Energy cost and carbon footprint of metals. Implications for PV-Silicon panels

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Abstract:

The demand for low-carbon technologies such as photovoltaic panels, wind turbines or batteries is increasing rapidly due to the energy transition, triggering the demand for metals needed to achieve the sustainable goals. Therefore, it is important to assess the energy consumption and carbon footprint of mining and metal production, as the environmental impact of future energy infrastructures will depend on them. This paper evaluates the energy cost and carbon footprint of one MW of PV panels considering a cradle-to-gate approach from a life-cycle perspective. The focus is on the metals since these are the largest contributors to energy costs (80%), distinguishing between the different stages of production: mining, metal production and the energy cost of the chemicals, and indicating the four most used fuels: coal, diesel, natural gas and electricity. To evaluate the total energy cost and carbon footprint, three different material intensity scenarios are proposed, considering a decrease over time: 2018, 2030 and 2050, and two electricity emissions scenarios: one mainly based on fossil fuels, and another based on renewable electricity. The energy return on investment (EROI) increases from 8.4 to 15.9 and carbon emissions decrease from 40 to 22 gCO_2/kWh, considering the material intensity of 2018 and 2050, respectively. If electricity from renewable sources is used, carbon emissions can be halved, reaching 11 gCO_2eq/kWh with the 2050 material intensity. Therefore, material intensity must be reduced and energy-intensive processes decarbonized to minimize the impacts of future renewable infrastructures.

Keywords:

Energy Cost; Carbon Footprint; Energy Transition; Life cycle assessment; Metal production; Photovoltaic panels.

1. Introduction

Technologies that enable the harnessing of renewable energy contain various metals that facilitate specific functionalities [1]. For instance, one MW of wind energy requires 113 to 132 tons of steel, 1 to 5 tons of copper, 0.5 to 1.6 tons of aluminum and up to 200 kg of REE; while, to manufacture one MW of photovoltaic (PV) panels 60 to 67 tons of steel, 4 to 5 tons of copper, 6 to 8 tons of aluminum and up to 20 kg of Ag are needed. This significant material intensity and the increasing demand for these technologies are triggering the demand for metals in the coming years [2]. Thus, in the case of wind energy, annual material demand is expected to increase by a factor from 2 to 15 in 2050 compared to 2018 values. In the specific case of some metals, such as rare earths elements (REE), the global demand could increase 8-9 times in 2030 and 11-14 times in 2050 compared to 2018 values. The case of solar PV technologies is similar. The most optimistic scenarios indicate a 3 to 8-fold increase in demand for materials by 2050. However, demand for specific metals such as silver or silicon could increase by 4 and 12, respectively [3].

On the other hand, mining and metal production are one of the most energy-intensive industries worldwide. It consumes about 38% of global industrial energy use, 15% of the global electricity use, and 11% of global energy use. This consumption is still based on fossil fuels since it comprises about 19% of global coal and coal products, 5% of global gas, and 2% of global oil supplied [4]. In addition, the energy required in mining is expected to increase in the future due to lower ore grade, finer grain and increasing ore complexity of newly discovered deposits [5,6]. Moreover, the trend of this growth is exponential. For example, a decrease in copper ore of 0.2% to 0.4% requires 7 times more energy [7]. Due to these facts, the energy demand in mining operations could grow 36% by 2035 [4].

Thus, it is observed that manufacturing the infrastructure to achieve the energy transition requires a large amount of metals, which in turn require fossil energy consumption and can generate significant carbon emissions. Other authors have studied this problem from different approaches. One of the most common approaches is through the Energy Return on Investment (EROI). In these studies, EROI at the final energy stage is used to calculate how much of the total energy is required by the energy system to extract, process,

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convert and deliver a unit of energy [8–10]. Another approach focuses on life cycle analysis (LCA). It is based on the accounting of the energy required and emissions generated to manufacture and commission an energy system. Generally, this analysis has only been used to estimate the impacts of current technologies in specific case studies [11,12]. One of the advantages of this methodology is that it permits to identify the processes from which the energy consumption or emissions originate [11]. Generally, most energy and emissions are consumed or emitted during the metal extraction and processing [3]. In addition, this methodology also allows the assessment of possible future scenarios with a dynamic approach, although few studies focus on it [13]. Thus, it is possible to establish different variable assumptions such as the material intensity, the energy consumed in the processes or the carbon intensity of the energy system.

