Received: 29 June 2022 | Revised: 7 October 2022 | Accepted: 11 October 2022

DOI: 10.1002/pip.3642

RESEARCH ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Sustainability of photovoltaic technologies in future net-zero emissions scenarios

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Funding information
Agencia Estatal de Investigación, Grant/Award Number: PID2019-104272RB-C55; FEDER Funds; Ministerio de Ciencia e Innovación

Abstract

Photovoltaic installed cumulative capacity reached 849.5 GW worldwide at the end of 2021, and it is expected to rise to 5 TW by 2030. The sustainability of this massive deployment of photovoltaic modules is analysed in this article. A literature review, completed with our own research for emerging technologies has been carried out following life cycle assessment (LCA) methodology complying with ISO 14040 and ISO 14044 standards. Different impact categories have been analysed for five commercial photovoltaic technologies comprising more than 99% of current market (crystalline silicon ∼94% and thin film ∼6%) and a representative of an emerging technology (hybrid perovskite). By using data from LCA inventories, a quantitative result for 15 impact categories has been calculated at midpoint and then aggregated in four endpoint categories of damage following ReCiPe pathways (global warming potential, human health damage, ecosystems damage and resources depletion) in order to enable a comparison to other renewable, fossil fuel and nuclear electricity production. In all categories, solar electricity has much lower impacts than fossil fuel electricity. This information is complemented with an analysis of the production of minerals with data from the British Geological Survey; the ratio of world production to photovoltaic demand is calculated for 2019 and projected to 2030, thus quantifying the potential risks arising from silver scarcity for c-Si technology, from tellurium for CdTe technology and from indium for CIGS and organic or hybrid emerging technologies. Mineral scarcity may pose some risk for CdTe and CIGS technologies, while c-Si based technology is only affected by silver dependence that can be avoided with other metals replacement for electrodes. When the risks grow higher, investment in recycling should boost the recovery ratio of minerals and other components from PV module waste.

KEYWORDS
amorphous silicon, CdTe, CIGS, crystalline silicon, life cycle assessment, perovskite solar cells, photovoltaic technology, sustainability

1 | INTRODUCTION

The energy transition is accelerating the deployment of new renewable energy capacity. In particular, photovoltaic (PV) installed cumulative capacity reached 849.5 GW at the end of 2021, with 125.6 GW installed in 2020 and a further 129.8 GW in 2021 (of which 53.0 GW in China and 10.3 GW in India) despite the economic shock produced by the COVID-19 pandemia. This increment of installed capacity has made PV energy the largest renewable energy technology measured as installed capacity, outgrowing wind technology which has experienced a slow-down in new added capacity.[1] Solar electricity produced by PV systems was 821 TWh in 2021 (3% of global world electricity), increasing by a record 156 TWh in a single year, and it is expected to rise up to 7000 TWh (19% of global world electricity) in 2030 according to the 'Net Zero Emissions by 2050: A Roadmap for the Global Energy Sector' by the International Energy Agency (edited in 2021[2]).

Part of the public economic expenditure approved to boost the economic recovery is being invested in building new renewable energy capacity. The different scenarios envisaged by the International Energy Agency indicate a strong increase in the share of solar electricity in future energy production worldwide; they include a Stated Policies Scenario (STEP) which has been updated to account of COVID impact on the economy, the Sustainable Development Scenario (SDS) and in particular, the Net Zero Emissions by 2050 scenario (NZE2050) which points to reaching almost 5 TW of PV cumulative capacity in 2030 and surpassing 10 TW in 2040.[2] This colossal growth will require the annual manufacture of millions of solar PV modules and a diversification of PV technologies in a market dominated so far by crystalline silicon technology. Although solar radiation is an inexhaustible renewable energy source, the future demand of raw materials, the energy required to manufacture the PV cells and the environmental impacts of production and operation of PV systems demands a sustainability analysis of solar electricity.[3]

The sustainability evaluation of PV technologies has been focused on the calculation of the energy payback time (EPBT) for many years; the EPBT is considered a non-standardized calculation that is sensitive to many value-choice parameters but which has the advantage of providing very straightforward comparison between PV technologies and with other energy technologies. EPBT is usually calculated for PV technologies considering the following operational values: insolation of 1700 kWh/m^2 per year, average performance ratio to account for all losses, including temperature losses, of PR $=$ 0.75 and a lifetime of 25 years[4]; a careful normalization of reported EPBTs to these values should be carried out with the purpose of comparing them.[5] Additionally, both the cumulative energy demand for production and the solar electricity production are strongly dependent on the geographical location of manufacture and operation of the system and strong differences may be found with different geographical combinations.[6] Values are ranging from less than 4 years for crystalline silicon (4.1[5] to 2.3 years[7]) to about 1 year for thin-film technologies (1.2 to 0.6 years for CdTe, 1.7 to 1.1 years for CIGS and 2.3 to 1.4 years for a-Si[4,5,7]) and with astonishing low values of a few months and even days for organic and hybrid emerging technologies.[8–10]

On the other hand, standardized life cycle assessment (LCA) of PV module manufacture has been carried out for all commercial and emerging technologies by many researchers. For crystalline silicon[11–16] and thin-film[17–20] technologies, the provided LCA impacts enables the possibility to obtain an average with moderated dispersion of data and with minimum and maximum values of the same order of magnitude in all midpoint impact categories. It is not the case for emerging technologies,[10,21–26] where the high dispersion of results is strongly dependent on processing routes that are far from established for a specific industrial production that may in the near future reach the market with massive manufacture of modules. Nevertheless, from a global perspective, the impact of the emerging technologies on world installed and projected capacities up to 2030 will be limited, since the trend of the market seems stabilized in the past 5 years with a market share for crystalline silicon higher than 94% and the remaining 6% occupied by commercial thin-film technologies (cadmium telluride [CdTe], copper indium gallium (di)selenide [CIGS] and amorphous silicon [a-Si]) and a marginal production of III–V technologies for space applications. A recent organized and critical review of sustainability studies of PV technologies can be found in Urbina.[3]

The end of life of PV systems will require adequate strategies at a global level when the massive amount of modules that have been deployed in recent years reaches the end of its operational life and will have to be dismantled and treated as electronic waste. An estimation carried out by Wambach and Sanders assuming a constant annual addition of PV capacity up to 2030 and that the modules are dismantled after a 40 years lifetime (with some small share of advanced replacement due to maintenance) led to an expected PV world waste generation between 1.54 and 7.11 million tonnes by 2030 for two limiting scenarios (minimum and maximum waste generation); Asia (465kt/2690kt) and Europe (744kt/2350kt) are leading the classification[27,28]; these calculated values are similar to the projections of the IRENA-PVPS report, which pointed to a range between 1.7 million and 8 million tonnes by the end of 2030.[29]

Different options can be considered at the end of life of PV systems: reuse of modules that still deliver enough power, recycling of modules and recovery of parts or materials, landfilling or a combination of them. Techniques to recycle silicon and thin-film modules are already available and implemented in several recycling plants, but still with low capacity and low percentage of recovered materials.[30,31] The recovery of secondary raw materials like tellurium, indium, gallium and selenium from recycling of thin-film modules requires further development of pre-treatment procedures that should be cost competitive in comparison to primary mining of these elements.[32] Improved techniques, regulations and logistics for end of life of PV systems and further research and development are strongly needed. These advances may lead to a feedback from recycling strategies to original manufacture lines that should incorporate 'design for recycling' approaches that reduce end of life impacts and maximizes materials and components recovery.[33–35]

The next section of this article is devoted to explain the methodology carried out for the sustainability assessment of PV technologies, first for the conventional LCA methodology and then for the study of dependability on critical minerals for the future deployment of PV capacity at the TW scale. The results and discussion section includes critical comments on the findings both for the risks associated to scarcity of most critical minerals and for the LCA study of 15 midpoint categories analysed and compared to fossil fuel and nuclear technologies in four aggregated endpoint categories of damage assessment. Finally, conclusions and recommendations are summarized in the last section.

