The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update

Authors:

Enrica Leccisi, Marco Raugei, Vasilis Fthenakis

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The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update

Enrica Leccisi [1,3], Marco Raugei [2,3] and Vasilis Fthenakis [3,4,*]

1 Department of Science and Technology, Parthenope University of Naples, Centro Direzionale-Isola C4, Naples 80143, Italy; enrica.leccisi@uniparthenope.it
2 Department of Mechanical Engineering and Mathematical Sciences, Oxford Brookes University, Wheatley OX33 1HK, UK; marco.raugei@brookes.ac.uk
3 Center for Life Cycle Analysis, Columbia University, New York, NY 10027, USA
4 Photovoltaic Environmental Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA
* Correspondence: vmf5@columbia.edu; Tel.: +1-212-854-8885

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Keywords: photovoltaic (PV); crystalline Si (c-Si); cadmium telluride (CdTe); copper indium gallium diselenide (CIGS); life cycle assessment (LCA); net energy analysis (NEA); energy return on investment (*EROI*); energy pay-back time (*EPBT*); environmental performance

1. Introduction

Nowadays, one of the most important environmental challenges is to reduce the use of fossil fuels, such as coal, oil, and natural gas, and the associated greenhouse gas (GHG) emissions into the atmosphere. In particular, electricity and heat production accounts for one quarter of the world's GHG emissions [1]; in parallel with this, United Nations projections show that world population is growing significantly, as are the related rates of per capita consumption [2].

Meanwhile, the global solar photovoltaic (PV) market has been growing rapidly to address this issue and to meet the increasing demand for green power; PV's cumulative installed capacity at the end of 2015 was 227 GW_p [3], resulting from 100-fold growth over 14 years of development. The compound annual growth rate (CAGR) of PV installations was 44% between 2000 and 2014. The market in Europe has progressed from 7 GW_p in 2014 to around 8 GW_p in 2015, while in the US it has grown to 7.3 GW_p, with large-scale and third-party ownership dominating. China and Japan have become the biggest PV markets with annual (2014) deployments of 11 GW_p and 9.5 GW_p respectively, and corresponding cumulative capacities of 28.2 GW_p and 23.3 GW_p [3]. In addition, several established markets have confirmed their maturity, including Korea with 1.0 GW_p, Australia with 0.9 GW_p, and Canada with 0.6 GW_p [3].

PV systems may be classified into first, second, and third generation technologies—first generation technologies are based on single- and multi-crystalline silicon (c-Si); second generation technologies consist of thin film technologies such as amorphous silicon (a-Si), multi-junction thin silicon film (a-Si/μc-Si), cadmium telluride (CdTe), copper indium (di)selenide/(di)sulphide (CIS), and copper indium gallium (di)selenide/(di)sulphide (CIGS); third generation technologies include concentrator PVs, organics, and others [4].

Within this variety of technologies, Si-wafer based (first generation) technologies account for approximately 92% of total production, while CdTe PV represents the largest contributor to non-silicon based PV systems. Currently, the market for CdTe PV is still virtually dominated by a single producer, First Solar (Springerville, AZ, USA), with over 10 GW installed worldwide [5].

Generally, PV systems can be mounted on roof tops—commonly named building adapted photovoltaic (BAPV) systems, and they can be integrated into building facades or roofs—also referred to as building integrated photovoltaic (BIPV) systems, or they can be mounted on frames directly on the ground.

There has been constant improvement in the material and energy efficiency of PV cells and panels [6–14]; therefore, an up-to-date estimate of the energy and environmental performance of PV technologies is of key importance for long-term energy strategy decisions.

This paper provides such an update from both the life cycle assessment (LCA) and net energy analysis (NEA) perspectives for the main commercially relevant large-scale PV technologies as of today [3], namely: single-crystalline Si (sc-Si), multi-crystalline Si (mc-Si), CdTe, and CIGS.

2. Methodology

2.1. Life Cycle Assessment

LCA is a discipline widely used in the scientific community and it is considered to be the most comprehensive approach to assessing the environmental impact and overall efficiency of a product or a system throughout all stages of its life cycle. LCA takes into account a product's full life cycle from the extraction of resources and the production of raw materials, to manufacturing, distribution, use and re-use, maintenance, and finally recycling and disposal of the final product—including all transportation and use of energy carriers. Since its inception and first standardization by the society of environmental toxicology and chemistry (SETAC) [15], LCA has become more and more complex, eventually leading to International Organization for Standardization (ISO) Standards 14040 and 14044 [16,17]. The latter are followed here, as well as the more PV-specific guidelines provided by the International Energy Agency (IEA) [18].

Besides addressing a number of environmental impact categories, such as global warming, ozone depletion, and acidification, LCA also allows the calculation of the total primary energy (*PE*) harvested from the environment in order to produce a given amount of end product (i.e., electricity in the case of PV), commonly named cumulative energy demand (*CED*) [19].