In this study we use the life-cycle approach focusing on the energy cost and carbon footprint of the metals needed to manufacture PV panels. The methodology is based on accounting for the resources required for the extraction and production of Ag, Si, Al, Cu, Sn, Fe, and some of their alloys used in steel, such as Cr, Mn, Nb and Ni. The scope covers cradle to gate, i.e., from extraction of raw materials to their use as finished products, in this case, one MW of PV-Silicon panels. In addition, the energy cost is classified by the main energy sources used in mining and metal production: natural gas, diesel, coal, and electricity. Here it also includes the energy and emissions due to the chemicals needed for manufacture. The disaggregation of the processes is sufficient to differentiate the two main stages of metal production: mining and metal production. Thus, it is possible to determine which processes are most critical for decarbonization. Following this idea, two carbon emission scenarios are proposed, depending on electricity's carbon intensity: One based mainly on fossil fuels and the other on renewable energies. The energy used to manufacture PV panels and the energy cost of other materials, such as cement or glass, are also considered. Besides the carbon emission scenarios, three material intensity scenarios are also proposed. Thus, it is possible to study the link between material intensity - energy - carbon emissions, applied to one of the fastest growing technologies, the photovoltaic panels.

2. Data and methodology

Figure 1 shows the main processes and intermediate products required to obtain silver from lead and zinc mines. This Figure is an example to explain the methodology used to calculate the energy cost of metals and the allocation method since there are several different products, such as Pb, Zn or Ag.

As can be observed, each process (M&C and MP in Figure 2) has inputs (materials, energy and chemicals) and outputs (materials for the next process or the final metal). M&C refers to those processes belonging to the mining and concentrating step and MP to those belonging to the metal production step. The cradle-to-gate approach is used; thus, the analysis begins with mining and ends with the product ready for its use in another industry. The reference product is one kg of silver. If there were no co-products, it would be sufficient to sum all the energy (natural gas, diesel, coal and electricity) and chemical resources (also measured in energy cost units) to calculate the energy cost of one kg of the reference product. This is the case for the other metals in this study. But in the silver production more metals are produced simultaneously, which makes it necessary to allocate the silver its corresponding share through an allocation method.

The allocation method depends on the criteria of the authors. Most studies use allocation methods based on the economic benefit provided by the metals. However, its disadvantage is the strong fluctuation of the metal's price in the market [14]. Therefore, this study uses a physical allocation method based on the elements' geological scarcity, which has been successfully used in other studies [15–17]. The main advantage of this method is that the energy or environmental cost of metals is allocated through physical criteria, reflecting their value according to their scarcity in the earth's crust.

The allocation factor is calculated through equation 1, where M_i is the extracted mass of metal i, measured in kg-metal, and CC_i is the concentration of metal i in the earth's crust, measured in kg-metal/kg-crust.

$$Allocation_i\ (\%) = \frac{CC_i^{-1} \cdot M_i}{\sum_{i=1}^{n} (CC_i^{-1} \cdot M_i)} \quad (1)$$

Table 1 lists the parameters used to calculate the allocation factors, which in the case of silver is 12%. Once the allocation of each individual metal es calculated, the allocation of each process can be derived. Thus, the 34% of footprint of the mining and concentration stage is allocated to Pb and Ag, and then the 35.8% of the footprint of the lead production is allocated to Ag, as shown Figure 1.

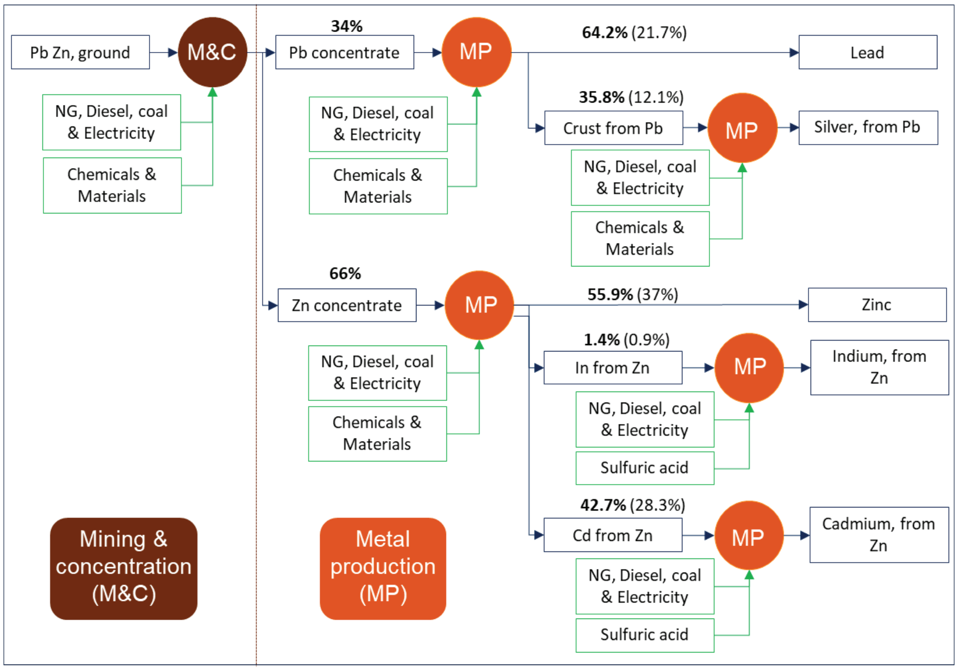

Figure 1. Block flow diagram of silver production from Pb-Zn mines.

