on the relative scarcity of metals in the Earth's crust [26]. This approach relies exclusively on physical considerations, based on the principle that geologically scarce metals hold relatively higher value, thus avoiding reliance on social valuations linked to specific historical moments (such as prices).

Fig. 1 shows the exergy cost of each material, indicating the percentage contribution of each production step (mineral exergy, mining & concentration (M&C), smelting & refining (S&C), and exergy cost of the chemicals (chem.)) and fuel sources (natural gas (NG), oil, coal and electricity (Elec)). The exergy cost of chemicals refers to the indirect consumption of chemicals during M&C or S&R. Data was obtained from Ref. [26], the Ecoinvent database [23], and chemical exergy present in minerals for metal production, calculated using Szargut's chemical exergies [27]. In certain metals, the exergy content in minerals is significant, which reduces the exergy required for its production. One example is chalcopyrite for copper production due to the presence of sulfur [28], as shown Fig. 1.

After establishing the five material intensity cases (Tables 1 and in kg/MW), and the exergy cost of materials (Fig. 1, in MJ/kg), it was possible to calculate the exergy cost infrastructure per MW of PV panel (ExC_{MW}) in MJ/MW, through equation (1).

$$ExC_{MW} = \sum_{i=1}^{n} MI_i \cdot ExCM_i \tag{1}$$

MI_i represents the quantity of a material i, $ExCM_i$ the exergy cost of the material i. $ExCM_i$ was disaggregated into the four types of fuel studied (natural gas, oil, coal and electricity), and the four stages of production, as shown Fig. 1.

2.2. Exergy cost, RExROI and carbon intensity of electricity

The electricity production of PV panels depends basically on two factors: (i) the capacity factor (*CF*), which can vary from 1000 to 2000 h per year depending on the location of the panel [13] and (ii) the lifespan (*life*) of the panels, between 20 and 30 years [4]. Table 2 shows the nine scenarios proposed considering these variations.

Thus, the exergy cost of electricity (measured in MJ/MJ) (ExC_{MJ}) was calculated by dividing the exergy cost of infrastructure (ExC_{MW}) by the *CF* and *Life* from Table 2, which represent the working time during the lifespan of the panel. Therefore, nine different results of ExC_{MJ} are obtained for each case.

$$ExC_{MJ}\left[\frac{MJ}{MJ}\right] = \frac{ExC_{MW}}{CF \cdot Life \cdot 3600}\left[\frac{MJ}{MW}\right] \tag{2}$$

ExC_{MJ}, as $ExCM_i$ (Equation (1)), has to components: one non-renewable ExC_{D_NR}, associated to the direct use of fossil fuels and minerals in the production process, and the electricity use in the process

Table 1
Material intensity (kg/MW) of PV panels in the studied cases.

Cases	Source	Concrete	Plastic	Glass	Steel	Sn	Al	Cu	Si	Ag[a]	Au[a]
2000	[22]	550,000	60,000	60,000	1,200,000	200	50,000	2300	50,000	0	100
2010	[22]	500,000	20,000	60,000	1,000,000	200	35,000	1200	30,000	0	50
2020	[4]	60,700	8600	46,400	67,900	150	7500	4600	4000	20	0
2030	[4]	58,400	8300	44,700	65,300	150	7200	4500	2750	6	0
2050	[4]	48,600	6900	37,100	54,300	150	6000	3700	1000	1	0

[a] Ag and Au are grouped as precious metals (PM).

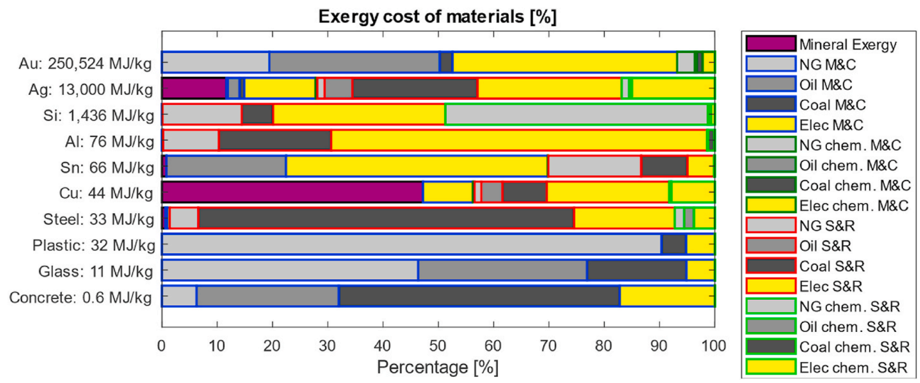

Fig. 1. Exergy cost of materials used in Si-PV panels.

Table 2
Nine scenarios for electricity production from Si-PV panels.

	Capacity factor (*CF*) (h/yr)	Lifespan (*Life*) (yr)
Scenario 1	1000	20
Scenario 2	1000	25
Scenario 3	1000	30
Scenario 4	1500	20
Scenario 5	1500	25
Scenario 6	1500	30
Scenario 7	2000	20
Scenario 8	2000	25
Scenario 9	2000	30

ExC_{I_Elec}. Since ExC_{I_Elec} is not a primary exergy has to be transformed into primary non-renewable exergy cost of electricity ($ExC_{I\_Elec\_NR}$), through equation (3). However, this requires knowledge of the non-renewable exergy cost of the electricity (in MJ/MJ) used to produce the panels ($ExC_{NR-production}$).

$$ExC_{I\_Elec\_NR} = ExC_{I\_Elec} \cdot ExC_{NR-production} \tag{3}$$

For the first case (2000), it was assumed that $ExC_{NR-production}$ originated from combined cycles. This scenario represents a newly industrialized country where most PV panels are made, and a significant portion of electricity production still depends on fossil fuels. The approximate $ExC_{NR-production}$ from a combined cycle is 2 MJ/MJ, i.e., the inverse of the efficiency (50–60 % [29]).