In the case of a PV system, the *CED* is thus defined as:

$$CED = (PE + Inv)/Out_{el} \tag{1}$$

where *PE* is the primary energy (sunlight) directly harvested from nature by the PV system and converted into electricity over its entire lifetime; *Inv* is the additional *PE* indirectly "invested" in order to produce, deploy, maintain, and decommission the PV system; Out_{el} is the total energy output over the PV system's lifetime, in units of electricity.

The main indication provided by the *CED* is related to the system's efficiency in using *PE* resources. However, consistent with LCA's long-term focus, the *CED* makes no differentiation between the energy that is directly extracted, delivered, and transformed (*PE*) and the energy that needs to be invested in order to do so (*Inv*).

2.2. Net Energy Analysis

NEA offers an alternative point of view on the performance of energy production systems such as PVs: it evaluates how effective (as contrasted to efficient) a system is at exploiting *PE* resources and converting them into usable energy carriers. In other words, the purpose of NEA is to quantify the extent to which a given system or process is able to provide a positive energy surplus to the end user, also referred to as net energy gain (*NEG*), after accounting for all the energy losses occurring along process chains (such as extraction, transformation, delivery, and others) as well as for all the additional energy investments that are required in order to carry out the same chain of processes [20–26].

The principle metric of NEA is the energy return on investment (*EROI*), which is calculated as the ratio of the energy delivered to society to the sum of energy carriers diverted from other societal uses. Specifically, for a PV system [27], and using the same nomenclature as in Equation (1):

$$EROI_{\mathrm{el}} = Out_{\mathrm{el}}/Inv \tag{2}$$

also:

$$EROI_{PE\text{-eq}} = Out_{PE\text{-eq}}/Inv = (Out_{\mathrm{el}}/\eta_{\mathrm{G}})/Inv \tag{3}$$

where $Out_{PE\text{-eq}}$ is the energy delivered to society in units of equivalent *PE*; η_{G} is the life cycle energy efficiency of the electricity grid of the country or region where the analysed PV system is deployed (calculated as the ratio of the yearly electricity output of the entire grid to the total *PE* harvested from the environment for the operation of the grid in the same year).

At the very minimum, the $EROI_{PE\text{-eq}}$ of an electricity production system must be higher than 1, i.e., the system must ensure the provision of a positive net energy gain (*NEG*) to the end user:

$$NEG = Out_{PE\text{-eq}} - Inv \tag{4}$$

In fact, it is actually important that the system has a sufficiently large *EROI*, beyond unity. In other words, $EROI_{PE\text{-eq}} > 1$ (implying $NEG > 0$) is a necessary but not sufficient condition, given that the purpose of an electricity production system is to contribute to the support of the entire energy metabolism of a modern society, and not just to provide enough net energy to support itself [28–30].

The accurate quantification of the minimum $EROI_{PE\text{-eq}}$ that makes a technology viable depends on a number of factors related to the energy supply mix for each country considered, and is beyond the scope of this paper. In any case, it is important to keep in mind the all-important non-linear relation of $EROI_{PE\text{-eq}}$ to the actual ratio of net–to–gross (*NTG*) energy output:

$$NTG = (Out_{PE\text{-eq}} - Inv)/Out_{PE\text{-eq}} = (EROI_{PE\text{-eq}} - 1)/EROI_{PE\text{-eq}} \tag{5}$$

The energy pay back time (*EPBT*) is also calculated for each PV technology considered. *EPBT* measures how many years it takes for the PV system to return an amount of electricity that is considered to be equivalent to the *PE* invested. In other words, the *EPBT* is the time after which the system is able to provide a positive *NEG*. Operationally:

$$EPBT = Inv/[(Out_{\mathrm{el}}/T)/\eta_{\mathrm{G}})] = T/EROI_{PE\text{-eq}} \tag{6}$$

where *T* is the lifetime of the PV system, measured in years.

In this paper, the calculations of $EROI_{PE\text{-eq}}$ and *EPBT* are based on a generalized average grid mix efficiency ($\eta_{\mathrm{G}} \approx 0.30$), assuming a common grid mix largely reliant on thermal technologies. This is in order to provide sufficiently generic information and to ensure that the comparison of all the analysed technologies is consistent both internally and externally with most other literature reviews. In other words, this means that the two metrics ($EROI_{PE\text{-eq}}$ and *EPBT*) do not refer to any specific country with its own electricity grid mix, but to a theoretical average representative mix, and that in order to be strictly applicable to a specific country, their values would have to be adapted based on the real life-cycle efficiency of its grid.

2.3. Data Sources and Scope

In order to carry out the analysis in the most consistent way possible, all the performance indicators were calculated based on the same underlying inventory data. The main background data source was the Ecoinvent V3.1 Database (Ecoinvent, Zurich, Switzerland) [31]; whenever needed, the data were adapted to the actual production conditions in order to be as accurate and realistic as possible. In particular, the latest electricity generation mixes of the countries of production were used.