Table 1. Mining production, crustal concentration and allocation factors of Pb-Zn mines.

Metal (i)	Mining (M_i) (kg_i)	Crustal concentration (CC_i) $\left(\frac{kg_i}{kg_{crust}}\right)$	Allocation factor
Ag	1	5.0E-08	12%
Pb	717	2.0E-05	22%
Zn	4333	7.1E-05	37%
In	0.08	5.0E-08	1%
Cd	4.6	9.8E-08	28%

As previously discussed, the remaining metals in this study do not require allocation since there are not co-products. The same applies to the calculation of the energy cost of chemicals. The process data inventories were taken from the Ecoinvent database version 3.9.1 [18], except for the Silicon processes, which are from the reference [19].

Once the energy cost is known, separated by fuel type, it is possible to estimate the carbon footprint through equation 2. Where, CF_i is the carbon footprint of metal i, measured in kg CO_2 eq; EC_j the energy cost of fuel j and EF_j is the emission factor of such fuel.

$$CF_i = \sum_{j=1}^{n}(EC_j \cdot EF_j) \quad (2)$$

Table 2 shows the data on the emission factors EF_j used. Two scenarios were established to study the impact on the carbon footprint of a decrease in electricity generation emissions. One scenario is based on fossil fuels; its emission factor is 0.488 kgCO_2eq/kWh. The other is based on renewable sources, and its emission factor is reduced to 0.021 kgCO_2eq/kWh.

Table 2. Emission factors for High Emission Scenario (HES) and Low Emission Scenario (LES)

		Emission factor HES	Emission factor LES	Source
Natural gas	kgCO_2eq/MJ	0.057	0.057	[20]
Diesel	kg CO_2eq/MJ	0.075	0.075	[20]
Coal	kg CO_2eq/MJ	0.1	0.1	[20]
Electricity	kg CO_2eq/kWh	0.488	0.021	[21,22]

The same procedure was used to calculate the energy cost of 1 MW of PV solar panels. Thus, a cumulative sum of all the energy sources needed to manufacture and install is made. In this case, the inventory data were obtained from Ecoinvent database version 3.9.1 [18] and Méndez et al. [12]. In addition, the material

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intensity, i.e., the amount of materials that constitute the solar panels, is fundamental to determining their energy cost and, consequently, their carbon footprint. Thus, three material intensity scenarios (Table 3) have been established based on the following study [3], where a decrease in material intensity is estimated for PV panels in 2030 and 2050 compared to 2018. Hence, two electricity emission scenarios and three material intensity scenarios are assessed.

Table 3. Material Intensity of the three scenarios assessed per MW of PV panel

kg/MW PV	Concrete	Plastic	Glass	Steel	Sn	Al	Cu	Si	Ag
2018	60700	8600	46400	67900	139	7500	4600	4000	20
2030	58400	8300	44700	65300	139	7200	4500	2750	6
2050	48600	6900	37100	54300	139	6000	3700	1000	1

To compare the results with the literature, two parameters of the solar panels are calculated: Energy Return of Investment (EROI) and carbon intensity, through equations 3 and 4, respectively.

$$EROI = \frac{Supplied\ energy}{Energy\ cost} = \frac{1MW \cdot t_{operation} \cdot life}{Energy\ cost\ 1MW\ PV} \quad (3)$$

The EROI represents the amount of energy units obtained from an energy system for each unit of energy invested on it, so it has no units. In this case, 1 MW of PV was taken as a reference. Thus, equation 3 shows in the numerator the amount of energy that 1 MW of PV will supply, assuming an operation of 1000 hours per year ($t_{operation}$) for 25 years ($life$). On the other hand, the denominator shows the energy cost required to manufacture and install 1 MW of PV.

$$Carbon\ intensity = \frac{Carbon\ footprint}{Supplied\ energy} = \frac{Carbon\ footprint\ 1MW\ PV}{1MW \cdot h \cdot life} \quad (4)$$

Equation 4 shows the calculation of the carbon intensity, which represents the CO_2 emissions produced by each energy unit. The numerator shows the entire carbon footprint of 1 MW PV measured in g of CO_2. At the same time, the denominator represents all the energy generated by one MW PV (measured in kWh), assuming 1000 hours per year and 25 years of life.

3. Results and discussion

The results of the energy cost and carbon footprint of metals used in a PV panel are presented, discussing their decarbonization possibilities. The specific case of 1 MW of photovoltaic panels is then analyzed.