2 | METHODOLOGY FOR THE SUSTAINABILITY ASSESSMENT

Sustainability is a concept broadly used but loosely defined and therefore a quantitative evaluation of sustainability will strongly depend on the product or service to be evaluated and the methodological tools used to do so. This article is mainly based on the well-established LCA methodology, which is the tool used for the calculation of many of the parameters presented and discussed in Section 3. It has been complemented with a more detailed compilation of data regarding the production of minerals required to manufacture PV modules of different technologies; the balance of production and demand, together with 'scarcity' indicators, provide information about the sustainability of the very large amount of PV capacity that is already installed in 2020 and that is predicted to be installed according to different future scenarios. More detailed information about the two different approaches to the sustainability presented in the article is provided in the following subsections.

2.1 | LCA applied to PV technologies

The most regulated approach is LCA methodology, which has been developed during many decades and has become the best tool to quantitatively assess impacts in well-defined categories; furthermore, it is regulated by ISO 14040 and ISO 14044 standards,[36,37] which define the different stages of a LCA study: (i) the goal and scope definition of the LCA, (ii) the life cycle inventory (LCI) analysis phase, (iii) the life cycle impact assessment (LCIA) phase and (iv) the life cycle interpretation phase. These stages applied to the study of PV module production, operation and decommissioning, including recycling processes are schematically indicated in Figure 1.

Different impact categories have been analysed; the focus is put on commercial technologies comprising more than 99% of current market (crystalline silicon and thin film) that are analysed in detail with the same methodology (LCIA ReCiPe with access to Ecoinvent 3.8 Swiss database and using SimaPro software). The impacts have been calculated in 15 midpoint categories and more broadly compared with other energy technologies when grouped in endpoint categories.[38] For the commercial technologies mentioned above, the literature review that has been carried out delivered slightly different results (it may depend on variations on the LCI, inventory or the LCIA, impact assessment method, that has been used), the compilation of these data have been included in the figures by using small bars to indicate the maximum and minimum values found in literature in comparison to the calculated ReCiPe average value (blue diamonds) for 15 midpoint impact categories. For emerging technologies, the calculation for hybrid perovskite with methyl-ammonium-lead iodide (MAPI) active layer on glass substrate has been included as a representative of a broad variety of technological options (green triangles); since there is a very large span of values and an increasingly large literature but still with too many methodological and results discrepancies, the maximum and minimum values have not been considered for this case (they are in some cases out of the scale) and a single value is provided; it may be considered as a low optimized option because the calculation is based on a hybrid perovskite cell including lead and spiroOmeTAD as hole transporting layer, both being substances that have high human health and environmental impacts.[24,39] Therefore, the method for obtaining the graphs in Figures 7–13 includes an approach that puts into value well-established methods for single-crystal, multicrystalline and microcrystalline silicon (sc-Si, mc-Si and micro-Si), CdTe and CIGS technologies by using an average of several calculations and including also the maximum and minimum value obtained (with calculations and from a detailed literature review), but it is more cautious regarding the representative for emerging technologies, which has been selected as an hybrid perovskite (calculation for methyl-

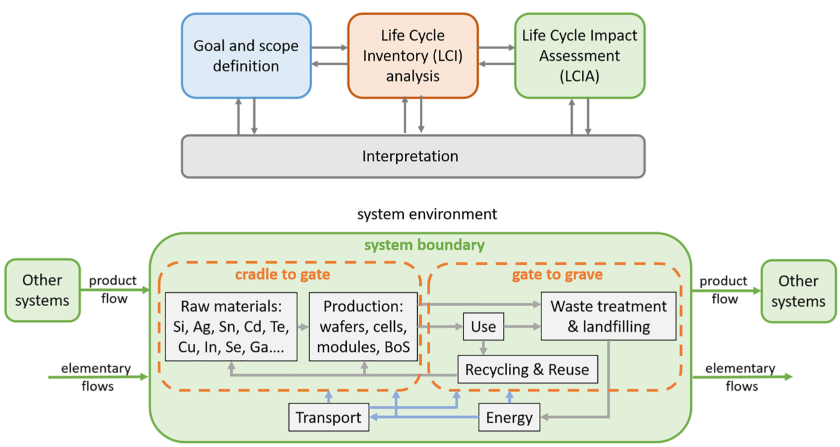

FIGURE 1 Life cycle assessment framework showing the four phases of a LCA study according to the standards ISO 14040 and ISO 14044 (top) and schematic flow of the product system of a LCA study applied to photovoltaic technology; the system boundary includes all stages of the product lifetime; other systems and the environment are out of the system boundary applied to photovoltaic technology assessment (down). [Colour figure can be viewed at wileyonlinelibrary.com]

ammonium lead iodide with SpiroOmeTAD acting as hole transporting layer and with glass substrate[24]). The rationale behind this selection is the following: hybrid perovskite PV technology is the emerging technology with higher potential to reach the market, thanks to its higher power conversion efficiency, more than 25%, and the rapid progress in research aimed to extend its lifetime; besides, within the whole portfolio of technological options within the family of hybrid perovskite PV technology, the one representing the benchmark option (using lead and SpiroOMeTAD) has been chosen despite its higher environmental impacts; this selection has the additional advantage of setting a cap in the impact of the several categories considered in this article that is expected to be improved (i.e., reduced) in the near future. The functional unit in all cases is 1 kWh_{DC} of produced electricity (averaged to lifetime of the operating PV system). Results for the following categories have been obtained: climate change (radiative forcing as global warming potential [GWP100], kg CO_{2eq}); ozone depletion (ozone depletion potential [ODP], kg CFC-11_{eq}); human toxicity, cancer effects (comparative toxic unit for humans [CTU_h, c]); human toxicity, non-cancer effects (comparative toxic unit for humans [CTU_h, n-c]); particulate matter/respiratory effects (intake fraction for fine particles, kg $PM2.5_{eq}$); ionizing radiation, human health (human exposure efficiency relative to U235, kBq $U^{235}{}_{eq}$); photochemical ozone formation (tropospheric ozone concentration increase, kg $NMVOC_{eq}$); acidification (accumulated exceedance, mol $H^{+}{}_{eq}$); eutrophication, terrestrial (accumulated exceedance, mol N_{eq}); eutrophication, freshwater (fraction of nutrients reaching freshwater end compartment, (P)kg P_{eq}); eutrophication, marine (fraction of nutrients reaching marine end compartment, (N)kg N_{eq}); ecotoxicity, freshwater (comparative toxic unit for ecosystems [CTU_{eq}]); land use (soil organic matter, kg C deficit); resource depletion, water (water abstraction related to local scarcity of water, m^3 $water_{eq}$); and resource depletion, mineral, fossil (scarcity kg Sb_{eq}). All these categories are midterm impact evaluation parameters and the LCA methodology provides well-established pathways to assess the corresponding impact in all cases. In order to provide an endpoint impact assessment, several categories are grouped into damage-oriented categories, also called areas or protection, aiming at more easily interpretable results in the form of damage indicators at the level of the ultimate social concerns.[40] Therefore, beside the 15 midterm categories, a grouping has been carried out to obtain endpoint categories and to compare the result with other means of electricity generation; they are Damage to Human Health (measured in disability adjusted life years [DALY] per TWh of generated electricity); Damage to Ecosystems, focused on biodiversity (measured in loss of species per year per TWh of generated electricity); and two more specific environmental-related categories that are greenhouse gas emissions (measured in grams of CO_{2eq} per kWh of produced electricity) and land occupancy (measured in m^2 per MWh and per year, considering the years of land occupancy). The comparison of solar electricity generation with fossil fuel and nuclear electricity generation is presented for this grouped endpoint categories, for data measured and calculated for 2010 technologies with and without carbon capture and storage in fossil fuel technologies and for the case of greenhouse gas emissions, also projections considering envisaged technology improvements for 2050 as proposed by the United Nations Environment Programme have been included.[41] Data for nuclear LCA calculations are obtained from the United Nations Economic Commission for Europe.[42] Attention has been devoted to end of life phases, including logistics of transport of decommissioned modules to the recycling factories and the urgent need to develop more effective means of mineral recovery from PV module scrap and specially reuse of glass.[43] The LCA results can be used to provide recommendations for more sustainable manufacture at laboratory scale and its subsequent up-scaling to industrial level, including recycling and/or landfilling at end of life of each of the components of the solar cell, especially for emerging technologies which are now starting their up-scaling towards industrial production.