Regarding the foreground inventory, all the outputs were estimated based on the latest available data. For CdTe PV, the most up-to-date production data were provided directly by First Solar, who also provided information on the balance of system (BOS) for typical ground-mounted installations (this same installation type was extended to apply to all other technologies too). For c-Si PV and CIGS technologies, the inventory data source was the latest IEA-photovoltaic power systems (PVPS) Task 12 Report [32].

In particular, the latter refers to a literature study published in 2014 but reporting data from 2011 [33]. This means that the original inventory database used for our c-Si analysis is ultimately not very recent—but it is still the most up to date reliable source of information available. Also, in our analysis, the efficiencies of all the PV technologies as well as the electric mixtures used in the Si supply chain and for PV module production (Section 3.2) have been updated to reflect the current (2015) situation.

End of life (EOL) management and decommissioning of the PV systems were not included in this work because these depend of a number of factors and specific conditions, such as the exact location of the PV plant, the type of PV panel, transport costs, logistic criteria, production quantities, weight per Wp, and others [34]—and making specific assumptions in this regard would not be consistent with the aim of the paper to provide an average worldwide high-level point of view. However, including EOL stages may in fact not result in a worsening of the overall energy and environmental performance, since the recycling of the PV components can often provide environmental and economic benefits, especially for c-Si PV panels, given the high value of recycled aluminium and silicon [35].

The contribution of energy storage is likewise not included in our analyses. First, since the main focus is on a high-level comparison between a range of different PV technologies—not an analysis of specific countries and particular locations—energy storage is beyond the scope of this paper. Secondly, many electricity production technologies, including but not limited to PVs, are unable to single-handedly follow the dynamics of societal electricity demand. Hence, energy storage deployment is required at grid level—rather than for each electricity generation technology taken in isolation [36]. Thirdly, even when performing an analysis at grid level, it is recommended to take into account the smoothing effect produced by the combination of renewable energy sources, such as PV and wind [37].

Finally, from a practical standpoint, the analysis was performed using the LCA software package SimaPro 8 (Pré Consultants, Amersfoort, The Netherlands) [38]—and impact assessment was performed by means of the CML method developed by Leiden University in the Netherlands [39].

3. System Descriptions

3.1. Photovoltaic System Process Stages

The PV systems analysed are composed of PV panels and BOS (mechanical and electrical components such as inverters, transformers, and cables, as well as system operation and maintenance). The PV panel technologies considered are: sc-Si, mc-Si, CdTe, and CIGS.

In particular, with regard to c-Si manufacturing, there are more steps to arrive at the final product in comparison with thin-film PVs (CdTe and CIGS), and a comparatively large amount of energy is required for the production of crystalline silicon [10,31].

Figures 1 and 2 show the respective flow diagrams for the c-Si and thin film PV systems. In particular, Figure 1 illustrates each step of the manufacturing chain for sc-Si and mc-Si PV panels. After the metallurgical (MG) and solar grade (SoG) Si production stages, mc-Si ingots are cast and sawn into wafers: sc-Si PV cells additionally require an intermediate Czochralski (CZ) recrystallization step. Then, the individual PV cells are encapsulated between glass panes and assembled into framed PV panels, and finally the PV system is completed by the addition of the BOS. In contrast, Figure 2 shows that the simpler flow diagrams for CdTe and CIGS technologies. Incidentally, the thin film PV panels are also glass-glass sandwiches, but devoid of metal frames.

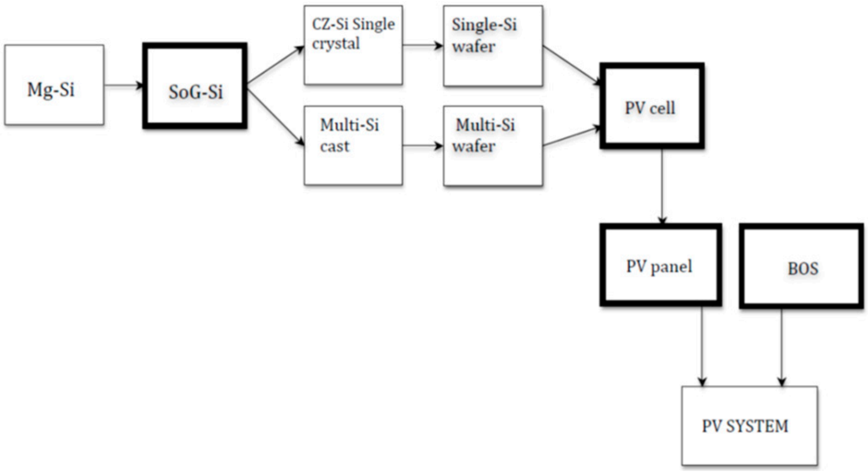

Figure 1. Flow diagram for single-crystalline Si (sc-Si) and multi-crystalline Si (mc-Si) photovoltaic (PV) systems. SoG: solar grade; and CZ: Czochralski.