3.1. Energy cost of metals

Figure 2 shows the energy cost of metals used in photovoltaic panels. The results are ordered from highest to lowest value in MJ/kg. Thus, the most energy-consuming is silver (11,000 MJ/kg), followed by Si (1,400 MJ/kg), Al (75 MJ/kg), Sn (64 MJ/kg), Steel (32 MJ/kg), Cu (23 MJ/kg). In addition, the energy cost is disaggregated into the four most common fuels (natural gas, diesel, coal and electricity), the most important steps (mining and concentration (M&C), and metal production (MP)) and the energy cost of chemicals used these processes.

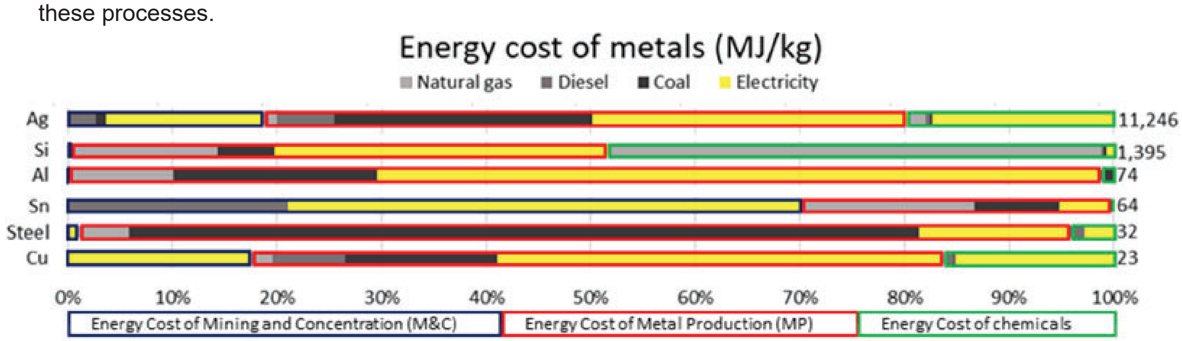

Figure 2. Energy cost of metals used in PV panels.

The mining and concentration step comprises all the processes from the rock extraction until the ore concentrate is obtained. As shown in Figure 2, this step's contribution is considerably lower than the metal production since it is always less than 20%. The exception is the case of Sn, where the M&C contribution is about 70% may be because the underestimation of the amount of chemicals used in this case, which is only 0.25%. On the other hand, for Si, Al and steel (mainly Fe) the contribution is very low (less than 1%) since these elements are very abundant in the earth's crust and therefore, their main energy cost is their metal production. These results are consistent with the literature since, as stated in Norgate et al. [5]: "Mineral processing & concentration, usually have much less impact than metal extraction and refining in terms of energy".

However, in the future, the energy cost of the mining and concentration step is expected to increase due to two factors: (1) a decrease in ore grade, (2) finer grain of many newly discovered deposits. First, this increase is because additional energy is needed to extract the waste material in low-grade ores [6,23]. Secondly, finer grains require grinding to finer sizes resulting in higher energy consumption [5]. Nevertheless, in some cases, technological improvement may play an important role. For instance, despite the decrease in niobium ore concentration between 2017 and 2019 in Brazil, total energy consumption per kg FeNb was lower in 2019 [24]. However, the exponential trend of energy consumption with decreasing ore grade suggests that increasing energy consumption will prevail despite technological improvements [7]. Thus, for example, a decrease in copper ore grade between 0.2% to 0.4% requires seven times more energy [4].

On the other hand, the energy consumption increase in the mining step need not increase the energy consumption of the metal processing steps since a fixed-grade concentrate is produced in concentrating stage regardless of the initial ore grade [5]. Thus, metal production processes start from the ore concentrate until the elements are produced in their metallic form. This is usually the step with the highest energy consumption, as can be appreciated in Figure 2, and as evidenced the literature [25,26].

In order to verify that the energy cost data are comparable with the literature, Table 4 has been constructed. The "This study" column shows the energy cost results obtained, the "mean" column contains the mean of all the samples from the literature (References column) and the "min", "max" and "SD" columns represent the minimum, maximum and standard deviation, respectively. It is possible to observe that all the metals studied are found between the minimum and maximum (Al, Cu, Fe) or in values close to the minimum (Si, FeCr, FeMn, FeNb) except for Ag and Sn. Instead of comparing the footprint of steel, its more important metallic components (iron and some alloys such as FeCr, FeMn or FeNb) have been compare with literature.

The difference with the Sn results could be due to the underestimation of the energy consumed by the chemicals, as previously explained. This would also reduce the percentage of energy used in mining and concentrating. The reason behind the differences lies in the use of different data inventories. However, in the case of Sn there is only one reference for comparison, so it is not easy to draw accurate conclusions with this comparison.

