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COMBINING REGION-SPECIFIC SUPPLY CHAINS WITH GEO-LOCATED PV ELECTRICITY PRODUCTION FOR LIFE CYCLE ASSESSMENT OF WORLDWIDE CRYSTALLINE SILICON PHOTOVOLTAIC SYSTEMS IN ENVI-PV V2.0

Paula PÉREZ-LÓPEZ[1], Benoit GSCHWIND[1], Rolf FRISCHKNECHT[2], Philippe STOLZ[2], Céline MEHL[3], Marie PAYEUR[3], Garvin HEATH[4], Isabelle BLANC[1]

[1]MINES ParisTech – PSL University, [2]treeze ltd, [3]French Environment & Energy Management Agency (ADEME), [4]National Renewable Energy Laboratory (NREL)

[1]Centre O.I.E., Sophia Antipolis BP 207, F-06904, Cedex France, tel.: +33 (0)4 97 15 7055;

ABSTRACT: The development of efficient future energy mixes needs the support of decision tools providing objective information on environmental impacts of existing and emerging systems. In life cycle assessments, environmental impacts during all stages of the life cycle of a product or a service are systematically inventoried and analyzed. Existing tools giving a large audience access to environmental results based on reported life cycle inventories of photovoltaic systems are mainly based on average models that fail to account for geographical dependence in the manufacture stage. The online tool presented here consists of an improved version of the Web service ENVI-PV, developed in the framework of Task 12 of the International Energy Agency Photovoltaic Power Systems Program. ENVI-PV v2.0 (http://viewer.webservice-energy.org/envi-pv_v2.0/) adds a new feature to allow the evaluation of dependencies of environmental results on the manufacturing region of crystalline silicon photovoltaic modules, while providing a selection of environmental impact categories based on recent advances in line with Task 12. The results show the decisive role of manufacturer selection on the environmental performance of photovoltaic systems and the importance of accounting for geographical factors in the environmental assessment of these technologies.

Keywords: environmental performance, solar irradiation data, geo-located PV modeling, IEA PVPS Task 12, regional life cycle module inventories, Web Service.

1 INTRODUCTION

The development of environmentally respectful future energy mixes will require a significant increase of installed renewable energy capacity. Renewable energy systems (RES) are already expanding and their worldwide capacity more than doubled in the last decade. With 2,378 GW of total renewable power, 33% of the current global installed capacity comes from renewable sources and solar photovoltaic (PV) systems accounted for 55% of new renewable capacity in 2018 [1].

RES are expected to have low emissions of pollutants during their operation phase, and thus, better environmental performance than fossil-based energy systems. For these RES, environmental impacts are mainly related with manufacture and installation phases [2, 3]. Life Cycle Assessment (LCA) has been identified by worldwide stakeholders and policy-makers as the best framework to assess the environmental impacts of products and services [4, 5]. The suitability of this method lies in its capacity to account for environmental burdens throughout the whole life cycle, from the extraction and transformation of the raw materials to the use and end-of-life phases [6].

However, existing tools giving a large audience access to environmental LCA results of RES are usually based on average models that rarely account for geographical dependence [2, 3]. In addition, they are often limited to the evaluation of greenhouse gas emissions and primary energy use and lack of a multi-criteria perspective, which leads to neglect other relevant environmental concerns [2]. A first attempt to provide comprehensive accessible environmental information for PV electricity generation was proposed with the interactive online tool ENVI-PV (http://viewer.webservice-energy.org/project_iea/), which was developed in the framework of Task 12 of the Photovoltaic Power Systems Program (PVPS), coordinated by the International Energy Agency (IEA) [2]. The tool, presented in detail in [2], consists of a Web service providing maps and exportable numeric data of environmental LCA results at screening level for representative PV technologies. ENVI-PV had a worldwide coverage and accounted for the geographical dependence and PV layout to estimate electricity production during the operation phase. Despite the range of potential applications of ENVI-PV v1.0 [2], the tool had a limitation regarding the specificity of the modeled systems for the manufacture phase. LCA results provided by the tool were based on worldwide average supply chains rather than on specific supply chains for each manufacture region [7, 8]. Previous LCA studies have already pointed out the importance of the PV manufacture country and its influence on the environmental profile of the systems [9, 10]. To address this limitation, the new version of the Web service, ENVI-PV v2.0 (http://viewer.webservice-energy.org/envi-pv_v2.0/), has been developed and is presented here.

