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Environmental impacts of large-scale grid-connected ground-mounted PV installations

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Abstract

This study characterizes the environmental performances of large-scale ground-mounted PV installations by considering a life-cycle approach. The methodology is based on the application of the existing international standards of Life Cycle Assessment (LCA). Four scenarios are compared, considering fixed-mounting structures with (1) primary aluminum supports or (2) wood supports, and mobile structures with (3) single-axis trackers or (4) dual-axis trackers. Life cycle inventories are based on manufacturers' data combined with additional calculations and assumptions. Fixed-mounting installations with primary aluminum supports show the largest environmental impact potential with respect to human health, climate change and energy consumption. The climate change impact potential ranges between 37.5 and 53.5 gCO_2eq/kWh depending on the scenario, assuming 1700 $kWh/m^2.yr$ of irradiation on an inclined plane (30°), and multi-crystalline silicon modules with 14% of energy production performance. Mobile PV installations with dual-axis trackers show the largest impact potential on ecosystem quality, with more than a factor 2 of difference with other considered installations. Supports mass and composition, power density (in MWp/acre of land) and energy production performances appear as key design parameters with respect to large-scale ground mounted PV installations environmental performances, in addition to modules manufacturing process energy inputs.

Keywords: Environmental impacts, LCA, PV installations

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1. Introduction

PV systems deployment and solar energy use are developing rapidly in Europe. In particular, Austria, Switzerland, Germany, France, Italy and the Netherlands experienced a two to four-fold increase in their annual installed photovoltaic power in 2009 [1]. Large scale PV systems (> 500 kWp) represent a lower share of the photovoltaic power production compared to small scale systems (< 3 kWp). However, their market is showing a dramatic increase in number of installations. In France a 90% increase was observed between the 2nd and 1st trimesters 2010 for installations of power superior to 500 kWp, compared to a 38% increase for small scale installations [2].

In this context of rapid development, the issue of PV systems environmental impacts characterization has been intensively addressed and discussed. While several initial publications underlined the higher external environmental costs of PV compared to those of nuclear energy and natural-gas-fuel power plants [3,4], new LCA databases have been built to comply with the improvements in PV systems [5,6]. They highlighted the photovoltaic potential for a low carbon energy supply and the environmental benefits of PV as opposed to fossil-fuel based energy [7, 8]. LCA data currently consider solar cells, panels and installation equipments production in the supply chain of different technologies. Up to now, most studies have focused on module technologies and small-scale installations. They exposed the key parameters for environmental performances of PV installations, when focusing on greenhouse gas emissions and primary energy use as environmental indicators: irradiation intensity received by PV installations, modules manufacturing electricity use and its corresponding fuel mix and PV technology [9, 12]. However, only few evaluations of large-scale PV installations can be found in the literature [13, 14].

This study aims at characterizing the environmental impacts of large-scale grid-connected ground-mounted PV installations (5MWp), considering one module technology (mc-Si) with different structures and types of supports (fixed-mounting or mobile). The results highlight key parameters related to large scale PV systems environmental performances on a life cycle perspective. Impacts on climate change and energy consumption are considered as indicators for the environmental assessment together with human health and ecosystem quality indicators. Recommendations are finally given to enable stakeholders in the field of large scale PV systems to minimize the environmental impacts of future installations.

2. Methodology

This Life Cycle Assessment (LCA) study was performed in compliance with the ISO standards 14040 and 14044 [15, 16] and followed the provisions of the International Reference Life Cycle Data System (ILCD) Handbook [17].

2.1. Scope of the study

The Functional Unit is defined as the kWh of electricity produced by a large-scale grid-connected ground-mounted PV installation (5MWp), considering 1700 kWh/m².yr of irradiation on an inclined plane (30°) and 30 years of life expectancy.

The system boundaries are described in Fig. 1. They include the manufacturing of core infrastructures (modules, mounting system, cabling, inverters, transformers), the manufacturing of complementary infrastructures (wire fences, control centers and road to access the plant), the plant installation (excavation and track construction), the use phase and the decommissioning (excavation, modules and structures end-of-life). Recycled waste material is assumed to substitute for primary produced material, without considering any correction factor.

Four grid-connected ground-mounted PV installations are compared in the study. Their differentiating key features are detailed in Tables 1 and 2. The multi-crystalline silicon (mc-Si) PV technology is chosen for every scenario. Consequently, only the type of structure and its related system energy production differentiate the scenarios.