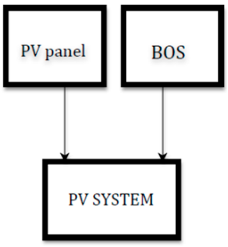

Figure 2. Flow diagram for cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) PV systems. BOS: balance of system.

3.2. Production Sites and Electricity Mixes

Each analysed PV system is also classified by country of production. The c-Si PV production chain is classified into three main producing regions: Europe, China, and the USA, according to the data source used [32]. The sc-Si and mc-Si wafers used in Chinese PV manufacturing are entirely sourced domestically; of those used in US PV manufacturing, 66% are produced in China and 34% domestically; and for those used in European PV manufacturing, 89% is produced locally and 11% in China. Regarding CdTe PV panels, the two production countries as of 2016 are Malaysia and the USA, in accordance with the data provided by the leading company in this sector (First Solar). The main production countries for CIGS PV are Japan (Solar Frontier) [40], to which our analysis refers, and China (Hanergy). All further upstream steps in the Si supply chain are analysed considering their actual geographical location—for instance, the production of MG-Si is divided among the main global producers, i.e., China, Russia, Norway and the United States [41].

The individual local updated electricity mixes used for all PV module manufacturing and for the Si supplying countries are also considered in our analysis, since they influence the amount of *PE* ultimately required for each production process, as well as the associated environmental impacts (Norwegian and Japanese data from the IEA [42]; Chinese and USA data from the U.S.

Energy Information Administration (EIA) [43]; Russian and European data from the World Bank (world development indicators) [44]; Malaysian data from the Peninsular Malaysia electricity supply industry outlook [45].)

4. Results and Discussion

4.1. Fixed-Tilt Ground-Mounted Photovoltaic Systems

Figure 3 shows the CED of the analysed PV systems, while Figures 4–6 illustrate the respective LCA impact indicators, namely global warming potential (GWP), acidification potential (AP), and ozone depletion potential (ODP), all expressed per kW_p—the stacked bars show the individual contributions of the main life cycle stages. Each PV technology is also shown separately according to the country or region in which it was manufactured. The average efficiency for each technology is assumed in accordance with the latest report by the Fraunhofer Institute for Solar Energy Systems [40], specifically: 17% for sc-Si PV, 16% for mc-Si, 15.6% for CdTe PV, and 14% for CIGS PV.

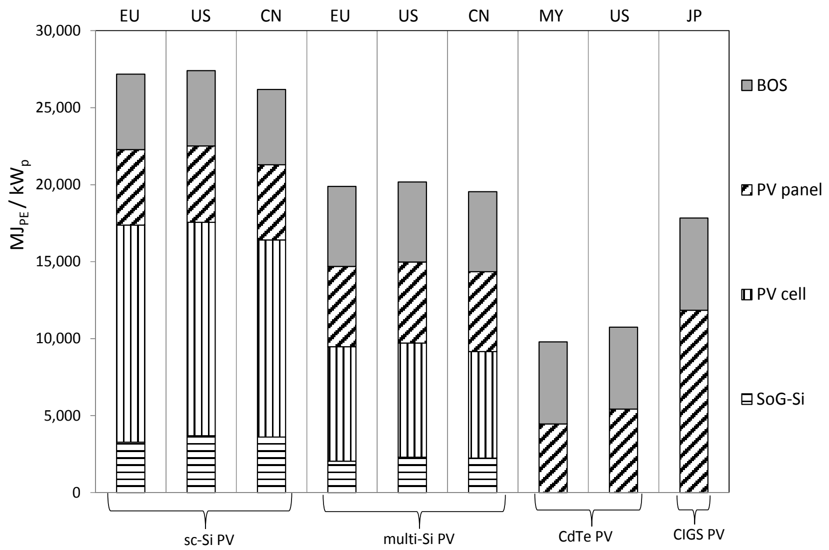

Figure 3. Cumulative energy demand (CED) per kW_p of the analysed PV systems.

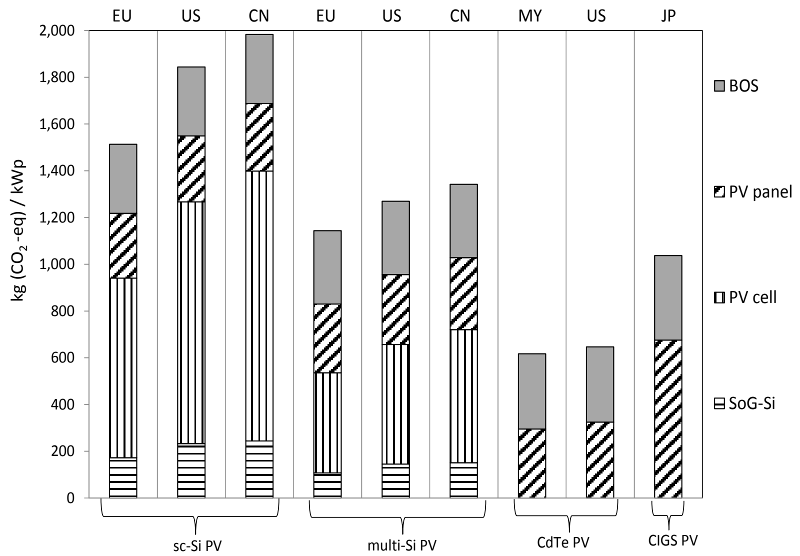

Figure 4. Global warming potential (GWP) per kW_p of the analysed PV systems.