2.2 | Scarcity and supply risks of minerals related to PV technologies

As a complement to the conventional LCA results for the resources depletion categories, the supply risks arising from the scarcity of materials have been identified and discussed in more detail taking into account data of mineral production from the British Geological Survey (BGS). Data are accessible in the public BGS database.[44] The data have been used to obtain a trend for 10 years of production change rates (2010–2019), and this 10 years average rate has been considered to extrapolate to mineral production in 2030 for the next 10 years (2021–2030). The choice of using data up to 2019 avoids the anomalies produced in 2020 due to COVID-19 restrictions which affected the production rate of that year. The evaluation of supply risks is carried out by obtaining a ratio of minerals required for PV module manufacture in 1 year to the world production of that year; the years selected to present the ratios are 2019 (calculated on actual real data) and 2030 (calculated with projected data both for mineral production and PV manufacture). Finally, an additional analysis has been carried out using the recently proposed midpoint-level mineral resource impact assessment method called the crustal scarcity indicator (CSI), with characterization factors called crustal scarcity potentials (CSPs) measured as kg silicon equivalents per kg element.[45] This method is especially interesting for the assessment of future risk supply of PV technologies because it relates silicon (with CSP = 1 by definition since it is used as the reference value) to all other materials, which are assessed relative to silicon. Silicon is selected as reference because it is the most abundant element on Earth's crust. They are calculated from the empirical crustal concentration (c_i, measured in ppm) of each element i: $CSP_i = c_{Si}/c_i$ and therefore by definition Si will have a $CSP_{Si} = 1$, all other CSPs being larger, some of them with very high value. The higher the CSP the scarcer is the material. Then, the CSPs proposed for each element can be multiplied by the amount of mass extracted from Earth's crust to obtain the CSI indicator for any other mineral; which has been done for the minerals required for the different PV technologies. Nevertheless, it is not only the supply risk of the raw minerals that may affect the value chain of PV module manufacture and therefore also an additional consideration of dependency of all production steps from mineral to module have been included for the commercial technologies using data from the IHS Markit consultant (used to generate Figure 4[46]). It is worth to emphasize that all minerals of interest for PV technologies, with the exception of tin and silver, are included in the 'Report on critical raw materials for the European Union'[47,48]; silicon metal is included in the report, although from the results presented in Section 3, it is clear that silver poses much higher risks for future PV manufacture than silicon (including both metal and ferrosilicon). The research for reduction of the amount of silver in alloys used for electrodes are providing several alternatives without seriously compromising the performance of the cells; it is worth mentioning alloys with increased tin content (although tin could also be subject to supply tensions in the future), copper-based alternatives,[49,50] and other materials such as graphene, carbon nanotubes or silver nanowires embedded in a polymeric matrix, just to mention a few potential replacements for indium-doped tin oxide (ITO), silver or gold electrodes in emerging technologies that could also be applied to crystalline silicon cells thus having a higher impact since silicon based technology is expected to dominate the market in the following decade.[51] Finally, the interdigitated back contact (IBC) silicon heterojunction technology could facilitate the reduction of silver in the electrodes, in this case, both in the back side of the cell.[52]

2.3 | Scenarios for materials demand for PV capacity installation and lifetime electricity production

Selection of scenarios may lead to discrepancies between different reports from international institutions and articles from the scientific community. In this work, the scenario that has been considered for the evaluation of future demands of minerals for PV production is a combination of the scenario proposed by the International Energy Agency in the report 'Net Zero by 2050. A Roadmap for the Global Energy Sector'[2] for which the data for installed PV capacity by 2030 is obtained and the data contained in several reports of the Fraunhofer Institute for Solar Energy. The information from these later reports provides a trend of technology breakdown of yearly installed total capacity, which has seen oscillations in the past, but that seems very stable in the last 5 years, with a clearly consolidated trend lead by silicon crystalline technology with ∼94% share in the market (with monocrystalline becoming clearly dominant), followed by CdTe (∼4%), CIGS (∼1%) and finally a-Si (less than ∼0.2%).[53] This market breakdown has been kept constant in its separation between crystalline silicon and thin-film technologies and the market share can be extrapolated to the next 8 years in order to obtain the 2030 projected values from which the demand for minerals has been calculated.

Also, a technological maturity stage has to be selected to estimate the amount of minerals required for the production of modules. Silicon content is the most critical element due to the high share of market for crystalline silicon technology, in this case, material usage for silicon cells was reduced significantly from around 16 g/W_p in 2000 to about 3.6 g/W_p in 2011 due to increased efficiencies and thinner wafers, which have evolved from 300 μm in 2004 to 175 μm in 2020, although it has remained stable for the past 10 years for commercial cells around 180 μm. In order to convert from material embedded per square metre of active surface of module to power delivered by the module, the following cell parameters have been used: c-Si cell thickness 170 μm, PCE = 15.8%[42]; and for thin-film technologies: CIGS cell thickness 3 μm, PCE = 12%, CdTe thickness 3 μm, PCE = 10%, a-Si thickness 5 μm, PCE = 10%. Additionally, the difference between the material finally embedded in the cell and the initial input required for cell production, that is, the utilization rate for c-Si is currently 50% and may be strongly improved up to 90% in optimistic scenarios by 2040; for a-Si is already at 90%, while for other thin films, there is still room for improvement from current 60% to 90% by 2040[54]; for thin-film technologies, the use of materials in the active layer is strongly reduced due to the much lower thickness of the active layer, around a few μm for all thin-film technologies, a value that has been kept very similar in the past 10 years; in particular, average values for use of main elements in the active layers are 0.068 g/W_p silicon in a-Si:H technology, 0.064 g/W_p cadmium and 0.067 g/W_p tellurium in CdTe technology and 0.019 g/W_p copper, 0.022 g/W_p indium, 0.004 g/W_p gallium and 0.031 g/W_p selenium in CIGS technology as calculated from averages of literature review (Table 1 for c-Si, Table 2 for CdTe, Table 3 for CIGS and Table 4 for a-Si). For this study, the following average embedded quantities of material have been considered:

The combination of market share and amount of material requirements for each technology have been used to calculate the 2019 ratio of world mineral production to PV demand of each of the materials for module production (installed capacity) and similarly using the

TABLE 1 c-Si technology: material requirements for a solar cell in kg/MW_p from several references indicated in first row and calculated average

c-Si	Moss et al.[55]	Moss et al.[56]	Elshkaki and Graedel[57]	Valero et al.[58,59]	Average
Si	3653.0			5377.5	4515.3
Al	10,593.0			12,511.0	11,552.0
Cu	2741.0	2194.1	7597.5	3554.0	4021.7
Sn	577.0	463.1		442.0	494.0
Ag	24.0	19.2	355.9	113.1	128.0
Mg	53.5			45.8	49.7
Ni			1.1	0.9	1.0

Note: It includes metals required for frames, soldering and cables of typical module.

TABLE 2 CdTe technology: material requirements for a solar cell in kg/MW_p from several references indicated in first row and calculated average

CdTe	Moss et al.[55]	Moss et al.[56]	Elshkaki and Graedel[57]	Fthenakis[18]	Berger et al.[60]	Bleiwas[61]	Andersson and Jacobsson[62]	Candelise et al.[63]	Average
Cd		61.1	63.3			85.0	63.3	49.2	64.4
Te	93.3	47.2	61.9	55.0		97.5		47.2	67.0
Cu					42.8				42.8
In (in TCO)	15.9	15.9							15.9
Sn (in TCO)	21.4							6.6	14.0

Note: It includes metals required for soldering and cables of typical module, which are considered frameless.