Based on this, two distinct alternatives were calculated for the remaining cases (2010–2050). In the first alternative, $ExC_{NR-production}$ is always produced by combined cycles, and therefore, it is constant. The second alternative, $ExC_{NR-production}$ is supplied by the previous generation of PV panels (ExC_{NR}), i.e., through equation (4). Consequently, the second alternative follows a dynamic process as the electricity of PV (ExC_{NR}) is used for manufacturing ($ExC_{NR-production}$) the next generation of PV panel.

$$ExC_{NR} = ExC_{D\_NR} + ExC_{I\_Elec\_NR} \tag{4}$$

The renewable exergy return on investment (*RExROI*) represent the actual exergy from renewable sources (Ex_R), which is the difference between the exergy of the electricity produced (Ex_{EL}) and the non-renewable exergy cost (ExC_{NR}), divided by this cost. This calculation is shown in equation (5). Since $ExC_{EL(NR)}$ is already normalized, i.e., represents the non-renewable exergy cost required to produced one MJ of electric energy (in MJ/MJ), Ex_{EL} is equal to 1.

$$RExROI = \frac{Ex_R}{ExC_{NR}} = \frac{Ex_{EL} - ExC_{NR}}{ExC_{NR}} \tag{5}$$

RExROI indicates the actual renewable energy produced compared to the non-renewable exergy invested. Therefore, solely all non-renewable exergy costs (due to minerals and fossil fuels, see equation (4)) are considered. Thus, RExROI is negative when the non-renewable exergy cost of production is higher than the electricity produced. Hence, exergy serves as an indicator that enables the connection between the energy-material-emissions nexus [8] in energy units [16]. For instance, it quantifies the amount of renewable exergy (free of emissions) generated by the infrastructure (materials) measured through the non-renewable exergy cost (energy). This approach overcomes some of the limitations of exergy efficiency [18], which ignores the exergy cost of materials only focusing in the exergy from the sun that can be transformed in electricity. The RExROI concept is generalizable to any energy system. For instance, the RExROI of a combined cycle with an exergy efficiency of 50 % would be less than −0.5 (considering the non-renewable cost of materials, see equations, 4 and 5). This indicates that electricity production from fossil fuels will always have a RExROI lower than zero since part of the non-renewable chemical exergy is inevitably destroyed during the transformation process. In contrast, renewable energies are the only ones capable of achieving a RExROI above zero. They are able to capture the "free" exergy from nature, such as the potential energy of water (hydropower), the kinetic energy of wind (wind turbines), or solar radiation (PV).

The carbon intensity of electricity (*CI*), in gCO_2eq/kWh, is calculated by multiplying the ExC_{MJ} by the emission factor (EmF_j) of each type of fuel (j). This calculation is shown in Equation (6) and EmF_j in Table 3.

$$CI = \sum_{j=1}^{n} ExC_{MJ_j} \cdot EmF_j \cdot 3600 \tag{6}$$

Thus, this study calculated the ExC_{MW}, *RExROI*, and *CI* for five different cases depending on the material intensity, nine scenarios depending on the capacity factor and lifespan, and two different electric exergy cost alternatives, depending on a fossil constant exergy cost or a renewable dynamic exergy cost. Fig. 2 illustrates the methodology, showing graphically all the equations and steps followed.

3. Results

First, the exergy cost of one MW of PV panels is analyzed, distinguishing between the fuels used, materials, and the manufacturing stages. Second, the RExROI and carbon intensity of electricity results for

Table 3
Emission factors.

		Emission factor	Source
Natural gas	$kgCO_2eq/MJ$	0.057	[30]
Diesel	$kg\ CO_2eq/MJ$	0.075	[30]
Coal	$kg\ CO_2eq/MJ$	0.1	[30]
Electricity[a]	$kg\ CO_2eq/kWh$	0.6	[31]

[a] Electricity factor is only used when the electricity cost is assumed to be constant in the first alternative and in the first case (2000) for second alternative.