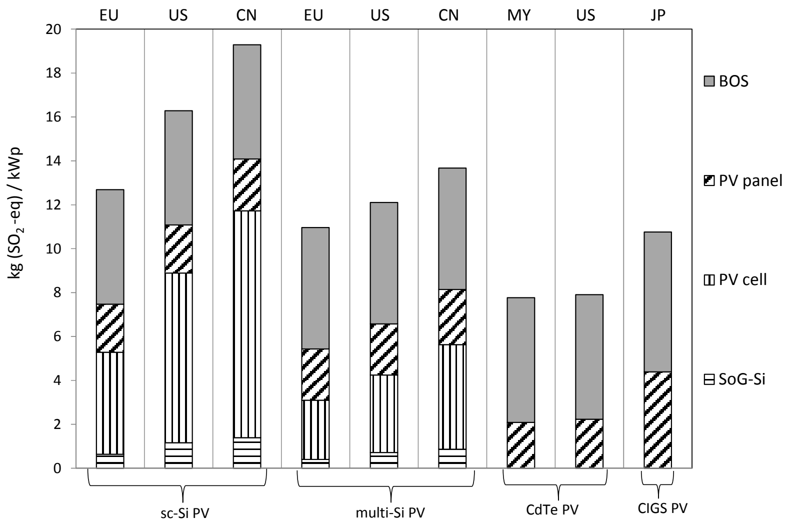

Figure 5. Acidification potential (AP) per kW_p of the analysed PV systems.

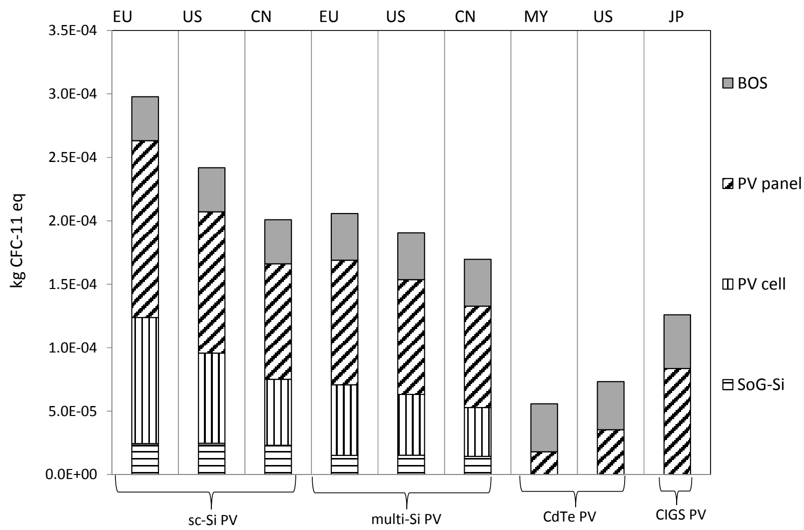

Figure 6. Ozone depletion potential (ODP) per kW_p of the analysed PV systems.

The results clearly show that the most impacting step for c-Si technologies is from SoG-Si supply to finished PV cells, which includes ingot/crystal growth and wafer and cell production, and especially so in the case of sc-Si PV systems (because of the energy intensive CZ crystal growth process).

Figure 3 highlights that, per kW_p, c-Si PV systems are overall twice as energy-demanding to produce as CdTe PV systems. Figure 4 illustrates the resulting GWP indicator per kW_p: c-Si PV technologies generally have higher values in comparison with thin film PV panels, and in particular, the lowest GWP values are for CdTe PV, especially when production takes place in Malaysia. A similar trend is shown in Figure 5, in which the lower values of AP per kW_p are those for CdTe PV, and secondly for CIGS PV; conversely, sc-Si PV shows the highest AP values, followed by mc-Si PV. Also in terms of ODP results (Figure 6), CdTe PV is still the best performer, followed by CIGS PV, and then mc-Si and sc-Si PV.

These new results show a remarkable improvement for current production CdTe PV modules when compared to similar modules produced in 2005 (the most recent production year for which CdTe PV inventory data are directly available in the Ecoinvent V3.1 Database). Over one decade, the CED per kW_p for the CdTe PV modules manufactured in the US has been reduced by approximately 62%, while the GWP, ODP, and AP results are also down by respectively 63%, 65%, and 71%. The current CdTe PV systems also show improvements when compared to previously published results [46] referring to more recent (2010–2011) production data; in this case the CED is down by approximately 30%, and the GWP is down by 37%.