Fig. 1. Scheme of system boundaries

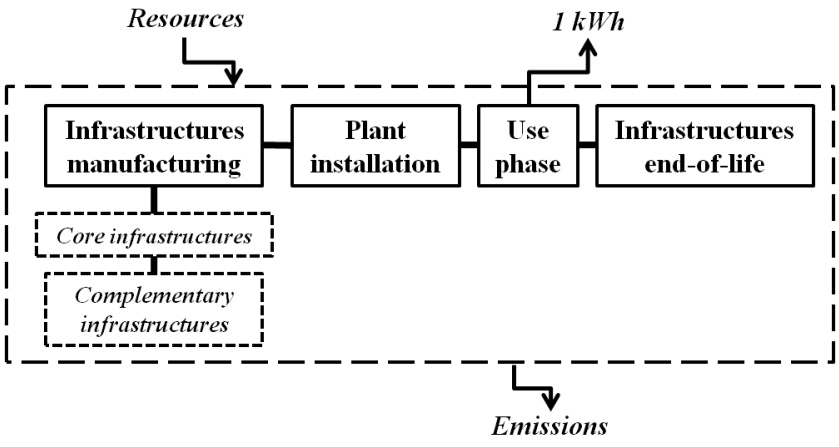


Table 1. Scenarios key features

Scenarios	1	2	3	4
Module Technology	mc-Si	mc-Si	mc-Si	mc-Si
Structure key features	Fixed mounting Primary aluminum supports	Fixed mounting Wood-based supports	Mobile Single-axis trackers	Mobile Dual-axis trackers

Table 2. Energy production in scenarios

Scenarios	1	2	3	4
Increase in production due to mobility	-	-	5% (Average data from a Spanish supports manufacturer)	32.5% (Average data from an Italian supports manufacturer)
Electricity production over 30 years (in GWh)	218.0	218.0	228.9	288.9

Life cycle impact assessment is performed with the use of the IMPACT 2002+ method (v2.04) [18]. The results focus on four damage impact categories: climate change, resources, human health and ecosystem quality. The temporary carbon storage in bio-based goods (wood supports in one scenario) is taken into account in compliance with ILCD provisions, i.e. by considering "-0.01 kg CO2-equivalents" per 1 kg of CO2 and 1 year of storage/delayed emissions.

2.2. Inventory

The inventory distinguishes between:

- foreground processes, corresponding to PV systems parameters, land occupation and electricity use and generation, for which specific data have been used.
- upstream and downstream processes, corresponding to materials extraction and transformation, PV modules fabrication, materials and products transport, electricity production mix, infrastructures end-of-life, for which semi-specific or generic data have been used. Ecoinvent v2.0 [19] was used as the reference database for semi-specific data.

2.2.1. PV installations electricity production

Energy efficiency of the PV modules is set to 14%, with an average performance ratio of 0.855 for the system. The increase in production thanks to mobility is respectively set to 5% for Scenario 3 considering single-axis trackers and to 32.5% for Scenario 4 considering dual-axis trackers, based on average manufacturers' data. The corresponding electricity generated over the 30 years installation life-time is given in Table 2 for the 4 scenarios.

2.2.2. Infrastructures

Data on infrastructures of large-scale PV installations have been either directly collected or calculated from manufacturers' data, as detailed in Table 3. Ten 500 kW inverters are necessary for each PV installation, assuming 10 years of life expectancy (i.e. 30 inverters over each installation life-time), and five 1MW transformers, considering 30 years of life expectancy.

2.2.3. Key additional assumptions

In the absence of specific or semi-specific data for plant building operations (track construction), for engines composition (used in mobile installations) and for waste structures management (waste modules and supports), a number of hypotheses are made. Firstly, tracks are supposed to represent 5% of the total plant area, while the necessary road to access the installation is assumed to be 3 km long. Secondly, engines for mobile installations are assumed to be mainly made of low-alloyed steel (50% in mass), magnet (45%) and integrated circuit (2%). Finally, multi-crystalline modules are assumed to be entirely recycled at the end of the installation life, by use of a thermal/chemical treatment. The life cycle inventory corresponding to modules recycling is partly based on literature data [20, 21]. In addition the quantities of chemicals used are extrapolated from inventories for CIS modules recycling [22]. 90% of the aluminium, 93% of the glass and 70% of the silicon are supposed to be actually recycled.