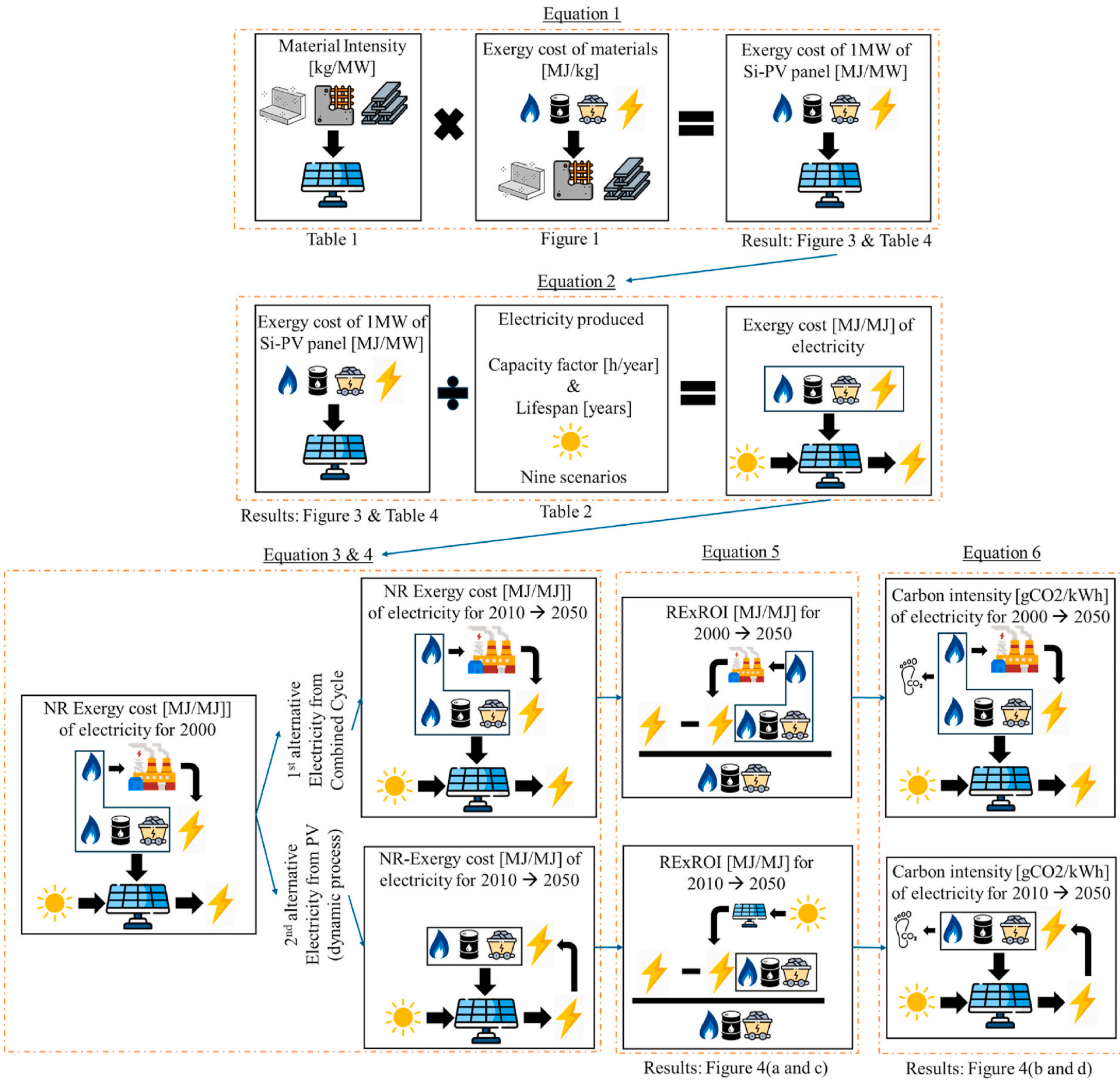

Fig. 2. Scheme of the methodology.

the PV panels are presented.

3.1. Exergy cost of one MW of PV panels

Fig. 3 illustrates the Sankey diagrams depicting the exergy cost of one MW of PV panels for the 2010 case (a), and for the 2020 case (b). The case of 2010 is also representative of the 2000 case, while the 2020 case is similar to 2030 and 2050. All the Sankey diagrams are available in the Supplementary Materials. Fig. 3 facilitates the analysis of the contribution of the different energy sources, materials, and production stages. Thus, two main types of materials are identified.

- Other materials: this category encompasses the exergy cost associated with concrete, plastic, and glass. In the 2020 case, these materials contribute to a higher proportion on the exergy cost (8.9 %) compared to the 2010 case (1.7 %). The remaining exergy cost is attributed to metals.
- Metals: metals are the primary contributors to exergy costs, with silicon and steel being the most significant. In the 2010 case, silicon and steel contribute 48 % and 36 %, respectively, while in the 2020 case, these figures rise to 64 % and 25 %.

Silicon's substantial contribution is attributed to its high exergy footprint, due to the refining to high-purity crystalline silicon required for PV panels (1400 MJ/kg, Fig. 2). Conversely, steel's significant contribution is a result of its large quantity used, accounting for 60 %–34 % of the mass of a PV panel (Table 1). Furthermore, the exergy cost of metals is divided according to their production steps:

- Mineral exergy: this category represents the chemical exergy found in minerals. In both cases, it represents the smallest contribution: 0.25 % in the 2010 case and 1.4 % in the 2020 case.
- Mining and concentration: this step comprises all the processes from rock extraction to obtaining the ore concentrate. The exergy cost associated with this step varies between cases: 12.9 % in the 2010 case and 1 % in the 2020 case. These differences arise from the mining of precious metals. In the 2010 case, gold is utilized, whose exergy cost is concentrated in mining and concentration steps. On the other hand, the 2020 case used silver, with its exergy cost concentrated in the smelting and refining step.

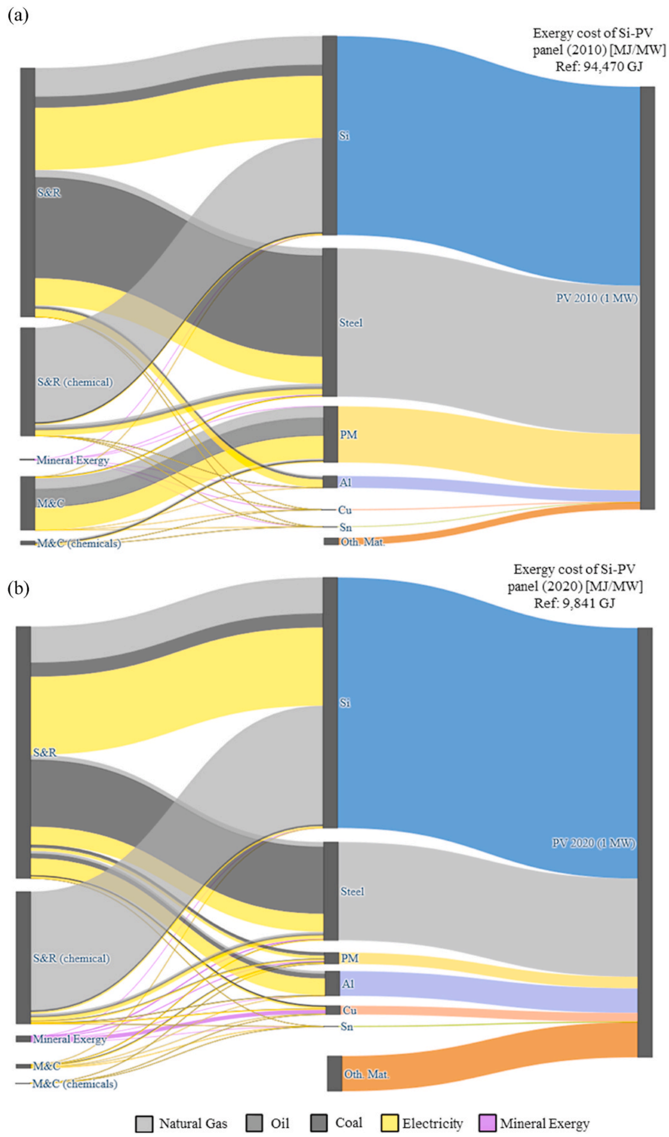

Fig. 3. Sankey diagram of the exergy cost of one MW of PV panels for the (a) 2010 case and (b) 2020 case. Ref. indicates the total exergy cost of the panel in each case.