It is noted, however, that the CED of complete ground-mounted CdTe PV systems are not much lower than previously reported values, because the new inventory data for the ground-mounted BOS provided by First Solar led to a higher energy demand (831 MJ/m^2) than the previously used data from the c-Si PV BOS (542 MJ/m^2, First Solar) [47]. The same also applies to the calculated *EPBT* values (Table 1).

Table 1. Energy pay-back time (EPBT) of the analysed PV systems (mean values for the various production sites), corresponding to the three considered irradiation levels.

Irradiation and Grid Efficiency (η)	sc-Si PV	mc-Si PV	CdTe PV	CIGS PV
1000 kWh/(m^2·yr); η = 0.3	2.8	2.1	1.1	1.9
1700 kWh/(m^2·yr); η = 0.3	1.6	1.2	0.6	1.1
2300 kWh/(m^2·yr); η = 0.3	1.2	0.9	0.5	0.8

From a geographical perspective, it is also clear from the results that the considered impact indicators (GWP, AP, ODP) are generally lower when the manufacturing takes place in Europe in comparison with the USA and China, and in particular the Chinese production chain consistently shows the highest indicator values. This is despite the fact that the CED associated to the Chinese c-Si PV production is actually slightly lower than that for the European and USA manufacturing chains—this seeming incongruence depends on the large reliance of the Chinese electric grid on coal [43]. The input grid mix composition is also responsible for a significant share of the impacts in the case of CIGS PV produced in Japan (a country where, after the 2011 nuclear incident in Fukushima, over 90% of the energy resources used for electricity generation are fossil fuels [42]).

The BOS contribution is generally fairly low, with the partial exception of the AP results, which are negatively affected by the comparatively large amounts of copper and aluminium required.

Figures 7–10 then illustrate the same results (CED, GWP, AP and ODP) expressed per kWh$_{el}$. These results are computed assuming a performance ratio of 0.8 and a lifetime of 30 years [18]. Also, in order to provide results applicable to different contexts, three different irradiation levels are used, which are respectively representative of irradiation on a south-facing, latitude-tilted plane in Central-Northern Europe (1000 kWh/(m^2·yr)), Central-Southern Europe (1700 kWh/(m^2·yr)), and the Southwestern United States (2300 kWh/(m^2·yr)). In the figures, different symbol sizes (small, medium, and large, respectively) are used to refer to these three specific irradiation levels.

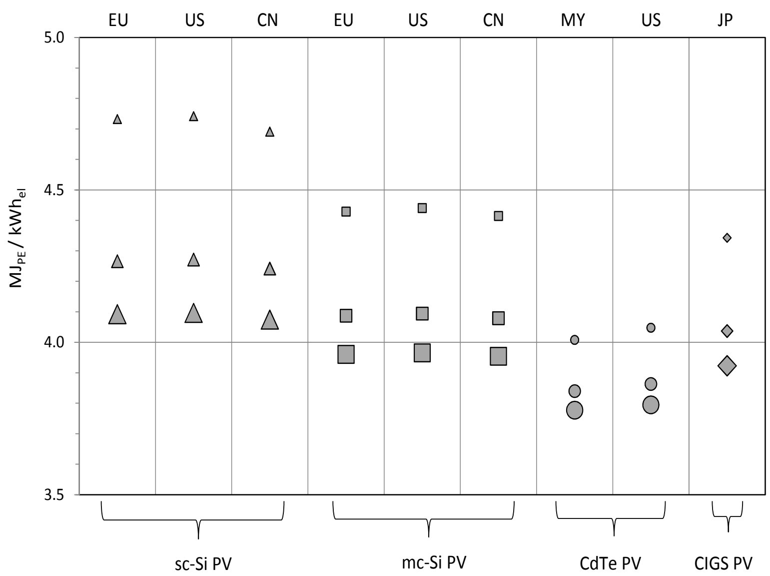

Figure 7. CED per kWh$_{el}$ of the analysed PV systems, under three irradiation levels. Small symbols: 1000 kWh/(m^2·yr); medium symbols: 1700 kWh/(m^2·yr); and large symbols: 2300 kWh/(m^2·yr).

Unsurprisingly, the best energy and environmental performance as measured by all considered metrics is that of CdTe PV systems installed in the Southwestern US, with CIGS PV as a close second.

At the other end of the scale, the highest impact in terms of GWP and AP are those for the Chinese produced sc-Si PV, mainly due to this technology's higher demand for input electricity, coupled with the prominence of coal in the Chinese electricity grid mix.