TABLE 3 CIGS technology: material requirements for a solar cell in kg/MW_p from several references indicated in first row and calculated average

CIGS	Moss et al.[55]	Moss et al.[56]	Elshkaki and Graedel[57]	Fthenakis[18]	Bleiwas[61]	Andersson and Jacobsson[62]	Candelise et al.[63]	Average
Cu	21.2	21.0					16.9	19.7
In	19.0	18.9	27.4	15.5	22.5	27.4	27.4	22.6
Ga	2.3	2.3	5.0		7.5	5.0	5.0	4.5
Se	9.6	9.6	45.3		45.0	45.3		31.0
In (in TCO)	44.3						94.3	69.3
Sn (in TCO)	6.0						85.8	45.8

Note: It includes metals required for soldering and cables of typical module, which are considered frameless.

TABLE 4 a-Si technology: material requirements for a solar cell in kg/MW_p from several references indicated in first row and calculated average

a-Si	Moss et al.[55]	Elshkaki and Graedel[57]	Fthenakis[18]	Andersson and Jacobsson[62]	Average
Si					68.6
In	5.3				5.3
Sn	0.7				0.7
Ge (in a-Si/Ge)		6.9	4.4	6.9	6.1

Note: The Si content in this case is a calculation for an a-Si module with 5 μm cell thickness and PCE = 10%. The calculation includes metals required for soldering and cables of typical module, which are considered frameless.

projected total amount of PV installed capacity (on an annual average) up to year 2030 according to the NZE2050 IEA scenario as indicated above.[2] When data for electricity production are considered as the functional unit for the LCA study or to compare with other electricity generation technologies, a further calculation has been accomplished using the same PV system performance ratio (PR = 0.75, including temperature losses) and the same average irradiance of 1700 kWh/m^2 per year, which is the one used by UNEP in its calculations.

3 | RESULTS AND DISCUSSION

The results are organized in two subsections. First, results regarding to an analysis of minerals required for the manufacture of modules of different PV technologies, including the geographical dependence of both the mineral and final product manufacture; second, the more conventional LCA study of the solar electricity produced from several PV technologies and compared with other renewable electricity technologies and the fossil fuel and nuclear alternatives.

3.1 | Mineral scarcity, world production and demand for PV systems manufacture

The initial analysis is independent of PV deployment scenarios, and it is based on the list of minerals that are used in any PV technology, either commercial or emerging still out of the market. From a potentially large list of minerals related to any step of manufacture production, including recycling processes, a more limited number is selected in this article for a cross comparison of CSP and worldwide yearly production which is presented in Figure 2.[3,44,45]

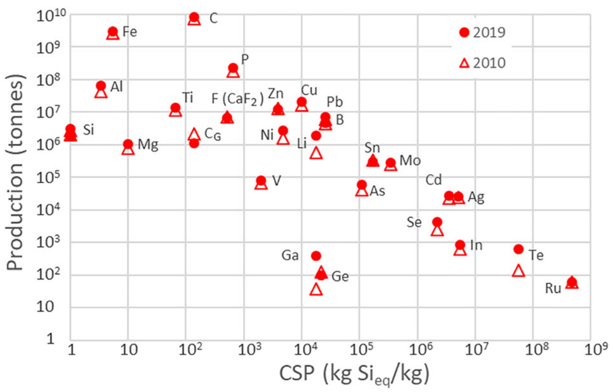

FIGURE 2 World production (in metric tonnes) and crustal scarcity potential (CSP in kg Si_{eq}/kg) in years 2010 and 2019 for minerals related to photovoltaic module production of any technology. Logarithmic scale has been used in both axis of the graph. Data from British Geological Survey[44] and Arvidsson et al.[45] [Colour figure can be viewed at wileyonlinelibrary.com]

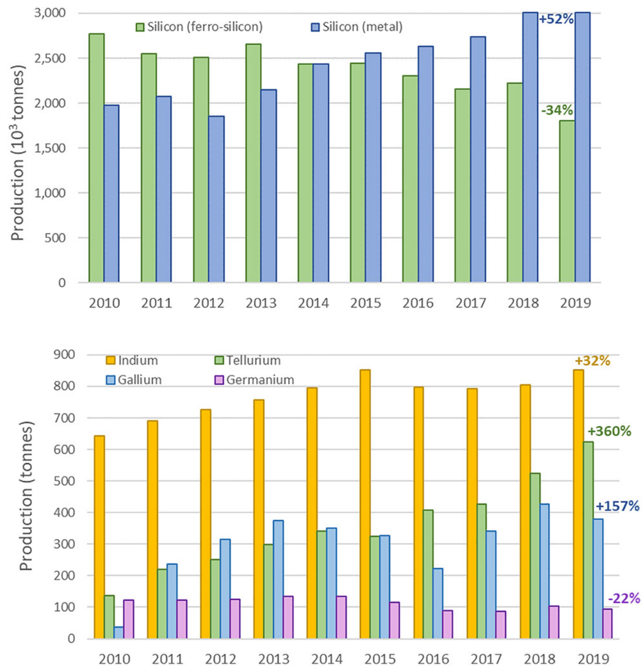

FIGURE 3 Evolution of annual production (in metric tonnes) of selected minerals related to the production of solar cells of several technologies. Production of silicon is of the order of a few billion tonnes, while for the other minerals is of a few hundred tonnes. The percentage numbers indicate the evolution in the past 10 years. Data from the British Geological Survey[44] [Colour figure can be viewed at wileyonlinelibrary.com]

With the log–log representation used in the graph, the distribution of the data points seems to indicate that there is a limiting boundary in the trend described by an inverse power law relating the CSP to the annual production; the elements well below this boundary may have a potential for higher production, as can be the case of gallium (which in fact has highly increased its production from 2010 to 2019) and germanium (in which case, data are not very reliable, since the BGS and USGS reports do not contain undisclosed production from some countries, and this is particularly sensitive for germanium, which is used as a substrate for III–V PV technologies, and also in future amorphous Si/Ge tandem cells). The inverse power law described above seems to saturate at higher production rates of a few billion tonnes (Fe and C) leading to smaller production such as observed for Al or Si that could have still a much larger production potential. The large increase in tellurium production in the past 10 years, although from much lower levels, should be emphasized. CdTe technology is strongly dependent on tellurium production, and although its market share is still reduced, it is the first thin-film technology and its module production has already surpassed 6 GW in 2020.[53]

The data for annual production of minerals have followed a trend that is shown in more detail for five minerals: silicon (both in ferrosilicon and metal stages) in the upper part of Figure 3, showing the production reaching more than 3 billion tonnes for silicon metal (increasing steadily +52% in the past 10 years) and complemented with an additional 1.7 billion tonnes of ferrosilicon (which has seen its production reduced by −34% in the past 10 years), put together, the silicon production has strongly increased. In the lower part of Figure 3, the data for indium, gallium, tellurium and germanium are shown, in this case, with much lower levels of annual production, of a few hundreds of tonnes, increasing +32% for indium and showing a much stronger increase for gallium (+157%) and tellurium (+360%) although with some oscillations, while germanium has reduced its production (−22%, although this reduction may be due to the lack of access to real production data in some countries, as mentioned above).