The case of Ag is different since is a by-product of Pb-Zn, Cu or Au mining. Therefore, allocating the share of costs corresponding to silver in the common processes is necessary, as explained in section 2 data and methodology. Thus, in this case, in addition to using different data inventories, a different allocation system has also been employed. The studies in the literature use an economic allocation, but in this study, we have used the physical allocation described in section 2 data and methodology. This adds more uncertainty in comparing the results. Thus, the higher energy cost of silver in this study may also be because this metal has a lower price relative to its concentration in the earth's crust when compared to its co-produced metals (such as Pb or Zn). However, the impact of this fact on the energy cost of PV panels is low, given the reduced silver content compared to other metals.

Table 4. Comparison of the energy cost of metals with literature

MJ/kg	This study	Mean	Min	Max	SD	Samples	References
Ag	11,246	1,745	210	3,280	2,171	2	[25,27]
Si	1,396	5,242	1,490	9,350	3,039	5	[28,29]
Al	74	169	23	263	66	16	[4,6,25,27,30–34]
Sn	64	321	321	321	--	1	[25]
Cu	23	59	18	168	41	18	[4,6,25,31,35,36]
Steel	32	--	--	--	--	--	--
Fe	24	19	7	30	7	8	[25,31,34]
FeCr	31	62	40	83	30	2	[25,27]
FeMn	20	29	24	34	7	2	[25,31]
FeNb	75	127	82	172	63	2	[25,37]

3.2. Carbon footprint of metals

To estimate the carbon footprint of metals, it is essential to know which type of fuel is used, since each of them has different emissions per unit of energy. For this reason, the fuel types in Figure 2 are discussed below. Firstly, the mining and concentration step and secondly the metal production step, pointing out the difficulties of decarbonization.

3.2.1. Fuels used in Mining and Concentration

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In the mining and concentration step, the predominant fuels are diesel and electricity since other fuels never exceed 10%. Diesel is primarily used in heavy mining machinery, such as drilling rigs, trucks, etc. For example, according to Sanjuan-Delmás et al. [36], 99% of the fossil fuels used in a copper mine were diesel in the trucks. Regarding electricity, its main use in mining and concentration step is comminution, a high-energy consumption stage. For instance, comminution uses an average of 15% of the total energy demand of iron production [4]. Another important electricity use is HVAC systems in underground mines [38].

Decarbonization of diesel use is a major challenge. However, some studies [36,39] propose using electric or fuel cell vehicles, but only a few mines currently operate such vehicles, and on a very small scale [40]. On the other hand, decarbonizing electricity is more accessible because renewable energies generate it directly. However, there are two main challenges to decarbonizing electricity from mining operations. The first challenge is integrating renewable energy in remote off-grid mining operations, which usually use fossil fuels for electric generation. However, the number of renewable projects has been increasing. In 2015 there were 600 MW, but by the end of 2019 about 5 GW were projected. But this renewable capacity is still a fraction of the total energy demanded by mining operations, showing a slow-paced development [4]. The second challenge is increasing renewables' share in the grid for connected mining operations.

3.2.2. Fuels used in Metal Processing

As mentioned in the previous section, the metal processing step usually has the highest energy cost. Therefore, its decarbonization would have a greater impact on reducing the carbon footprint. As shown in Figure 2, the most common fossil fuels are natural gas and coal since provide at least 70% of the fossil energy in all the metals. They are used as a source of heat and reducing agents. The use of coal in steel production is noteworthy, as 73% of the total energy comes from this fuel, since its use is inherent to the steel-making process [31].

On the other hand, electricity is mainly used in electrolysis or electrorefining processes. The use of electricity is particularly important in copper and aluminum since contributes to 42% of the total energy cost of copper and 70% in aluminum case. In copper, it is due to its electrorefining stage and in aluminum to the electrolysis process.

Bioreducers and hydrogen are the most promising substitutes for natural gas and hydrogen [26], although with some problems, for example, the sustainable production of bioreductants (such as charcoal) on a global scale, the costs of transporting them or other problems due to their physical characteristics [4]. On the other hand, the use of hydrogen as a reductant is much better in terms of an environmental impact than biomass when it is produced using renewable electricity [41]. However, its generation is still expensive [4], and new infrastructure designed for its use needs to be developed due to its different properties than other fossil fuels [42]. Again, electricity is the most accessible source to decarbonize since metal production plants are usually connected to the grid, not being in remote locations.

3.2.3. Chemical consumption

Chemicals and other auxiliary materials considerably contribute to the energy cost of the processes. This share is significant in the case of Si, Ag and Cu, with a contribution of 48%, 20% and 16%, respectively. In the case of Si, this is mainly because silicon for solar panels must have very high purity, for which a large amount of chemicals is consumed. In the case of Ag and Cu, chemicals are mainly used in electrolysis processes.

In this case, decarbonization depends not on the mining industry but on the chemical industry that provides the products necessary to manufacture metals.