- Smelting and refining: these processes start with the ore concentrate and continue until the metals are obtained in their metallic or final form. This stage constitutes the largest contributor to the exergy cost, accounting for 59.9 % and 63.9 % in the 2010 and 2020 cases, respectively.
- Exergy cost of chemicals: this category represents the exergy cost for the production of chemicals used across both mining and concentration, as well as smelting and refining steps. The predominant contribution arises from the smelting and refining step (26 % and 33 %) compared to the mining and concentration step (0.92 % and 0.02 %). In both cases, the main contributor was the manufacturing of solar-grade silicon.

Table 4 shows the material intensity and exergy cost categorized into non-renewable (including chemical exergy of minerals, natural gas, oil, and coal) and electricity of the five cases studied. Both material intensity and exergy cost exhibit a decline with technological advancements. For instance, the comparison of 2000 and 2050 cases revels a reduction of 90 % in material intensity and 94 % in exergy cost. The most significant change is denoted between the 2010 and 2020 cases, with an 88 % decrease in material intensity and a 90 % decrease in exergy cost. Consequently, the results range from 143,400 to 8157 GJ/MW, comparable to the reference energy cost of 40,000–14,500 GJ/MW [10,22]. However, the results outlined in our study are more extreme due to the inclusion of both very old [22] and very modern [4] PV panels. Consequently, the study illustrates the maximum and minimum exergy costs associated with solar panels.

The contribution of each fuel is also an essential aspect since electricity is the easiest energy carrier to be decarbonized compared to the direct use of fossil fuels (natural gas, oil and coal). Electricity constitutes between 29 and 32 % of the total exergy cost, with its role in metal production of metals varying from 22 % (in steel) to 68 % (in aluminum). Consequently, the reminder (68–71 %) comprises non-renewable exergy costs. Among this non-renewable exergy cost, natural gas emerges as the most significant fuel, contributing between 39 and 41 %, mainly due to the exergy cost of chemicals in crystalline silicon production (Fig. 3). This fuel is also consumed significantly in the manufacture of other materials, like concrete or solar glass. Coal accounts for 23–28 % of the exergy cost, primarily attributed to its use in steel production, the second-largest metal contributor to the total exergy cost after silicon. A substantial portion (73 %) of the exergy cost of steel originates from coal (Fig. 1), as its utilization is inherent in its production [32]. Conversely, oil demonstrates the lowest contribution to exergy cost, ranging from 3 to 6%. Its primary use is observed in the mining and concentrating stage, which represents the step with the least exergy cost share.

3.2. REXROI and carbon intensity of electricity from PV panels

Fig. 4 shows the results of REXROI and carbon intensity of electricity for the five cases, the nine scenarios and the two alternatives regarding the exergy cost of electricity. Alternative 1 (Fig. 4 a, b) utilizes a constant exergy cost of electricity based on natural gas consumption. In contrast, the alternative 2 (Fig. 4 c, d) employs a dynamic exergy cost derived from the exergy cost of the electricity from the previous PV generation. The results for the 2000 case remain the same in both alternatives, as the exergy cost and carbon footprint of electricity originates from a combined cycle in both alternatives.

The scenarios exhibit very different results. The scenario 9 demonstrates approximately three times higher REXROI compared to scenario 1. For instance, in the 2050 case, REXROI ranges from 5.7 MJ/MJ to 19 MJ/MJ. This fact highlights the importance of the location and durability of PV panels, which are the variables embedded in the scenarios. Consequently, some scenarios within the 2000 and 2010 cases exhibit a negative REXROI, indicating that more fossil exergy is destroyed than electricity produced. This phenomenon arises due to the high material intensity of these cases. For instance, the 2000 case in the worst scenario (scenario 1) presents an ExROI of −0.6 MJ/MJ and a higher carbon intensity compared to a combined cycle (736 vs 600 gCO_2eq/kWh [31]). Conversely, in the best scenario (scenario 9) for the 2010 case, REXROI reaches only 0.7 MJ/MJ, with a carbon intensity of 162 gCO_2eq/kWh. However, in the 2020 case, REXROI increases to 4.6 MJ/MJ, with carbon intensity decreasing to 49 gCO_2eq/kWh, even in the least favorable scenario (scenario 1). Furthermore, when considering the best scenario, REXROI reaches 15.7 MJ/MJ, and the carbon intensity drops to 16 gCO_2eq/kWh, once more indicating significant variability across scenarios. This variability is also documented in the literature results. Therefore, the carbon intensity is used for comparison with literature since this study is the first using REXROI. Carbon intensity of cases 2020–2050 ranged from 7 to 49 gCO_2eq/kWh, averaging 21 gCO_2eq/kWh, which aligns with findings from other review study [33,34], reporting 14–73 gCO_2eq/kWh. These similarities indicate that our findings are consistent with the literature. However, in our study the carbon footprint values are lower because future technological developments and more decarbonized manufacturing are considered.

The exergy cost of electricity remains constant in the alternative 1

Table 4
Material intensity and exergy cost of the cases studied.