This approach should be complemented with a study of the relationship of the world annual production of minerals and the actual demand for the manufacture of PV modules of different technologies. As indicated in the methodological section, two levels of correlation have been established: the first one comparing data from real production of year 2019 both for minerals and modules which demand those minerals. The amount of mineral for each technology is calculated according to the methodology described in Section 2, which combines the amount of element embedded in the modules and the total production (real data in 2019 and projected for 2030). The technological advancements in the past few years and expected in the next 8 years which may reduce the amount of elements has not been taken into consideration and therefore this risk level is putting an upper limit that will probably be lower in the future due to: first, that the production of PV modules could be lower than the one proposed by the relatively optimistic NZE2050 scenario taken into account for 2030 and second, that technological advancements will lead to reduction of embedded elements per W_p of module power. The results of the correlation are summarized in Figure 4 presenting annual production versus demand for PV module manufacture of selected minerals and its change from 2019 (with market data) and for 2030 (for projected data, according to NZE2050 IEA scenario) and taking into account the same market share for the different PV technologies as of 2020, which has been

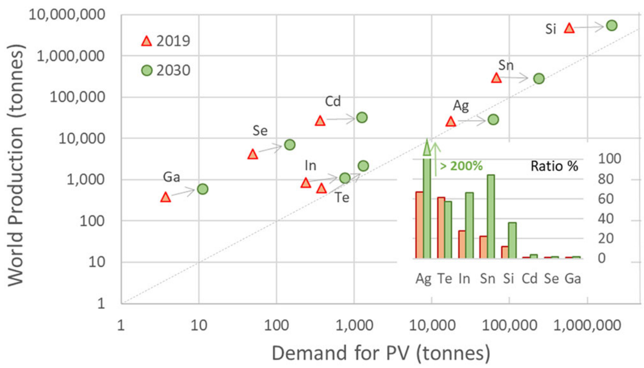

FIGURE 4 World production (in metric tonnes) versus demand for PV manufacture (in metric tonnes) of selected minerals, both in logarithmic scale and showing the change from 2019 (markets) and 2030 (projection according to NZE2050 IEA scenario). The inset shows the ratio (%) between annual PV demand and annual world production for each mineral for both years. [Colour figure can be viewed at wileyonlinelibrary.com]

stable for the past 5 years. The logarithmic scale in both axes point to a power law relationship between both values, but it also makes very clear how the demand for PV is moving must faster to higher values than world production, thus increasing the ratio presented in the inset for all minerals.

The ratio between the annual demand of any element required for PV manufacture and its annual production has been calculated based on real market data of production and demand for year 2019 and based in the projections from the NZE2050 scenario for year 2030; these ratios are shown in the inset of Figure 4. The most worrying finding shown in Figure 4 is the high ratios shown in the inset; for all minerals in 2019 are still below 100% (i.e., points above the diagonal line in the graph, with production every year covering the annual demand, with no need to use already extracted reserves), but the ratios are especially high for silver (used in all technologies for electrical contacts) and tellurium (affecting only CdTe technology). This fact is emphasized by the projection, which strongly increases the ratio of silver (above 200%, thus crossing the diagonal) making compulsory to look for replacements, which is a very intensive field of research in silicon based technologies; the best replacement are alloys with higher tin content and with aluminium; tin may also create market tensions (reaching a ratio >80%), while aluminium (being one of the most abundant metals on Earth's crust) is a better replacement although it has a higher embedded energy due to its production process. Indium has since long time been identified as a critical metal, required for microelectronics industry and used in a broad class of applications in alloys for III–V active layer compounds for PVs, advanced high mobility microelectronic devices and transparent conducting oxides (TCOs) in many electronic applications, where indium-doped tin oxide, ITO, with around 0.022 g/W_p indium and 0.045 g/W_p tin could be a restriction to massive deployment of new emerging technologies requiring TCOs as front electrode unless it is replaced by fluorine-doped tin oxide (FTO).

Despite these findings, the study of risks associated to mineral scarcity for PV systems manufacture provides an optimistic view with limited supply tensions for the next 8 years (up to 2030) even for the case of the NZE2050 scenario, which considers a high deployment of renewable electricity (and good compliance with nationally determined contributions related to the Paris Agreement, which only if they are supported by political commitments and technological capabilities are included in the IEA model). Therefore, the deployment of 4956 GW_p worldwide considered for the calculations is not threatened by a mineral scarcity that may hinder its manufacture.

Regarding the geographical dependence and associated risks of mineral production and PV modules manufacture, the results go beyond standard LCA methods. The analysis of the mineral production and potential risks due to geographical location of mines or of main primary producer is shown in Figure 5, including the share of production for the most relevant minerals for commercial PV technologies. It is clear that China holds the larger share in the seven selected minerals for the study. Silver production led by Mexico is the only exception, which reduces the risk supply for the most critical element for crystalline silicon technology, the one holding the highest market share (now and in the near future).

Beyond mineral production and its geographical distribution shown in Figure 5, the next stages in the production of PV modules are also strongly dependant on Chinese manufacture, as can be observed in Figure 6. Starting with the production of silicon crystalline ingots, China produced more than 40% in 2010 and more than 75% in 2021, thus showing an increasing market dominance, despite the efforts to install silicon manufacturing centres in other countries. The trend is similar for the other stages of production, especially for silicon wafer production, where Chinese dominance is very strong with more than 95% of production in 2021; and for cells, where China produces 79% of world supply in 2021, the rest being produced by other Asian countries. Only the final assembly of modules seems to be stable with

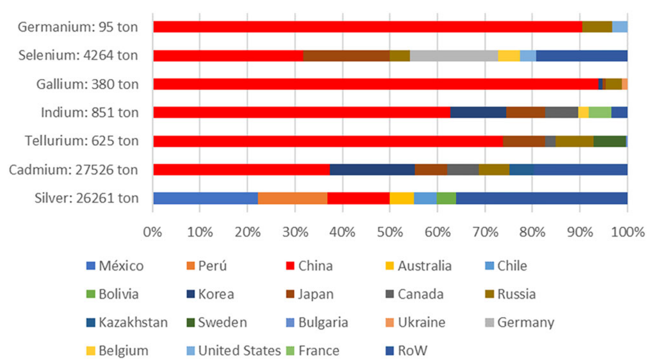

FIGURE 5 Share of mineral production for seven principal elements that are used to manufacture commercial PV technologies. c-Si technology is only affected by silver use which can be replaced with other metals for electrodes. CdTe and CIGS technologies are more affected by potential supply risks (tellurium and indium respectively). Data from British Geological Survey (data for 2019).[44] Units for total production in metric tonnes [Colour figure can be viewed at wileyonlinelibrary.com]

a more diversified market share still dominated by China with 'only' 66% (approximately the same in the past 10 years, but with an increasing participation of other Asian countries in detriment of European production). There is no indication that these trends may vary in the near future up to 2030, and therefore, it is essential that China and other Asian countries are inserted in world markets and are able to distribute their production without custom tariffs wars. From the sustainability point of view, the embedded emissions in the produced wafers, cells and modules, could be strongly reduced if the energy mix of China and the other Asian countries evolves towards reduced greenhouse gas emissions and a more efficient primary energy to electricity conversion (improving the actual rate of around 35%) and the direct input of renewable energy into the grids. This objective is within reach since China is not only the main PV module producer but also the main PV module installer of the world (with 253.8 GW_p installed cumulative capacity at the end of 2020, of which 48.2 GW_p where installed that year[64]).

3.2 | LCA of PV technologies

The second approach to the sustainability study is the LCA of the production, operation and end-of-life of PV technologies; it is therefore a cradle-to-grave study, following ISO 14040 and ISO 14044 recommendations. The methodology has been explained in detail in Section 2.1 for a functional unit of 1 kWh_{DC} of electricity production for five commercial PV technologies and one emerging technology. The results of the LCA study are presented in three groups of midpoint categories. The first group shown in Figure 7 includes three categories directly related to human health: human toxicity cancer and non-cancer effects and impacts of ionizing radiation on human health, where all technologies have the same order of magnitude of impacts, with CdTe slightly lower (contrary to expectations due to potential cadmium risks) and perovskite solar cells with the highest impact on human toxicity due to lead in the active layer (MAPI cells were considered for the calculation), but lower in ionizing radiation (indirectly due to the lower cumulative energy demand for its production[24,26]). A detailed list of all substances embedded in the solar cells or used during its manufacture is provided in Urbina,[3] with an additional discussion of health risks for selected 'issues' which are commented in more detail with information obtained from the Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA), both in the United States of America and also the European Chemicals Agency (ECHA); the two substances that deserve more attention are cadmium (extremely toxic, with cancer effects and kidney toxicity) and lead (which affects the central nervous system, gastrointestinal, blood, kidney and reproductive organs), in both cases encapsulation techniques are being developed which focus on sequestration processes to retain the substance in order to avoid accidental release in case of accident (broken modules, flooding and even fire events) or at the end of life[18,65]; or in the case of perovskite technologies, the replacement of lead with other metals in the MAPI structure at the cost of slightly lower power conversion efficiency.[39] A special mention should be made about silicosis, a severe lung disease linked to quartz mining (which is an initial stage for glass and silicon production); in the past, incidence of the sickness was high, and although it has been reduced thanks to health and safety improvements in the mining industry, it is increasing again, especially in emerging economies of developing countries. Many experts consider that silicosis could become a pressing global health issue and that it should be considered an 'epidemic in the making'.[66]