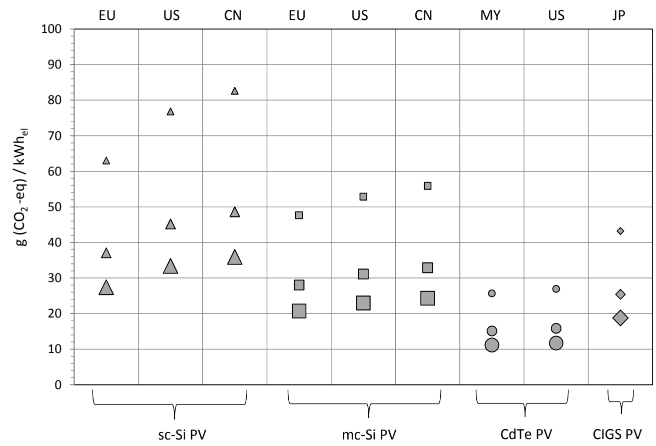

Figure 8. GWP per kWh_{el} of the analysed PV systems, under three irradiation levels. Small symbols: 1000 kWh/(m^2·yr); medium symbols: 1700 kWh/(m^2·yr); and large symbols: 2300 kWh/(m^2·yr).

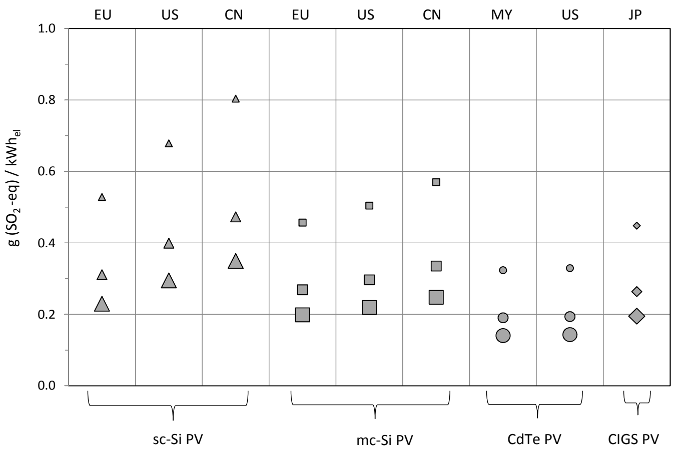

Figure 9. AP per kWh_{el} of the analysed PV systems, under three irradiation levels. Small symbols: 1000 kWh/(m^2·yr); medium symbols: 1700 kWh/(m^2·yr); and large symbols: 2300 kWh/(m^2·yr).

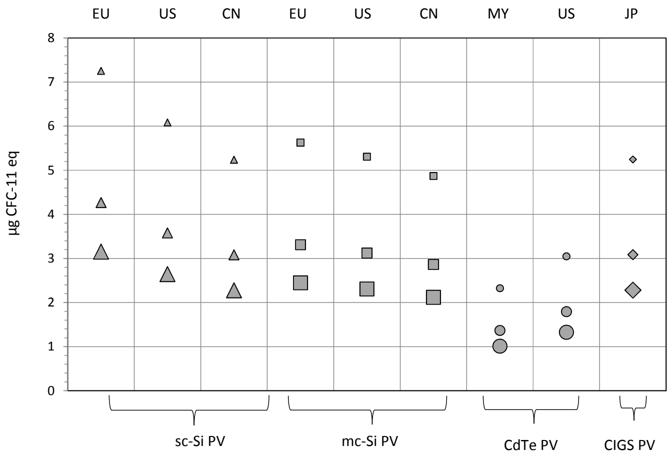

Figure 10. ODP per kWh_{el} of the analysed PV systems, under three irradiation levels. Small symbols: 1000 kWh/(m^2·yr); medium symbols: 1700 kWh/(m^2·yr); and large symbols: 2300 kWh/(m^2·yr).

As illustrated in Table 1, the energy pay-back times of the analysed PV technologies were found to range from 6 months (for CdTe PV installed in the US South-West) to approximately 2–3 years (for c-Si PV installed in Central-Northern Europe).

Figure 11 illustrates the positioning of the analysed PV systems along the curve defined by the non-linear relation of $EROI_{PE\text{-eq}}$ to NTG (often referred to as the "net energy cliff" [48]). This figure makes it abundantly clear that, while the individual $EROI_{PE\text{-eq}}$ values for the different PV systems over the three considered irradiation levels span a comparatively large range—from ~10 for sc-Si PV at 1000 kWh/(m^2·yr) to ~60 for CdTe PV at 2300 kWh/(m^2·yr)—in fact, all data points sit on what may be considered the "safe", quasi-horizontal portion of the "cliff". In other words, all PV systems afford the benefit of over 90% of their gross energy output being available as net usable energy to the end user ($NTG > 0.9$).