Table 3. Data collection for infrastructures in scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Modules	35714 m² - value based on calculations from energy production performances			
Area	92 888 m²(*)	92 888 m²(*)	96 922 m²(*)	418 770 m²(*)
Supports	Primary aluminum – Mass values from technical sheets from a German manufacturer	Wood, primary aluminum and iron – Mass values from data from a multi-MWp installation in France	Galvanized steel – Mass values from technical sheets from a Spanish manufacturer	Galvanized steel – Mass values from technical sheets from an Italian manufacturer
Foundations	Cast iron stakes - approximation based on technical sheets from an Austrian manufacturer	Concrete – Mass values from data from a multi-MWp installation in France	Concrete - Mass values from implementation schemes (*)	Concrete - Mass values from implementation schemes (*)
Cabling	Copper, aluminum and PVC – Mass values from implementation schemes (*)			
Transformers	Reference flows data compiled from a French manufacturer			
Complementary infrastructures	Control center building made of steel reinforced concrete + steel wire fences - Reference flows data compiled from a German manufacturer for one installation			

(*) computed from the experience of the consulting and engineering partner (Transénergie)

3. Results

3.1. Scenarios comparison

The Life Cycle Impact Assessment results are shown in Figure 2 and Table 4. Negative values represent the environmental benefits of recycling. Those environmental benefits are not taken into account in the global results since they could be applied in another production chain where recycled aluminum is used. Scenario 1, considering fixed-mounting virgin aluminum supports, shows the largest environmental impacts in terms of human health, global warming and resources, while Scenario 4 (dual-axis tracker systems) generates the largest impacts on ecosystem quality. Scenarios 2 and 3 (fixed-mounting wood-based and single-axis trackers) globally show the best environmental performances, with gaps between their potential damage impacts ranging from 1 to 3% depending on the considered category.

3.2. Detailed environmental performances

3.2.1. Climate change

Modules manufacturing represents the largest share of climate change impact for all scenarios (38 - 56% of the total impact). Moreover, virgin aluminum supports manufacturing stands for a large proportion of the total impact of scenario 1 (36%, if including environmental benefits due to aluminum recycling), contrarily to wood-based fixed-mounting supports (Scenario 2, 21% of the total impact) and galvanized steel mobile supports (Scenarios 3 and 4, respectively 5 and 12%). The climate change impact due to supports is 2 to 10 times larger in scenario 1 than in scenarios 2, 3 and 4. As a consequence, the total climate change impact is 28% larger in scenario 1 than in scenario 2, whereas the climate change impact due to modules is equal for both scenarios (21.4 g. CO_2 eq/kWh, a relatively low value to be related with the assumed use of the French electricity mix for modules manufacturing in scenarios).

Table 4. Damage impact assessment results for the four scenarios (Impact 2002+method v2.04)

Study case	*Human health (DALY/kWh)*	*Ecosystem quality (PDF.m².yr/kWh)*	*Climate change (g. CO_2eq./kWh)*	*Resources (MJ primary/kWh)*
Scenario 1	4.65E-08	2.46E-02	53.5	1.10
Scenario 2	3.24E-08	2.35E-02	38.0	0.88
Scenario 3	3.34E-08	2.32E-02	37.5	0.90
Scenario 4	4.12E-08	5.15E-02	42.8	0.88

Depending on the considered scenario, electric equipments (inverters, transformers and engines in case of mobile structures), complementary infrastructures (road, control centers) and foundations may represent a significant share of the total impact. For example, for scenario 4, these elements represent up to 50% of the total climate change burden. This large share is partly due to the increase in electricity production, generating the decrease in environmental impacts of modules (16.1 g. CO_2eq/kWh), combined with an increase of the impacts of these balance of system (BOS) components.