2 PURPOSE OF THE WORK

The aim of this work is to improve the existing tool ENVI-PV that gives access to screening-level environmental results for worldwide PV electricity production. The new version substitutes the worldwide average life cycle inventories for crystalline silicon PV modules by country- or region-specific inventories. Such inventories will provide a wide range of user profiles, including both private and public stakeholders as well as concerned citizens, with a simple tool to obtain environmental performances that account for the geographical context in both the manufacture and the operation stages of crystalline silicon PV systems. More accurate environmental evaluations will feed the debate and enhance the reliability of the comparison between alternative energy technologies. This information is essential to make informed decisions for the effective development of future electricity mixes.

3 METHODOLOGY

ENVI-PV v1.0, the online tool that we aim to improve in this work, provides environmental results based on the LCA approach to quantify environmental impacts of PV electricity [2]. LCA methodology allows the assessment of potential impacts by quantifying all the input and output flows over the life cycle of a product, system or service, in order to estimate the quantities of all the consumed resources and emitted pollutants [6]. Following ISO 14040 standard, substances in the obtained life cycle inventories (LCI) are then classified into impact categories and converted into equivalent amounts of reference substances (e.g. CO_2eq for climate change impact category) by means of specific characterization factors. Results are expressed with respect to a specific unit representing the function of the evaluated system (i.e. functional unit), which, in the case of PV systems is usually the kWh of electricity produced or supplied to the grid. Thus, the environmental performance is obtained according to the following equation:

$$\text{Environ. performance} = \frac{\text{Total impact over lifetime}}{\text{Generated electricity over lifetime}} \quad (1)$$

Environmental impact results from ENVI-PV v1.0 were based on methodological recommendations from IEA PVPS Task 12 [11] and LCIs published in 2015 [7, 8]. These LCIs were based on a cradle-to-gate approach that included the raw material extraction and processing, manufacture of PV cells, modules and balance-of-system components, assembly, transport and operation. Impact assessment methods included ILCD 2011 midpoint+ impact categories, Cumulative Energy Demand, IPCC 2013 and IMPACT 2002+ categories, among others [2, 12, 13, 14].

Electricity estimates were obtained from geo-located irradiation data according to Eq. 2, where P_{peak} is the nominal power in kWp based on irradiation at standard test conditions (STC), H_{STC} is the irradiance at STC (equal to 1 kW/m^2), PR is the performance ratio ranging between 50% and 90% and R_{loss} is a coefficient accounting for the average efficiency lost during the panel life, estimated by assuming 0.7% of loss per year according to [11].

$$\text{Generated electricity} = P_{peak} \frac{\text{Irradiation}}{H_{STC}} \, PR \; Lifetime \; R_{loss} \quad (2)$$

$$R_{loss} = \frac{1}{\text{lifetime}} \sum_{i=1}^{\text{lifetime}} \frac{100 - 0.7(i-1)}{100} = \frac{200 - 0.7(\text{lifetime} - 1)}{200} \quad (3)$$

In particular, worldwide maps of multi-annual monthly averages of surface solar irradiations from to the freely available solar irradiation NASA SSE database (https://power.larc.nasa.gov/) were used [15]. As described in [2], ENVI-PV v1.0 was built as an interoperable and open standard Web service, which enables users to develop new applications by accessing and reusing the results supplied by this tool.

ENVI-PV v2.0 exploits these elements as a basis and adds a new feature to the LCA online platform by implementing region-specific inventories for mono- and multi-crystalline silicon (mono-Si and multi-Si) technologies with low and high power output (3 kWp and 570 kWp, respectively). Original generic inventories are maintained for other technologies, where either LCI data are not available or production is concentrated in few countries. These inventories account for the geographical specificities of the manufacture stage for the PV module, in particular by referring to the country electricity mix used for the manufacture [7], which is a key factor affecting the environmental performance [9, 10].