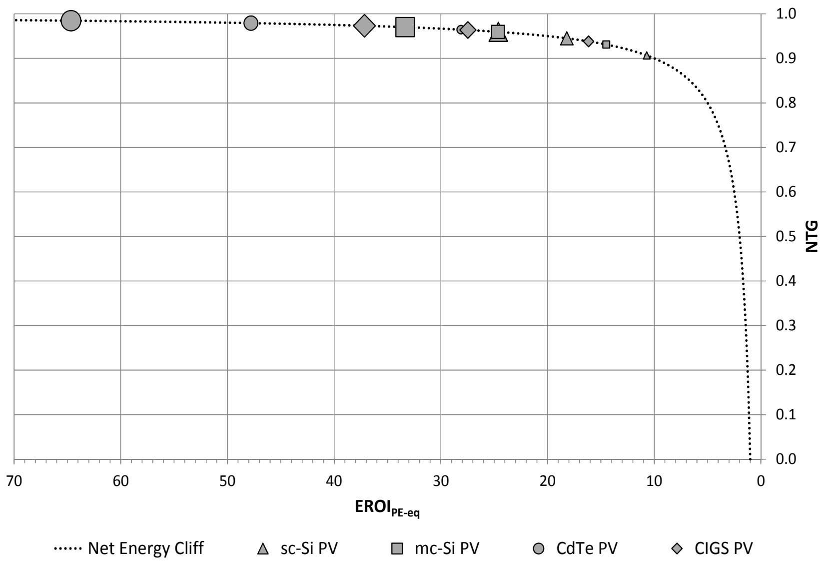

Figure 11. Positioning of the analysed PV systems on the "net energy cliff" (illustrating the non-linear relation of the net-to-gross energy output ratio to the energy return on investment ($EROI_{PE\text{-eq}}$)), under three irradiation levels. Small symbols: 1000 kWh/(m^2·yr); medium symbols: 1700 kWh/(m^2·yr); and large symbols: 2300 kWh/(m^2·yr).

4.2. A Comparison to 1-Axis Tracking Installations

Generally, tracking PV systems provide the benefit of boosting the energy yield in comparison with fixed-tilt installations because the panels are mounted on a structure that follows the movement of the sun. In particular, one-axis trackers have one degree of freedom (the movement occurs along a single axis of rotation). The results shown below correspond to a horizontal rotational axis in the North-South (N-S) direction with the panels facing East in the morning and facing West in the late afternoon. Tracking could be further optimized with the horizontal rotational axis tilted south if the topography allows, which would give the benefit of a flatter profile throughout the day.

On one hand, the invested energy (and associated environmental impacts) for building the tracking BOS are higher than for conventional fixed-tilt PV systems, since tracking installations require larger amounts of structural steel and copper cabling; also, they use electricity during the usage phase for tracking actuators. On the other hand, the key advantage of tracking systems is the ability to harvest more direct beam irradiance, thereby requiring fewer PV modules per kWh produced in comparison with fixed-tilt installations.

The energy and environmental performance of tracking systems are highly influenced by site latitude and diffused light conditions; in particular, sites with lower (<40%) diffused light benefit more from tracking systems. Also, the gain in PV yield is reported to range from +10% to +24% over tropical and subtropical latitudes (0°–40°) [49].

Table 2 shows the maximum achievable variations in LCA impact assessment results (GWP, AP, OPD) and EPBTs for a range of one-axis tracking PV systems, expressed as relative to the corresponding values for fixed-tilt PV installations, assuming a best-case scenario of 2300 kWh/(m^2·yr) irradiation, and +24% enhanced capture efficiency with respect to latitude tilt fixed installations.

Table 2. Life cycle impact assessment (LCIA) and EPBT results for one-axis tracking PV system installations, per kWh_{el} and relative to fixed-tilt installations. Assumed irradiation: 2300 kWh/(m^2·yr); assumed energy harvesting gain due to tracking: +24%.

Indicator	sc-Si PV	mc-Si PV	CdTe PV	CIGS PV
GWP	−14%	−11%	−1%	−6%
AP	−12%	−9%	−7%	−16%
ODP	−13%	−11%	−4%	−9%
EPBT	−13.2%	−10.5%	−2.3%	−7.8%

In general terms, the c-Si PV systems were found to benefit the most from tracking installations (over −10% impact). Instead, the advantage from tracking for CdTe PV (and also to a lesser extent for CIGS PV) appear to be much smaller, due to the very good performance of these thin film technologies in the first place, and hence the comparatively larger share of their overall impacts are due to the BOS itself.

5. Conclusions

Overall, the ongoing improvements in terms of material usage for and energy efficiency of the range of commercially-available PV technologies have been shown to be paralleled by correspondingly better life-cycle energy and environmental performance. The most remarkable achievements have been obtained by CdTe PV, which can boast a two-thirds reduction in environmental impacts over the decade since its introduction to the market. Also importantly, our results definitively put to rest the often voiced concerns about PV not providing large-enough net energy returns per unit of energy invested: all analysed PV technologies have been shown to be able to afford a >90% net-to-gross energy return ratio, even when deployed in less-than-optimal locations (e.g. at Central-Northern latitudes). On the other hand, the additional benefit of employing a tracking BOS is not as clear-cut, and depends on the individual PV technology as well as on specific local conditions (high irradiation, low diffused light).

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