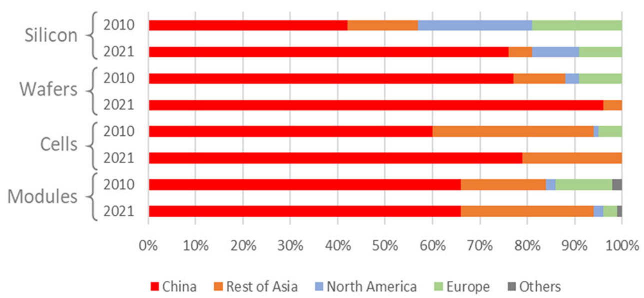

FIGURE 6 Share of production of silicon ingots, wafers, cells and modules between the different manufacturing countries or regions, with comparison between 2010 and 2021. Data from IHS Markit[46] [Colour figure can be viewed at wileyonlinelibrary.com]

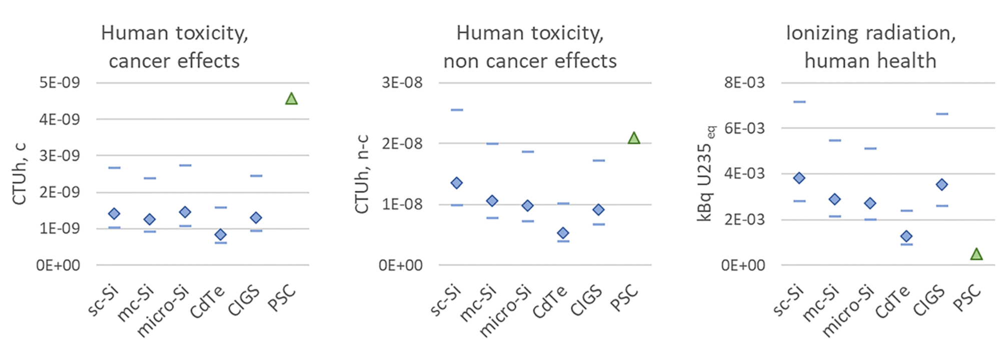

FIGURE 7 Midpoint impact categories directly related to human health for five commercial PV technologies (single-crystalline silicon [sc-Si], multicrystalline silicon [mc-Si], microcrystalline silicon [micro-Si], cadmium telluride [CdTe] and copper indium gallium (di)selenide [CIGS]) and one example of emerging technology (hybrid MAPI perovskite, PSC) [Colour figure can be viewed at wileyonlinelibrary.com]

The next group, presented in Figure 8, includes nine midpoint categories directly linked to environmental damage (and indirectly related also to human health toxicity); again, all PV technologies are of the same order of magnitude, although presenting a higher dispersion of values compared to the previous group. In this case, single-crystal silicon technology has the higher impact in all categories, and thin films the lowest, either commercial CdTe or CIGS (in all but three cases, where perovskite cells have lower impacts: GHG emissions and freshwater and terrestrial eutrophication); on the other hand, PSCs present the highest impacts in freshwater ecotoxicity, again linked to the use of lead and the complex chemical route for SpiroOmeTAD synthesis.[24,67] Despite crystalline silicon solar cells being the

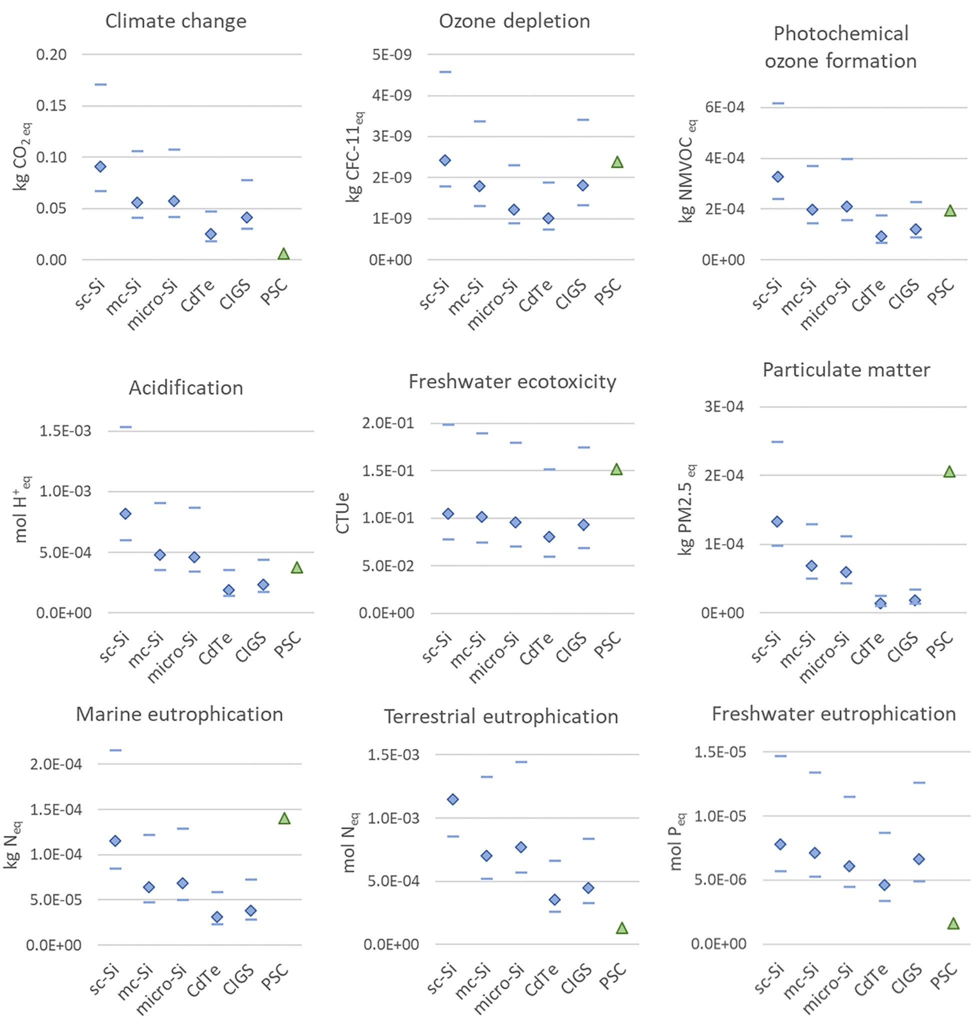

FIGURE 8 Midpoint impact categories directly related to environment (and indirectly to human health) for five commercial PV technologies (single-crystalline silicon [sc-Si], multicrystalline silicon [mc-Si], microcrystalline silicon [micro-Si], cadmium telluride [CdTe] and copper indium gallium (di)selenide [CIGS]) and one example of emerging technology (hybrid MAPI perovskite, PSC) [Colour figure can be viewed at wileyonlinelibrary.com]

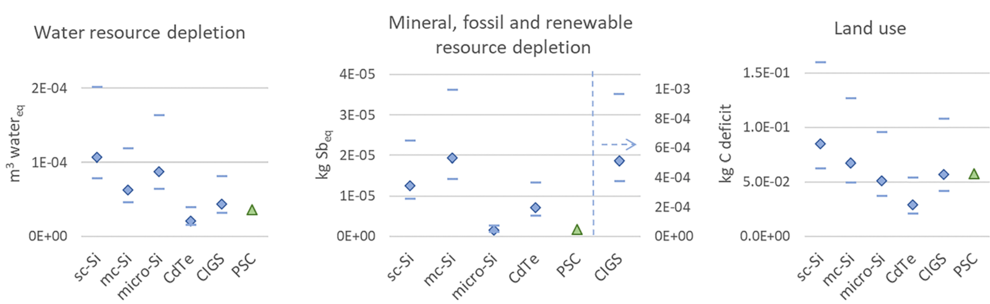

FIGURE 9 Midpoint impact categories directly related to resources depletion for five commercial PV technologies (single-crystalline silicon [sc-Si], multicrystalline silicon [mc-Si], microcrystalline silicon [micro-Si], cadmium telluride [CdTe] and copper indium gallium (di)selenide CIGS) and one example of emerging technology (hybrid MAPI perovskite, PSC). Note the secondary axis for CIGS data in mineral, fossil and renewable resource depletion. [Colour figure can be viewed at wileyonlinelibrary.com]

dominant technology with more than 94% of market share and very optimized industrial production, either already commercial thin-film or emerging technologies may provide the same electricity (considered as a functional unit) with lower environmental impacts.