			Si	Steel	PM	Al	Cu	Sn	Oth. Mat.	Total
2000 case	Mat. Intensity	ton/MW	50	1200	0	50	2	0	670	1973
	Exergy cost	GJ/MW	71,793	39,778	25,052	3777	101	13	2894	143,409
	* Non-Ren. Ex.	GJ/MW	48,970.8	30,868.6	14,337.1	1205.7	61.6	6.3	2705.6	98,156
	* Electricity	GJ/MW	22,822.1	8909.9	10,715.3	2571.7	39.4	6.9	188.5	45,254
2010 case	Mat. Intensity	ton/MW	31	1000	0	35	1	0	580	1647
	Exergy cost	GJ/MW	44,512	33,149	12,526	2644	53	7	1580	94,470
	* Non-Ren. Ex.	GJ/MW	30,361.9	25,723.8	7168.6	844.0	32.1	3.2	1463.5	65,597
	* Electricity	GJ/MW	14,149.7	7424.9	5357.6	1800.2	20.5	3.4	117.0	28,873
2020 case	Mat. Intensity	ton/MW	4	68	0	8	5	0	116	200
	Exergy cost	GJ/MW	5743	2251	260	567	202	10	808	9841
	* Non-Ren. Ex.	GJ/MW	3917.7	1746.6	119.8	180.8	123.2	4.7	762.4	6855
	* Electricity	GJ/MW	1825.8	504.1	140.3	385.8	78.7	5.2	45.8	2986
2030 case	Mat. Intensity	ton/MW	4	68	0	7	5	0	116	199
	Exergy cost	GJ/MW	5025	2251	143	544	202	10	808	8983
	* Non-Ren. Ex.	GJ/MW	3428.0	1746.6	65.9	173.6	123.2	4.7	762.4	6304
	* Electricity	GJ/MW	1597.5	504.1	77.2	370.3	78.7	5.2	45.8	2679
2050 case	Mat. Intensity	ton/MW	3	68	0	7	5	0	116	198
	Exergy cost	GJ/MW	4308	2251	65	514	202	10	808	8157
	* Non-Ren. Ex.	GJ/MW	2938.2	1746.6	29.9	164.0	123.2	4.7	762.4	5769
	* Electricity	GJ/MW	1369.3	504.1	35.1	349.8	78.7	5.2	45.8	2388

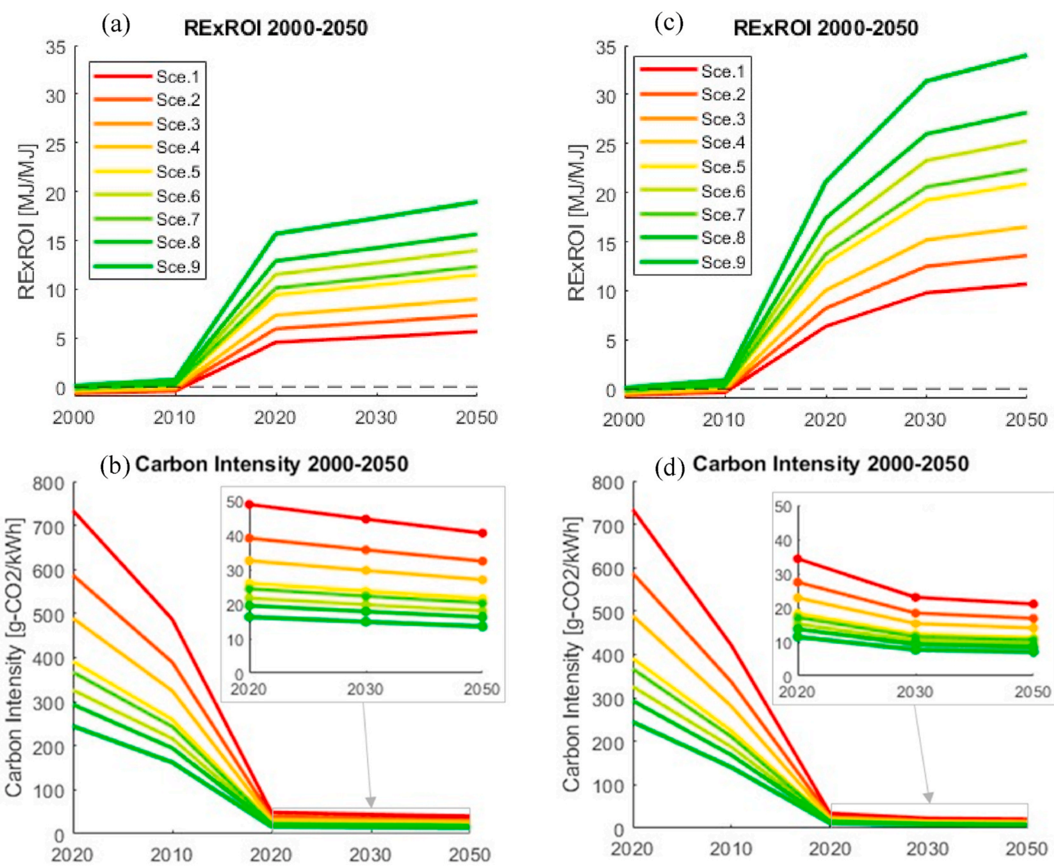

Fig. 4. RExROI and carbon intensity results. The dashed line indicates RExROI zero.
Alternative 1: constant exergy cost and carbon footprint of electricity from combined cycle. **Alternative 2**: dynamic exergy cost and carbon footprint of electricity from PV panels of the last generation.

(Fig. 4 a, b). These graphs highlight an important difference between 2000 and 2010 cases, and 2020, 2030 and 2050 cases. This discrepancy arises due to the substantial improvement in material intensity observed between 2010 and 2020 cases, as also denoted in Table 4. For instance, in the scenario 5, RExROI increases from 0.1 MJ/MJ in 2010 case to 9.4 MJ/MJ in 2020; and the carbon footprint decreases from 260 gCO_2eq/kWh to 26 gCO_2eq/kWh. Therefore, solely with the material improvement between 2010 and 2020, the environmental indicators improve by one order of magnitude. Furthermore, the material improvement continues in 2030 and 2050 cases, increasing RExROI to 10.4 and 11.5, while carbon intensity decreases to 24 gCO_2eq/kWh and 22 gCO_2eq/kWh, respectively.

The best results are obtained with the alternative 2. This approach utilizes the electricity from the previous generation PV panels to manufacture the PV panels of the subsequent generation. Consequently, the decarbonization of electricity utilized in manufacturing is considered. For instance, if RExROI in scenario 5 of alternative 1 was 11.5 MJ/MJ, it increases to 20.9 MJ/MJ in the alternative 2, representing an 82 % increase. On the other hand, carbon intensity is reduced by 48 %. Similar improvements in percentages are observed across the remaining scenarios.