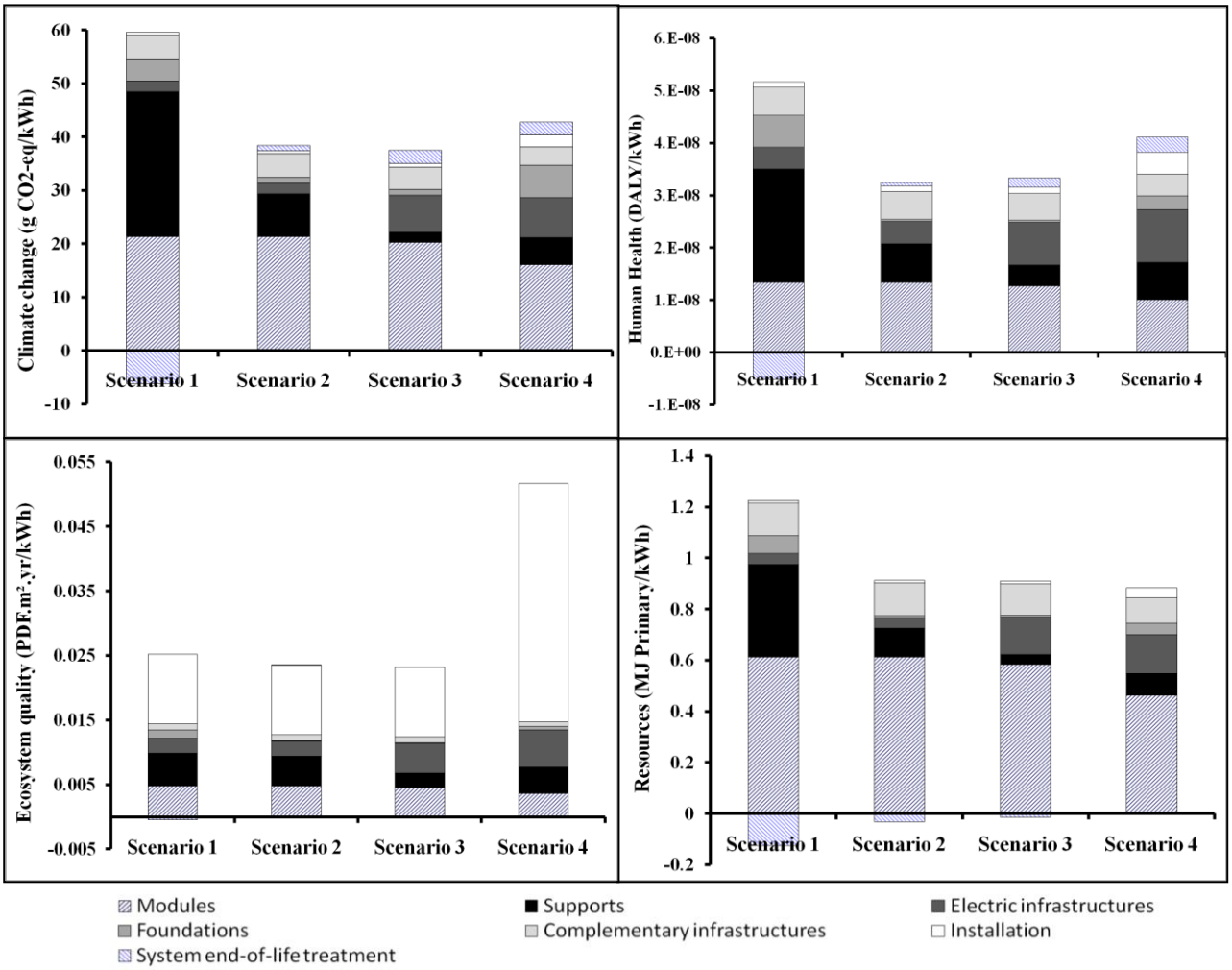


Fig. 2. Detailed environmental impacts of the 4 scenarios (considering 1700 kWh/m².yr of irradiation on an inclined plane (30°), mc-Si modules with 14% of energy production performance and IMPACT2002+ v2.04 damage indicators)

3.2.2. Human health

Impacts on human health show a similar trend with the impacts on climate change, both in terms of overall impact comparison and predominant Life Cycle phases. Modules manufacturing generates the largest environmental burden for scenarios 2, 3 and 4 (from 29 to 41% of the total impact depending

on the scenario), while virgin aluminum supports manufacturing represents the largest share for scenario 1 (33% if including benefits due to recycling). Small particulates, NOx and SO_2 air emissions related to aluminum production (due in particular to electricity requirements and mostly emitted in the aluminum country of origin) represent 22% of the total impact on human health for scenario 1. On the other hand, the human health impact of wood (scenario 2) and galvanized steel supports (scenarios 3 and 4) is lower in absolute value and also stands for a lower share of the total impact.