In the final group shown in Figure 9, three midpoint categories most directly linked to resources depletion have been included: In this case, CIGS technology presents much higher impacts than the other PV technologies, mainly due to the higher risks associated to the depletion of indium, although tellurium scarcity is also a concern for CdTe technology. A more detailed discussion of the sustainability linked to mineral resources and actual and future demand for materials has been included in the previous subsection.

Finally, the comparison of life cycle impacts of electricity production by different renewable, fossil and nuclear means is presented in endpoint categories that are built by using pathways to impact which relate the midpoint categories to broader damage assessment 'endpoint' categories. This comparison is better used to communicate to stakeholders, including policy makers and lay public, the implications of the different electricity production means in different scenarios. With this purpose, the following graphs have been prepared for climate change (greenhouse gas emissions, CO_{2eq} per kWh of produced electricity), human health (DALY), ecosystems (loss of species per year per TWh) and land occupation (m^2-year per MWh) impacts. In all the graphs, commercial PV technologies, either rooftop or ground mounted, are compared with other renewable sources, with fossil fuel sources (coal and natural gas) and with nuclear (average data of different technologies and for a 1 GW plant). For nuclear, it must be emphasized that lifecycle emissions are estimated at 5.5 g CO_{2eq}/kWh on a global average, with most of the emissions occurring in the front-end processes (extraction, conversion, enrichment of uranium and fuel fabrication), operation and maintenance are considered incident-free and end-of-life long-term treatment in deep storage of nuclear waste is not included due to the high uncertainties for the calculation, although encapsulation by enclosing spent fuel in copper-cast iron canisters for interim storage has been included; a lifetime for the nuclear plant of 60 years is considered, which is higher than the most commonly used of 40 years, although some nuclear plants have already surpassed this lifetime. With all these assumptions, nuclear is treated with an optimistic point of view that delivers values that can be considered a lower bound for GHG emissions and other environmental impacts; no serious nuclear accident is considered throughout the lifetime of the plant.

Greenhouse gas emissions (in grams of CO_{2eq} per kWh of produced electricity) are shown in Figure 10 and compared to the same impact category for other means of electricity production (be aware of the logarithmic scale in the axis of the figure). The differences between PV technologies are small compared to this quantitative huge jump for fossil fuels. All renewable sources have the same order of magnitude of emissions in the range of tens of grams of CO_{2eq} per kWh, while fossil fuels jump between one or two orders of magnitude up to several hundreds of CO_{2eq} per kWh, even with the inclusion of carbon capture and storage technologies; interestingly, the data show the possibility of a much higher reduction of emissions in the horizon of 2050 for PV technology than for any other technology. Nuclear is a low emissions technology, of the same order than PV technology, but with less room for improvement due to technological constrains (and the uncertainty about long-term nuclear waste treatment mentioned above).

When human health damage endpoint impact is considered (Figure 11), the difference between renewable technologies and fossil fuel technologies is again high with at least one order of magnitude difference in DALY per TWh between the PV technologies with lower impact (thin film) and the average of fossil fuel technologies; if crystalline silicon is considered, this difference is reduced to 'only' between three to four times larger; in this case, the inclusion of carbon capture and storage systems in the carbon or natural gas plants significantly increases the human health impacts. Nuclear have impacts in the lower range, comparable to wind onshore and medium-size hydro, but

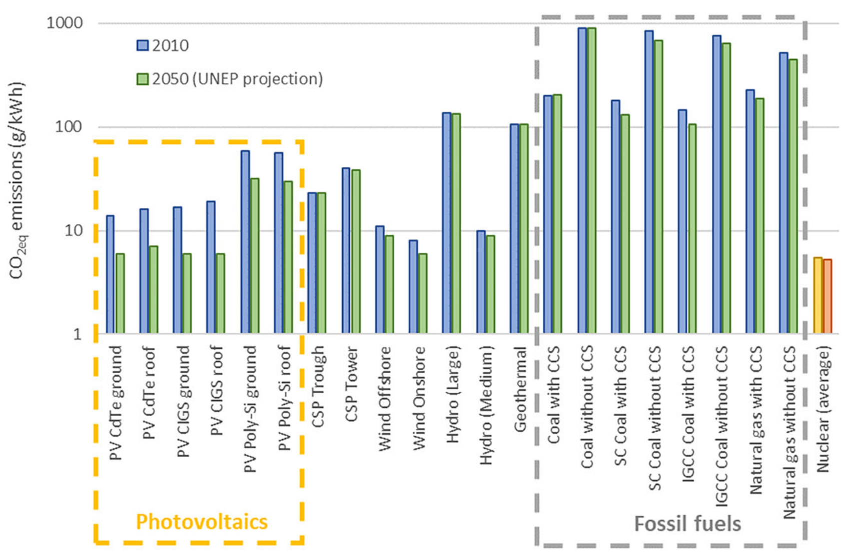

FIGURE 10 Life cycle greenhouse gas emissions (in grams CO_{2eq} per kWh) of different electricity supply technologies, modelled for 1 kWh produced in Europe, comparing photovoltaic, fossil fuel and nuclear technologies (CO_2 capture and storage [CCS], integrated gasification combined cycle [IGCC] and gravity-based [GB] foundation). Calculations with data from previous studies[3,41,42,68] [Colour figure can be viewed at wileyonlinelibrary.com]

for this calculation of human health impacts, neither the risks of nuclear accident nor the long-term nuclear waste treatment risks have been taken into account.[42]

Regarding the endpoint aggregated impacts on ecosystems (Figure 12), the trend is similar to human health impacts. Again, the group or renewable energies have much lower impacts than the group of fossil fuel. Within PV technology, CdTe shows lower impacts, followed by CIGS and with crystalline silicon on top, but still with impacts four times lower than the fossil fuel technology with lowest impacts; again, the inclusion of carbon capture and storage systems in the carbon or natural gas plants significantly increases the environmental impacts (others than climate change).