In summary, as technology advances (from the 2000 case to the 2050 case), RExROI increases from −0.6 MJ/MJ and 0.1 MJ/MJ (both in 2000 case but value change depending on the scenarios) to 5.7 and 19 MJ/MJ (both in 2050 case). Therefore, the RExROI of PV panels can triple when installed in an optimal situation combined with a long lifespan. Increasing lifespan from 20 to 30 years, results in approximately a 55 % rise in RExROI, while placing the panel in an advantageous position (increasing the capacity factor from 1000 to 2000 h/year) doubles the RExROI. In addition, it can increase by approximately 80 % (from 19 MJ/MJ to 34 MJ/MJ) if electricity from PV panels is used for manufacturing (alternative 2). Thus, RExROI of PV panels can range from −0.6 MJ/MJ (non-renewable) to 34 MJ/MJ, and carbon intensity can decrease from 736 gCO_2eq/kWh to 7 gCO_2eq/kWh, representing a change of two orders of magnitude.

4. Discussion: Ways to improve the RExROI of energy systems

[Fig. 4 shows the considerable variability of the RExROI, across the different cases. In the 2000 and 2010 cases, RExROI ranges from −0.6 to 0.9 MJ/MJ. In other words, in some scenarios, electricity from PV panels was non-renewable. This fact indicates that older PV panels situated in unfavorable locations and with short lifespans consumed more non-renewable exergy during their manufacturing than the electricity they produced. Therefore, the carbon intensity of the worst-case scenario (734 gCO_2eq/kWh) is higher compared to a combined cycle (600 gCO_2eq/kWh [31]). However, the 2020, 2030, 2050 cases show a significant improvement in RExROI (ranging from 4.6 to 34), leading to a decrease in carbon intensity (49 and 7 gCO_2eq/kWh). This signifies that investing energy (fossil fuels) in mining and producing renewable energy materials is significantly more profitable (in terms of exergy) than burning them directly for electricity generation.

One strategy to enhance RExROI involves utilizing renewable electricity to produce PV panels. This impact is assessed by comparing alternatives 1 and 2. In the former, electricity is generated by a combined cycle, while in the latter, it is generated by the previous generation of PV panels. By merely implementing this measure, RExROI increase ranging from 26 % to 89 %. This demonstrates the potential for enhancing RExROI across generations; however, it also underscores the challenge of minimizing the non-renewable footprint of renewable energies.

Non-renewable exergy constitutes between 68 and 71 % of the exergy cost (see Table 4). However, this study provides a disaggregation by (i) energy sources, (ii) materials, and (iii) production stages, facilitating the derivation of certain conclusions. For instance, natural gas emerges as the most utilized fuel, contributing between 36 and 43 % of the cost. This predominance is primarily attributed to its extensive usage in silicon production, especially for chemicals. Therefore, decarbonization should occur not only in the metal industry but also in the chemical industry. This is an example of the strong interconnection between industries, highlighting that decarbonizing one industry necessitates decarbonizing others. The second most used fossil fuel is coal, with a cost contribution of 23–28 %. It is primarily employed as a heat source and reducing agent during steel production, which consumes nearly 70 % of the cost (Fig. 3). Promising substitutes are hydrogen or biochar [35]. However, the use of biochar presents some problems, such as its sustainable production on a global scale or its different physical characteristics compared to coal products [5]. Hydrogen is significantly cleaner in terms of environmental impact than biochar when produced using renewable electricity [36]. Nevertheless, its generation remains costly [5], and new infrastructure designed for its use needs to be developed [37].

Another possibility to improve RExROI involves utilizing recycled metals, which would avoid primary extraction, and reduce fossil fuel consumption. This study shows that silicon, steel, and precious metals have the highest exergy cost (see Fig. 3) and, therefore, should be prioritized for recycling. For instance, recycled silicon presents an energy saving of 70 % [38] or steel 60–70 % [39]. However, specific studies focusing on PV panels are required given the large volume of this waste expected in the future [40]. Nevertheless, the availability of some of these resources is very limited in the short term, especially the specific metals for renewable technologies, such as PV panels [41]. Furthermore, recycling is an essential stage at the end-of-life of the panels since e-waste represents the fastest-growing waste stream and causes a significant environmental impact on ecosystems [40]. Therefore, it is imperative to establish policies for PV panel collection and pollution emission reduction [42], especially in socioeconomically disadvantaged communities [43].

It should be stated that this study contains several limitations. Firstly, no consideration was given to other materials needed in the power system, such as transmission networks or storage. Additionally, the possible use of hydrogen as a renewable fuel in the production of metals or the effect of using recycled metals was not considered. Furthermore, the exergy cost of electricity was simplified by assuming generation solely from combined cycles. However, the electricity mix is significantly more complex, necessitating further investigation to accurately calculate the global exergy cost of electricity. Finally, it is important to highlight that the contribution of PV to global electricity could increase from 1.7 % in 2017 [44] to 35.7 %, according to the IEA Net-Zero scenario [1]. Since renewable energy infrastructures require more raw materials per megawatt of installed capacity than existing fossil fuel-based facilities [3], the energy transition would require more metals and, therefore, energy (fossil fuels) for their mining, refining, and manufacturing. Thus, improving RExROI and reducing the carbon intensity of electricity entails increasing pressure on mineral primary extraction, which require further research in the future.

5. Conclusions

The concept of renewable exergy return on investment (RExROI) quantifies the actual renewable electricity produced by investing one unit of non-renewable exergy, applicable to any power generation system. RExROI includes the exergy cost and chemical exergy of materials with a life cycle perspective, thereby integrating the energy-material-emissions nexus using energy units. In contrast, exergy efficiency overlooks this material dimension. Fossil plants exhibit RExROI values below zero since the destruction of non-renewable exergy during the energy transformation process is always greater than the electricity produced. However, renewable energies have the potential to present RExROI above zero since they can capture renewable exergy from natural sources.