3.2.4. Carbon footprint scenarios

Due to the limitations of substituting fossil fuels (either diesel from mining trucks or coal and natural gas as heat sources and reducing agents in metal processing), this study proposes only the decarbonization of electricity as a first approach to decarbonization. For this purpose, two scenarios are considered: one with high emissions (HES) and the other with low emissions (LES), based on renewable energies. The carbon footprint results are shown in Table 5. The "HES" (high emissions scenario) column shows the results of the scenario in which the electricity has higher emissions; the "LES" (low emissions scenario) column shows the results of the scenario with lower emissions; and the "Diff" column shows the percentage difference between the two scenarios. In addition, a comparison is made with other sources in the literature: the "mean" column shows the mean of all samples; in the "min" column, the minimum; in "max" the maximum; in SD "Standard Deviation", in "simple" the number of samples and finally in “references”, the sources used.

As in Table 4, Table 5 shows that all metals have a carbon footprint in the range of the literature when compared to the "HES" scenario, except for Ag and Sn. The reasons for these exceptions are the same as those explained in section 3.1 above. As seen in Table 5, significant reductions can be achieved just by using renewable energies in electricity generation. The smallest reduction (29%) corresponds to steel due to the large contribution of coal in its energy cost. In addition, the use of coal is inherent in the manufacturing process. However, the footprint of the remaining metals can be reduced from 50% (for Si) to 78.8% (for Cu).

This can have significant implications in the energy transition since using renewable energies in mining reduces the carbon footprint of metals that will later be used in the renewable energy infrastructure, following a feedback process. The following section uses the example of solar panels to expose this idea.

Table 5. Comparison of the carbon footprint in the HES and LES scenarios of metals with literature.

Metal	HES	LES	Diff	Mean	Min	Max	SD	Samples	References
Ag	1333	422	68.4%	283	34	815	301	10	[15,25,43,44]
Si	119	59	50.0%	461	114	775	238	5	[28,29]
Al	8.9	2.2	74.8%	16	5.9	41	9	21	[4,25,30–35,44,45]
Sn	6.8	2.3	65.6%	17	17	17	--	1	[25]
Cu	2.8	0.6	78.8%	5.1	1.1	64.9	9	46	[4,15,25,31,34–36,46]
Steel	3.3	2.3	29.2%	--	--	--	--	--	--
Fe	2.4	1.9	22.3%	3.9	1.2	23.3	7	11	[25,31,34,47]
FeCr	3.5	1.8	48.8%	2.4	2.4	2.4	--	1	[25]
FeMn	2.3	1.1	52.7%	5.2	1.0	9.6	3	10	[25,31,35,43,45]
FeNb	8.8	3.1	64.8%	8.4	5.1	12.5	4	3	[24,25,37]

3.3. Energy cost and carbon footprint of PV Power

Figure 3 shows the Sankey diagram of the energy cost embedded in one MW of solar panels, which amounts to about 10.7 TJ. The diagram allows the analysis by the different stages of the production processes and by the types of fuels. For the first, three phases can be identified:

- Manufacturing and installation: This phase includes all the energy consumption related to the manufacture and installation of a solar panel, but not the energy embedded in the components needed. The energy cost is about 846 GJ, contributing to 7.9% of the total cost.
- Other materials: Besides metals, materials such as concrete or solar glass contribute to energy costs. In this case, they account for 1295 GJ, i.e., 12 % of the total.
- Metals: Metals contribute the most to the energy cost, with 8,623 GJ and 80% of the total. Silicon and steel alone account for 52% and 20% of the total footprint, respectively. Furthermore, the cost of the metals has been divided according to their production steps. As mentioned above, the metal production step is the most important, with 52% of the total cost, followed by the cost due to chemicals, contributing 27%. Finally, the cost of mining is very low, only 0.8%, although, as mentioned in section 3.1, it is expected to grow exponentially in the coming years due to the decrease in ore grades.