Users of version 2.0 of the tool can either obtain environmental results for regional supplies set by default for each country or select a specific regional manufacturer among the available options that are listed in Figure 1. For European countries and the United States, the average European supply mix (EU supply) and the average US supply mix (US supply) are set by default, respectively, while the Chinese average production is considered as the default value for the rest of the world, since it is the main manufacturer with about two thirds of total PV capacity in 2017 [16]. Additionally, the user can select a specific regional production among four different regions: Asia and Pacific (APAC), China, Europe and the United States.

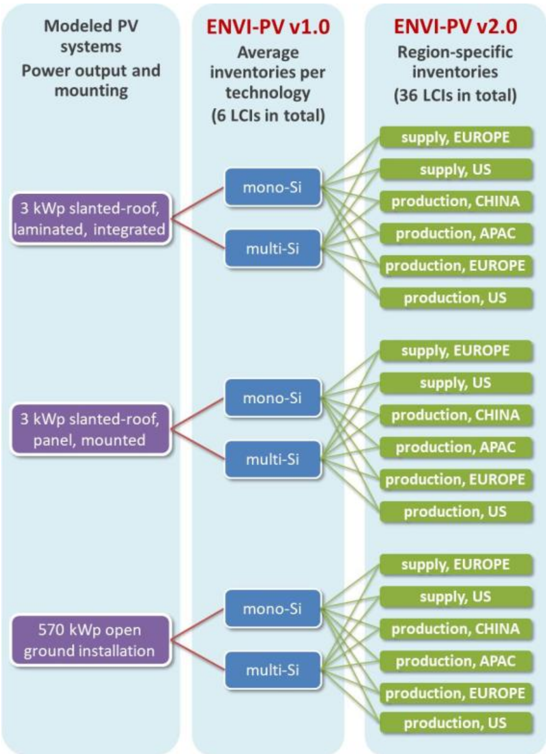


Figure 1: Evolution of life cycle inventories for mono-Si and multi-Si modules available in ENVI-PV v1.0 and v2.0

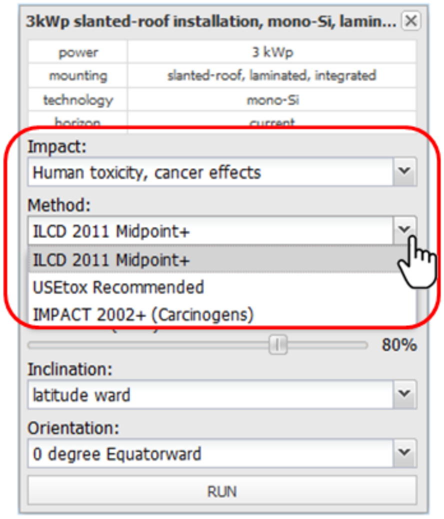
Concerning user choices for the impact assessment indicators, some of the methods available in ENVI-PV v1.0 have become either redundant or obsolete. To promote simplicity, the impact categories implemented in ENVI-PV v2.0 are based on recommendations of IEA

PVPS Task 12 methodology guidelines [11] together with those of the Product Environmental Footprint (PEF) Guide developed by the European Commission [17, 18]. These impact categories include all indicators of ILCD 2011 Midpoint+ [12] (with IPCC 2013 version [14] for climate change), together with other indicators recommended by the Task 12 methodology guidelines: non-renewable cumulative energy demand, renewable cumulative energy demand, and nuclear wastes. Figure 2 shows an example referred to the category of human toxicity. In the previous ENVI-PV version, three possibilities were offered to the user:

i) ILCD 2011 Midpoint+
ii) USEtox Recommended
iii) IMPACT 2002+

However, the first and second options actually refer to the same method, while the third method is less common nowadays [19]. Thus, the category in ENVI-PV is by default evaluated with USEtox model, as recommended in ILCD 2011 Midpoint+ method [12], as well as IEA PVPS methodological guidelines and PEF [11, 18].