Silicon PV panels show a RExROI from −0.6 to 0.9 in the 2000 and 2010 cases and from 4.6 to 34 in the 2020, 2030 and 2050 cases. This significant variance is due to the technological improvement, which results in a significant decrease in material intensity. Besides the material intensity, the capacity factor and the lifespan of the panel are crucial, since RExROI increases threefold when comparing the worst and best scenarios. Another critical factor is the source of electricity utilized in manufacturing, as utilizing electricity from PV panels enhances RExROI by 26 % and 89 %, compared to fossil electricity usage.

This study disaggregates the exergy cost into (i) energy sources, (ii) materials (using a physical allocation), and (iii) production phases. This allows for the identification of new opportunities to increase RExROI. For instance, replacing natural gas in silicon production or coal in steel production with hydrogen, or opting for recycled metals, especially silicon, steel or precious metals, as these are the main contributors to exergy costs.

The material dimension of infrastructure is gaining relevance as the energy transition progresses, therefore, indicators such as RExROI are needed to compare different power generation systems. The gradual reduction in material usage, the increase in operating hours, and the integration of renewable energies in the manufacturing of renewable infrastructure contribute to a progressive increase in RExROI and reduction in carbon intensity. These factors collectively play a crucial role in determining the sustainability of future energy sources.

Finally, RExROI can be seen as a *Renewation Index* (RI) that can be applied to any energy production system, indicating the degree of renewability of such technologies. The message of the word is powerful because it can be extrapolated to any type of energy technology. And since human beings have always needed energy, this index can indicate how far our society is from a fully renewable society. Thus, a value close to zero or negative indicates a society with no renewable production. The first PV panels needed more non-renewable energy than they produced over their lifetime. But as technology improved, in efficiency, durability, and critical metals substitution, the value increased to 4, and by 2050, it could go to 34. But a deeply renewable society would reach very high values. It must be said that Nature has an infinite RI; it is completely renewable, even when supplying itself with its inorganic nutrients, such as nutrients containing P, K, and more than 20 microelements. Also, it uses biomass, sunlight, and water without burning any non-renewable energy. Future work will delve into investigating how the *Renewation Index* of our society has evolved over time.

CRediT authorship contribution statement

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

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

Data will be made available on request.

Acknowledgements

This research was funded by the Spanish Ministry of Science and Innovation (grant number PID2020-116851RB-100) and Horizon Europe project REDOL (Grant Agreement 101091668).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.131961.

References

[1] International energy agency *Net Zero by 2050 - a Roadmap for the global energy sector*. 2021.

[2] Bartie N, Cobos-Becerra L, Fröhling M, Schlatmann R, Reuter M. Metallurgical infrastructure and technology criticality: the link between photovoltaics, sustainability, and the metals industry. Mineral Economics 2022;35:503–19. https://doi.org/10.1007/s13563-022-00313-7.

[3] Vidal O, Rostom F, François C, Giraud G. Global trends in metal consumption and supply: the raw material-energy nexus. Elements 2017;13:319–24. https://doi.org/10.2138/gselements.13.5.319.

[4] Carrara S, Alves Dias P, Plazzotta B, Pavel C. Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. 2020.

[5] Igogo T, Awuah-Offei K, Newman A, Lowder T, Engel-Cox J. Integrating renewable energy into mining operations: opportunities, challenges, and enabling approaches. Appl Energy 2021;300. https://doi.org/10.1016/j.apenergy.2021.117375.

[6] Wang P, Chen LY, Ge JP, Cai W, Chen WQ. Incorporating critical material cycles into metal-energy nexus of China's 2050 renewable transition. Appl Energy 2019;253. https://doi.org/10.1016/j.apenergy.2019.113612.

[7] Elshkaki A. Material-energy-water-carbon nexus in China's electricity generation system up to 2050. Energy 2019;189. https://doi.org/10.1016/j.energy.2019.116355.

[8] Elshkaki A. Materials, energy, water, and emissions nexus impacts on the future contribution of PV solar technologies to global energy scenarios. Sci Rep 2019;9. https://doi.org/10.1038/s41598-019-55853-w.

[9] Belongeay M, Shirkey G, Lunardi MM, Rodriguez-Garcia G, Sinha P, Corkish R, Stewart RA, Anctil A, Chen J, Celik I. Photovoltaic systems through the lens of material-energy-water nexus. Energies 2023;16. https://doi.org/10.3390/en16073174.

[10] Ludin NA, Mustafa NI, Hanafiah MM, Ibrahim MA, Asri Mat Teridi M, Sepeai S, Zaharim A, Sopian K. Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: a review. Renew Sustain Energy Rev 2018;96:11–28.

[11] Muteri V, Cellura M, Curto D, Franzitta V, Longo S, Mistretta M, Parisi ML. Review on life cycle assessment of solar photovoltaic panels. Energies 2020;13.

[12] Hall CAS, Lambert JG, Balogh SB. EROI of different fuels and the implications for society. Energy Pol 2014;64:141–52. https://doi.org/10.1016/j.enpol.2013.05.049.

[13] Dupont E, Koppelaar R, Jeanmart H. Global available solar energy under physical and energy return on investment constraints. Appl Energy 2020;257. https://doi.org/10.1016/j.apenergy.2019.113968.

[14] Zhou Z, Carbajales-Dale M. Assessing the photovoltaic technology landscape: efficiency and energy return on investment (EROI). Energy Environ Sci 2018;11:603–8. https://doi.org/10.1039/c7ee01806a.

[15] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical. Metallurgical processes. First.; Taylor & Francis Inc; 1988. ISBN 0891165746.

[16] Gonzalez Hernandez A, Cullen JM. Exergy: a universal metric for measuring resource efficiency to address industrial decarbonisation. Sustain Prod Consum 2019;20:151–64. https://doi.org/10.1016/j.spc.2019.05.006.

[17] Lozano MA, Valero A. Theory of the exergetic cost. Energy 1993;18:939–60.

[18] Bayrak F, Abu-Hamdeh N, Alnefaie KA, Öztop HF. A review on exergy analysis of solar electricity production. Renew Sustain Energy Rev 2017;74:755–70.