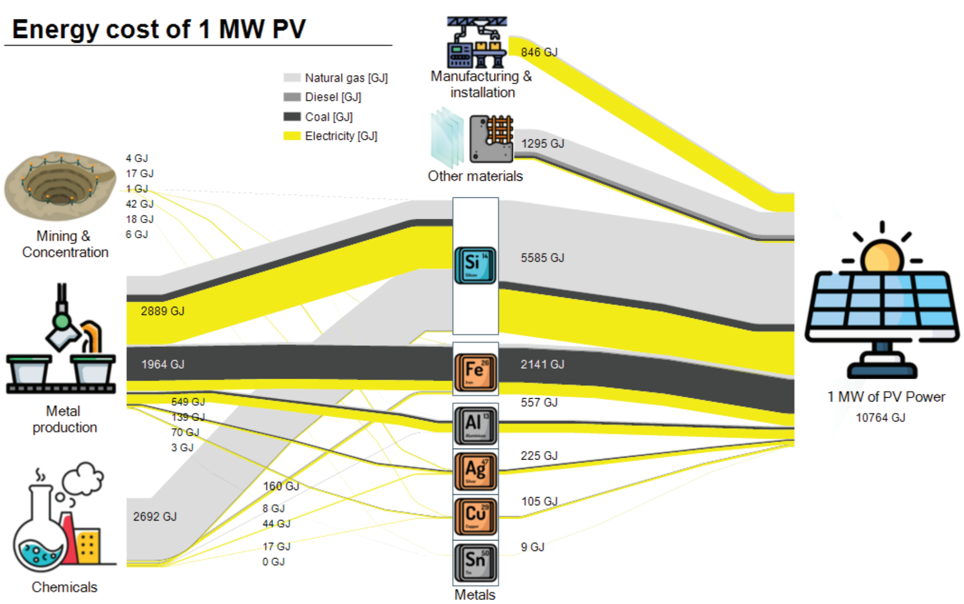

Figure 3. Sankey diagram of energy cost distribution of 1 MW of PV Panels.

Regarding the types of fuels:

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- Natural gas is the most consumed fuel (43% of energy), mainly due to the energy cost of chemicals and crystalline silicon production. Another important consumer is manufacturing other materials, such as concrete or solar glass.
- Electricity holds the second highest share (35%). It is used primarily in the solar panel manufacturing process itself, as well as in the production of the metals such as silicon.
- Coal accounts for 19% of the energy cost. Its main use was in steel production, the second largest contributor to the total footprint after silicon.
- Finally, diesel consumption is residual, as it contributes only 2% of the energy cost and is mainly used in mining and concentrating the metals.

Table 6. Material intensity (kg/MW), Energy cost (GJ), Carbon footprint (kg CO_2 (HES & LES), EROI and Carbon Intensity (C.I.) of 1 MW of PV panels according to the contribution of metals or other materials.

		Other materials	Si	Steel	Al	Ag	Cu	Sn	EROI	C.I g/kWh
Case 1 2018	kg/MW	115700	4000	67900	7500	20	4600	139	-	-
	GJ	1,295	5,585	2,141	557	225	105	9	8.4	-
	kg CO_2 (HES)	86309	474478	223850	66950	26653	12971	949	-	40.0
	kg CO_2 (LES)	77716	237382	158381	16855	8434	2748	326	-	20.4
Case 2 2030	kg/MW	111400	2750	65300	7200	6	4500	139	-	-
	GJ	1,267	3,840	2,059	535	67	103	9	10.3	-
	kg CO_2 (HES)	84317	326204	215278	64272	7996	12689	949	-	32.8
	kg CO_2 (LES)	75940	163200	152316	16181	2530	2688	326	-	16.9
Case 3 2050	kg/MW	92600	1000	54300	6000	1	3700	139	-	-
	GJ	1,141	1,396	1,712	446	11	84	9	15.9	-
	kg CO_2 (HES)	75324	118620	179014	53560	1333	10433	949	-	21.9
	kg CO_2 (LES)	67917	59346	126658	13484	422	2210	326	-	11.2

As was done for metals, two scenarios are established, one conventional, with high emissions due to electricity generation, and the other with low emissions. Additionally, three other scenarios are established depending on the demand for materials for photovoltaic generation: one for 2018 and others for 2030 and 2050, based on literature forecasts [3]. The results are shown in Table 6 and the 2018 scenario is the same represented in the Sankey diagram of Figure 3. In addition, the EROI (see section 2 data and methodology) and the carbon intensity (gCO_2/kWh) have been estimated depending on each case. Thus, Table 6 shows the effect of decreasing material intensity in the EROI, which increases from 8.4 in the 2018 scenario to 15.9 with the most optimistic forecasts for the year 2050. The opposite happens with carbon intensity, decreasing from 40 gCO_2/kWh to 22 gCO_2/kWh. These results are obtained only with the reduction of the material intensity. If low-carbon electricity were additionally used, the carbon intensity of solar panels could be halved. That is, from 40 gCO_2/kWh in 2018 scenario, it could decrease to 20 gCO_2/kWh and in 2050 scenario from 22 gCO_2/kWh to 11 gCO_2/kWh. This emission reduction is limited because electricity contributes 35% of energy costs and is the only energy source that reduces emissions according to our assumptions. Therefore, to achieve complete decarbonization, replacing natural gas and coal in metal production processes with other fuels, such as hydrogen, is necessary. However, this would imply the use of more materials, as new infrastructure would need to be developed. Thus, the total energy costs could increase, although it would reduce the carbon footprint. Furthermore, complete substitution should not only occur in the metal industry, but also in the chemical industry, since a large part of natural gas consumption comes from it (Figure 3). This is an example of the strong interconnection between industries and shows that decarbonization of one industry cannot be achieved without decarbonizing others. For instance, manufacturing solar panels with a lower carbon footprint would require reducing the footprint of metal mining, but also reducing the footprint of the chemical industry that supplies it with essential materials for its production.