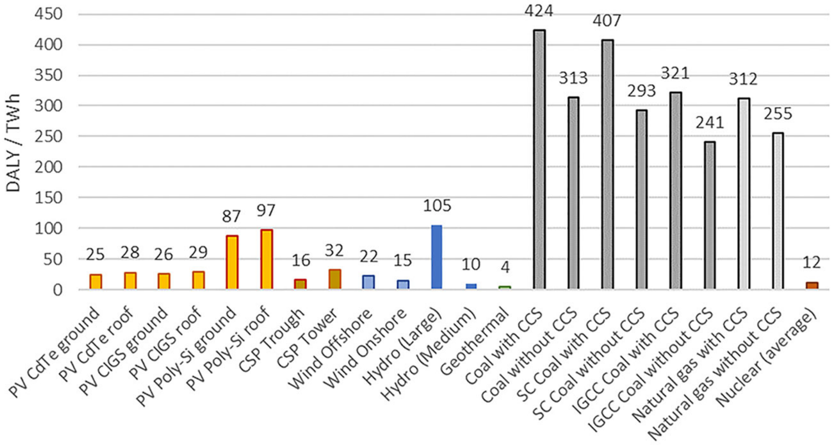

FIGURE 11 Comparative human health impact of electricity production, in aggregated endpoint category measured in units of disability adjusted life years (DALY) per TWh of electricity generated following different damage pathways according to the ReCiPe (H) impact assessment methods (CO_2 capture and storage [CCS], integrated gasification combined cycle [IGCC] and supercritical [SC]). Calculations with data from previous studies[3,41,42,68] [Colour figure can be viewed at wileyonlinelibrary.com]

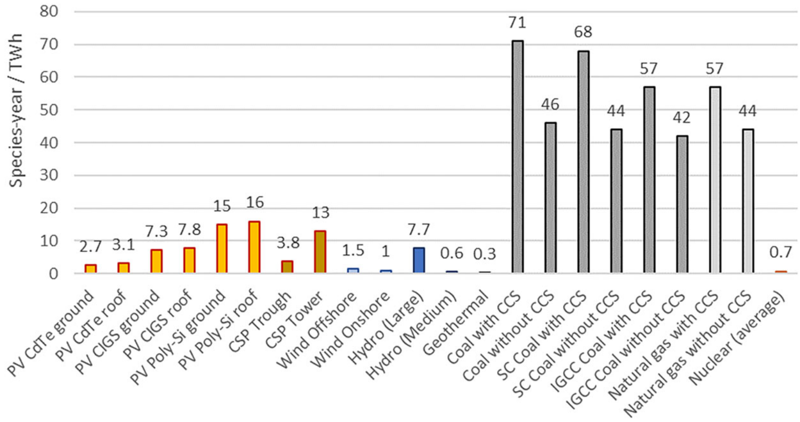

FIGURE 12 Ecosystem impacts of electricity production measured in species-year affected per TWh of electricity following different damage pathways according to the ReCiPe (H) impact assessment method (CO_2 capture and storage [CCS], integrated gasification combined cycle [IGCC] and supercritical [SC]). Calculations with data from previous studies[3,41,42,68] [Colour figure can be viewed at wileyonlinelibrary.com]

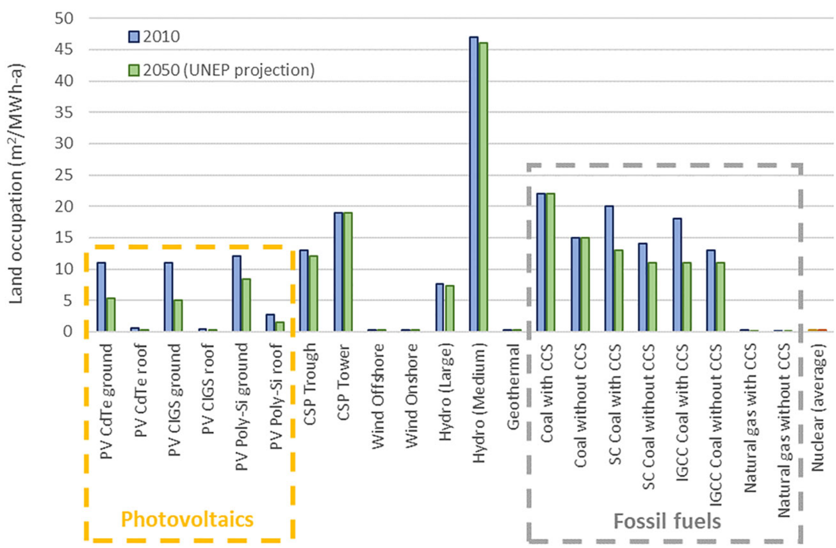

FIGURE 13 Land occupation required for the production of electricity (CO_2 capture and storage [CCS], integrated gasification combined cycle [IGCC] and supercritical [SC]). Calculations with data from previous studies[3,41,42,68] [Colour figure can be viewed at wileyonlinelibrary.com]

Finally, land occupation is the only impact category in which renewable energy technologies are comparable to fossil fuel technologies (Figure 13). Nevertheless, in this case, the difference of impact between rooftop and ground-mounted systems is very strong and only in this later case the impact is comparable (and still lower) than fossil fuels; the apparent contradiction that can arise from the fact that large PV plants occupy more land than the relatively compact coal or gas plants is due to the inclusion in the calculation of impacts in land occupation arising from coal mining and oil or gas extraction; if they are included, the impact on land occupation is larger for fossil fuels.

Nevertheless, the massive deployment of grid-connected utility scale PV plants occupies large swathes of land (hundreds of hectares). This competition for land use between electricity and food production, or the strong visual impact of the PV plants, are generating social alarm and in some cases even provoking social unrest and mobilizations against the PV utility plants. This socio-economic impact, whose quantitative evaluation goes beyond the conventional LCA approach that only measures land occupation, is out of the scope of this article but should be taken into consideration in any future planning of massive deployment of PV plants. A recent approach is the combination of food production with electricity production in agrivoltaic systems which combine both uses of land.[69]

4 | CONCLUSION AND RECOMMENDATIONS

The global impacts of PV future deployment for the three main IEA scenarios have been calculated according to LCA methodology (following ISO 14040 and ISO 14044 standards and IEA-PVPS recommendations). All PV technologies have midpoint impacts of the same order of magnitude for 15 impact categories, with crystalline silicon in the upper range of many of them, and thin films in the lower range (with the exception of CIGS in resources depletion category). Hybrid perovskite technology, chosen as a representative of emerging technologies, shows a large variation of impacts, with higher impacts in human health-related categories, and lower in ecosystem and greenhouse gas emissions categories. When endpoint categories are considered and impacts compared with fossil fuels, PV technology shows significantly lower impacts (four times lower for human health and ecosystem categories and two orders of magnitude lower for GHG emissions), and only land occupation impacts are comparable.

China holds the larger share of production in six of the seven selected minerals for the study (silver production, led by Mexico is the only exception), and it also dominates the value chain for PV module manufacture, with a strong dominance in the main three stages: silicon ingot production, wafer and cell fabrication and module manufacture. Therefore, confrontation with China will increase the risks, and scientific and technological collaboration is strongly recommended. Besides, other countries, and specially Europe, should consider developing (again) manufacturing capabilities to recover part of the value chain for PV module production, which may comprise all cycle from crystalline silicon ingots to module manufacture to cover, at least in part, the future capacity installation in Europe.

The already installed capacity and the estimated deployment of future capacity that will reach its end of life within three decades requires a global approach to deal with the decommissioning stage of the PV modules. Ideally, all PV modules should be recycled, but actual recycling capacity is well short of the required capacity, and although there is an important research effort (and patent registrations) for PV technology recycling, the value of recovered materials still do not cover the cost of an effective recycling route. Mineral scarcity may pose some risk for CdTe and CIGS technologies, while c-Si-based technology is only affected by silver dependence that can be avoided with other metals replacement for electrodes. When the risks grow higher, the investment in recycling facilities will boost the recovery ratio of minerals from PV module waste.

A final conclusion is the actual weakness of the end-of-life stage of PV systems, both at a fundamental scientific level and at an applied industrial level. On the one hand, scientific knowledge progresses steadily but slowly and from relatively low recovery rates regarding elements, with recycling methods based on rough chemistry and mechanical procedures that still have a very large room for the improvement of recovery rates. On the other hand, at industrial capacity level, more facilities for dismantling modules are required; and then, either in situ or in other specialized sites to which the dismantled parts could be sent for further treatment, facilities to increase element recovery and specially glass recycling will have to be built. A logistical approach at regional level (e.g., European scale) should also be considered for the end of life of PV modules, with transport to recycling sites being a substantial part of future emissions associated to the PV systems' full life cycle.

ACKNOWLEDGEMENTS

Funding from Agencia Estatal de Investigación (MCIN/AEI/10.13039/501100011033, Spain) (Grant PID2019-104272RB-C55), FEDER Funds and Ministerio de Ciencia e Innovación is acknowledged.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Urbina A. Sustainability of photovoltaic technologies in future net-zero emissions scenarios. *Prog Photovolt Res Appl*. 2022;1-15. doi:10.1002/pip.3642