3.2.3. Resources

Modules manufacturing contribution to the total burden on resources amounts to 53 to 70% depending on the scenario. The environmental benefit gained from the increase in electricity production in case of mobile installations, which is directly reflected in terms of modules impacts, is counterbalanced by different requirements in infrastructures (e.g. electric equipments). As a consequence, whereas scenarios 3 and 4 consider larger electricity production from 5 to 32.5% compared to scenario 2, the gap in impacts on resources between these 3 scenarios is lower than 2%.

Impact on resources of virgin aluminum supports accounts for 24% of scenario 1 total impact (if including benefits from aluminum recycling). This impact is 2 to 6 times larger than impacts of wood-based and galvanized steel supports of scenarios 2, 3 and 4.

3.2.4. Ecosystem quality

The impact on ecosystem quality is mainly influenced by land occupation, which represents 44 to 47% of the impact in case of scenarios 1 to 3 and up to 72% of the impact in case of scenario 4. The difference in impacts on ecosystem quality amounts to a factor 2.1-2.2 between mobile scenario 4 (dual-axis trackers) and scenarios 1 to 3, to compare with a 4.5 ratio between scenario 4 and scenarios 1-3 occupied surfaces. Indeed, power plants with dual-axes trackers require expanding the distances between each element of the PV field, because the shades induced by the moving PV planes are more important: the “power density” in terms of MWp/acre of land used is therefore much lower than for fixed-mounting systems.

4. Discussion

4.1. Key environmental parameters

Irradiation intensity received by PV installations, modules manufacturing electricity use and its corresponding fuel mix and solar radiation conversion efficiency were shown to be key environmental parameters of PV installations in several studies [9, 12]. Similarly, this study highlights the large influence of modules production, and to a lower extent of electricity production increase in mobile conditions, on the environmental performances of large-scale grid-connected ground-mounted PV installations. In addition, two other critical parameters arise: structure supports and occupied surfaces.

4.1.1. Metal/Wood supports

The environmental impact of supports production is predominant considering climate change, resources consumption and impacts on human health, and is responsible for the environmental gap between scenarios in several cases (e.g. between Scenarios 1 and 2). The impact of supports is firstly related with their weight: as observed by Mason et al. [15], decreasing the quantity of metal supports in large-scale installations results in significant environmental improvements. However, materials nature appears as an even more critical environmental parameter. For example, the galvanized steel supports mass is 8% larger in scenario 4 than the primary aluminum supports mass in scenario 1 (considering mass per produced kWh), whereas the corresponding impact on e.g. climate change is 81% larger for supports of scenario 1. Moreover, a sensitivity analysis has been conducted on aluminum supports, by considering secondary material (from old scrap) instead of virgin material. The use of secondary material generates significant decreases in environmental impacts of scenario 1: 42% for climate change, 39% for human health and 25% for resources, in compliance with the predominance of supports composition on the impacts of a large-scale PV installation.

4.1.2. Occupied surface

The occupied surface mainly determines the impact of large-scale PV installations on ecosystem quality. Consequently, land consuming alternatives such as mobile installations with dual-axis trackers will show relatively large impacts on ecosystem quality compared to fixed-mounting solutions, if considering the same modules technology.

4.2. Comparing large-scale grid-connected ground-mounted PV installations

The ranking of alternatives and their associated key parameters may differ from one environmental indicator to another, as observed when putting in perspective large-scale PV installations impacts on climate change and ecosystem quality. This study therefore enhances the need for a multi-criteria impact assessment method when comparing large-scale grid-connected ground-mounted PV installations. In addition, the results underline the multiplicity of parameters which may affect large-scale PV installations environmental performances. The environmental impacts of large-scale PV installations are the result of the interplay between a number of distinct parameters (e.g. energy production, supports mass and nature, electric equipments, etc.), whose related influence may counterbalance each other.

5. Conclusions, recommendations and perspectives

The impact assessment of large-scale ground mounted PV installations therefore gives a detailed picture of their related environmental performances. Key installations design parameters arise in an environmental perspective: supports mass and composition, power density (in MWp/acre of land) and

energy production performances, in addition to key parameters related to modules manufacturing (in particular electricity consumption and electricity production mix).

The environmental performances of large-scale PV installations are not in linear correlation with a unique quantified plant parameter. In that sense, for example, increasing the electricity production thanks to mobile technologies does not necessarily bring environmental benefits if combined with an increase in requirements in materials. A multi-criteria perspective - with respect to environmental indicators and installations key design parameters - should be undertaken with a view to optimizing PV large-scale installations environmental performances in a near future.

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