The results obtained are comparable to those in the literature. EROI only includes the extraction and operation of the energy source, so it is defined as standard [8]. According to Raugei et al. [48], the standard EROI of photovoltaics is between 6 and 12, with numbers on the range from 8 to 10 obtained in this study for the 2018 and 2030 scenarios. Regarding carbon intensity, the 2018 scenario (20 to 40 gCO_2eq/kWh) is comparable to those obtained 25-40 gCO_2eq/kWh by the reference [49].

However, this study has some limitations. First is the quality and detail of the data inventory used. Although results comparable with the literature have been obtained for most of the metals and the solar panels, this has not been the case for some metals such as Sn. In addition, when using the physical allocation, silver has a much higher cost than reported in the literature. However, these deviations have not influenced calculating the PV energy cost much due to the low material intensity of Sn and Ag. Another problem lies in the global

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view of this study since the electrical energy mixes vary greatly depending on the regions. However, this study has simplified it by taking two carbon intensity scenarios. In addition, the cost of transportation has not been considered due to the global view. Therefore, in future studies, the estimated origin of the metals should be considered since the energy cost and carbon footprint also depend on it.

Finally, it is important to remark that this study has been limited to studying solar panels. Still, other technologies, such as wind turbines, are required to achieve complete electrification and decarbonization. In addition, studying batteries and electrolyzers (for hydrogen production) is indispensable for continuous electricity supply and for substituting fossil fuels. However, their consideration will decrease the EROI and increase the carbon intensity of the system because, despite consuming a large amount of metals and materials, these technologies do not provide any extra energy.

4. Conclusions

This study estimates silicon solar panels' energy cost and carbon footprint from a life cycle perspective cradle-to-gate. It focuses on the required metals, i.e., Fe, Al, Si, Cu, Ag and Ag, which contribute 80% of the total energy cost together. Si and Fe have the highest contribution with 52% and 20%, respectively, while Al, Ag, Cu and Sn have only 5%, 2%, 1% and 0.1%, respectively. The great impact of Si is not due to its mass contribution (only 2%), but to its high energy cost, which amounts to 1,400 MJ/kg. In contrast, Fe contributes 32% of the mass, but its energy cost is much lower, 32 MJ/kg. The remaining 20% of the cost corresponds to energy consumption due to the manufacture of other materials, such as concrete or glass, and to the manufacture and installation of the photovoltaic panels. At current material intensity, 10.8 TJ is required to produce and install 1 MW, which results in an EROI of 8.4. However, the material intensity of the future PV panels is expected to be lower, which could reduce the energy cost to 8.7 TJ by 2030 and 5.6 TJ by 2050, driving a direct increase in EROI, reaching 10.3 and 15.9, respectively. Nevertheless, it does not consider the effect of the decrease in ore grade, which could lead to an increase in energy consumption in the mining process, and therefore to a decrease in EROI.

On the other hand, the type of fuel and the stage at which it is used is also important, as it indicates the current carbon footprint and the potential ease of decarbonization in the future. Thus, the most consumed fuel is natural gas, accounting for 43% of energy, followed by electricity (35%), coal (19%) and finally diesel (only 2%). Diesel is mainly used in mining, which is the phase that contributes least to the energy costs. Coal has an important share due to steel production. Natural gas owes its contribution mainly to the refining of silicon and the chemical production. And the electricity consumption is the most distributed among all the processes. In addition, two scenarios of electricity system emissions have been established, one with high and the other with low emissions. Under the last scenario, the carbon footprint is reduced by half in all cases of material intensity.

Thus, two variables affect the EROI and the carbon intensity of solar panels: the material intensity and the emissions associated with the types of fuel. Material intensity influences both EROI and carbon intensity. If material intensity decreases, EROI increases and carbon intensity decreases. On the other hand, fuel-related emissions only affect carbon intensity. If the former decreases, the latter also decreases. With the best material intensity and using renewable electricity the carbon intensity is 11gCO_2eq/kWh, thus to achieve an even lower impact it would be necessary to decarbonize all fuels, either through the electrification of processes or the use of alternative fuels such as green hydrogen. In conclusion, future variations in the material intensity and the fuels used in the production of metals, chemicals and other materials will determine the sustainability of future energy sources.

Nomenclature

Ag	Silver
Al	Aluminium
CO_2eq	Carbon Dioxide equivalent emissions
Cu	Copper
EROI	Energy Return on Investment
Fe	Iron
FeCr	Ferro Chromium
FeMn	Ferro Manganese
FeNb	Ferro Niobium
HES	High emissions scenario

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LES	Low emissions scenario
M&C	Mining and concentration stage
MP	Metal production stage
Pb	Lead
PV	Photovoltaic
REE	Rare Earth Elements
Si	Silicon
Sn	Tin
Zn	Zinc

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