[19] Mostafa Nosratabadi S, Hemmati R, Bornapour M, Abdollahpour M. Economic evaluation and energy/exergy analysis of PV/wind/PEMFC energy resources employment based on capacity, type of source and government incentive policies: case study in Iran. Sustain Energy Technol Assessments 2021;43. https://doi.org/10.1016/j.seta.2020.100963.

[20] Font de Mora E, Torres C, Valero A. Assessment of biodiesel energy sustainability using the exergy return on investment concept. Energy 2012;45:474–80. https://doi.org/10.1016/j.energy.2012.02.072.

[21] Hassan AM, Ayoub M, Eissa M, Musa T, Bruining H, Farajzadeh R. Exergy return on exergy investment analysis of natural-polymer (Guar-Arabic Gum)Enhanced oil recovery process. Energy 2019;181:162–72. https://doi.org/10.1016/j.energy.2019.05.137.

[22] Ashby MF. Materials for low-carbon power. In: Materials and the environment. Elsevier; 2013. p. 349–413.

[23] https://ecoinvent.org/Ecoinvent.Database.Version.3.9.1. [Accessed 7 March 2023]. https://ecoinvent.org/the-ecoinvent-database/.

[24] Nassar NT, Graedel TE, Harper EM. By-product metals are technologically essential but have problematic supply. Sci Adv 2015;1. https://doi.org/10.1126/sciadv.1400180.

[25] Elshkaki A, Graedel TE. Solar cell metals and their hosts: a tale of oversupply and undersupply. Appl Energy 2015;158:167–77. https://doi.org/10.1016/j.apenergy.2015.08.066.

[26] Torrubia J, Valero A, Valero A. Energy and carbon footprint of metals through physical allocation. Implications for energy transition. Resour Conserv Recycl 2023;199:107281. https://doi.org/10.1016/j.resconrec.2023.107281.

[27] Valero A, Valero A, Stanek W. Assessing the exergy degradation of the natural capital: from Szargut's updated reference environment to the new thermoecological-cost methodology. Energy 2018;163:1140–9. https://doi.org/10.1016/j.energy.2018.08.091.

[28] Jose-Luis P, Abadias A, Valero A, Valero A, Reuter M. The energy needed to concentrate minerals from common rocks: the case of copper ore. Energy 2019;181:494–503. https://doi.org/10.1016/j.energy.2019.05.145.

[29] Ibrahim Tk, Kamil M, Awad OI, Rahman MM, Najafi G, Basrawi F, Abd Alla AN, Mamat R. The optimum performance of the combined cycle power plant: a comprehensive review. Renew Sustain Energy Rev 2017;79:459–74.

[30] https://ghgprotocol.org/.Fossil.Fuels.Emission. [Accessed 7 March 2023]. https://ghgprotocol.org/.

[31] Schlömer S, Bruckner T, Fulton L, Hertwich E, McKinnon A, Perczyk D, Roy J, Schaeffer R, Sims R, Smith P, et al. Annex III: technology-specific cost and performance parameters. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC, editors. Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.

[32] Van der Voet E, Van Oers L, Verboon M, Kuipers K. Environmental implications of future demand scenarios for metals: methodology and application to the case of seven major metals. J Ind Ecol 2019;23:141–55. https://doi.org/10.1111/jiec.12722.

[33] http://www.webservice-energy.org/incer-acv.Life.Cycle.Impact.of.Photovotaic.Systems.INCER-ACV. [Accessed 7 March 2023]. http://www.webservice-energy.org/incer-acv.

[34] Tawalbeh M, Al-Othman A, Kafiah F, Abdelsalam E, Almomani F, Alkasrawi M. Environmental impacts of solar photovoltaic systems: a critical review of recent progress and future outlook. Sci Total Environ 2021;759. https://doi.org/10.1016/j.scitotenv.2020.143528.

[35] Hamuyuni J, Tesfaye F, Iloeje CO, Anderson AE. Energy efficiency and low carbon footprint in metals processing. J Miner Met Mater Soc 2022;74:1886–8.

[36] Röben FTC, Schöne N, Bau U, Reuter MA, Dahmen M, Bardow A. Decarbonizing copper production by power-to-hydrogen: a techno-economic analysis. J Clean Prod 2021;306. https://doi.org/10.1016/j.jclepro.2021.127191.

[37] Yazdi M, Zarei E, Pirbalouti RG, Li H. A comprehensive resilience assessment framework for hydrogen energy infrastructure development. Int J Hydrogen Energy 2024;51:928–47. https://doi.org/10.1016/j.ijhydene.2023.06.271.

[38] Deng R, Chang NL, Ouyang Z, Chong CM. A techno-economic review of silicon photovoltaic module recycling. Renew Sustain Energy Rev 2019;109:532–50.

[39] He K, Wang L. A review of energy use and energy-efficient technologies for the iron and steel industry. Renew Sustain Energy Rev 2017;70:1022–39.

[40] Torrubia J, Valero A, Valero A, Lejuez A. Challenges and opportunities for the recovery of critical raw materials from electronic waste: the Spanish perspective. Sustainability 2023;15:1393. https://doi.org/10.3390/su15021393.

[41] Lallana M, Torrubia J, Valero A. Metals for energy & digital transition in Spain: demand, recycling and sufficiency alternatives. Resour Conserv Recycl 2024;205. https://doi.org/10.1016/j.resconrec.2024.107597.

[42] Flowers ME, Smith MK, Parsekian AW, Boyuk DS, McGrath JK, Yates L. Climate impacts on the cost of solar energy. Energy Pol 2016;94:264–73. https://doi.org/10.1016/j.enpol.2016.04.018.

[43] Bose D, Saini DK, Yadav M, Shrivastava S, Parashar N. Review of sustainable grid-independent renewable energy access in remote communities of India. Integr Environ Assess Manag 2021;17:364–75.

[44] Pinto R, Henriques ST, Brockway PE, Heun MK, Sousa T. The rise and stall of world electricity efficiency: 1900–2017, results and insights for the renewables transition. Energy 2023;269. https://doi.org/10.1016/j.energy.2023.126775.