a) ENVI-PV v1.0 selection menu for the impact category



b) ENVI-PV v2.0 selection menu for the impact category

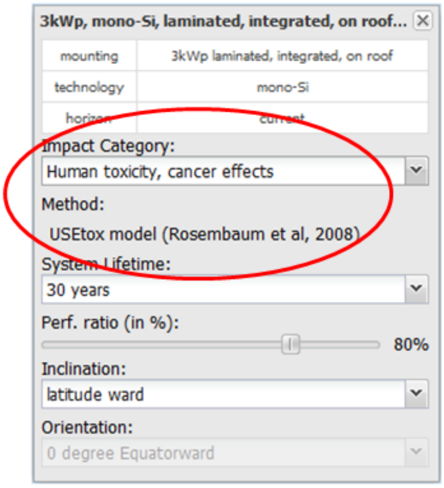
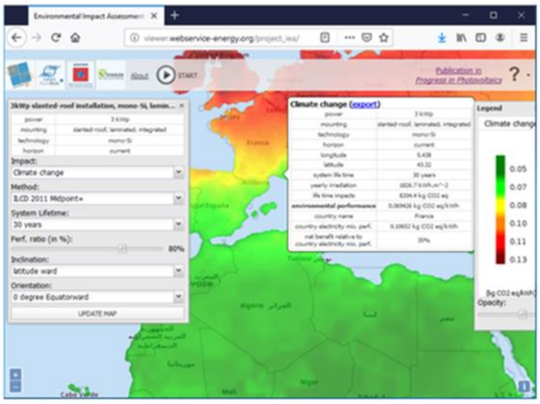


Figure 2: Comparison between the selection menu for the impact category in ENVI-PV v1.0 and v2.0

4 RESULTS AND DISCUSSION

The environmental results for the new region-specific LCIs implemented in ENVI-PV v2.0 are obtained according to the same procedure as the one presented for the previous version [2]. Therefore, by selecting the PV technology, the operational parameters and the impact category, the user can obtain worldwide maps of environmental performance together with specific values for each point in the map. Figure 3 shows the differences between the previous and the new results interface.

a) ENVI-PV v1.0 results interface



b) ENVI-PV v2.0 results interface

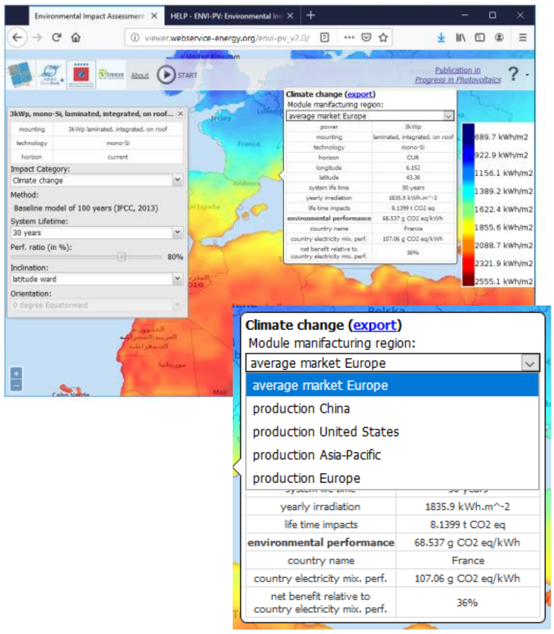


Figure 3: Comparison between the selection menu for the impact category in ENVI-PV v1.0 and v2.0

One difference between the two versions to be observed at a glance in Figure 3 is that color code has been modified: the legend in ENVI-PV v1.0 refers to the environmental performance for the selected impact category, while in ENVI-PV v2.0 it is now based on the solar irradiation. This change allows for faster runs of the algorithm to obtain environmental performances of the selected scenario and avoids the need for running the algorithm every time the user aims to obtain results for another impact category. Run time was a less critical issue when each technology was assessed according to an average LCI but became an issue in the new version due to the increased number of available scenarios for mono- and multi-Si technologies (from 6 scenarios in ENVI-PV v1.0 to 36 in ENVI-PV v2.0), which require a recalculation to calibrate the color every time a new impact category is selected. The environmental performance is inversely proportional to the solar irradiation, according to Eqs. 1 and 2, which means that locations with high solar irradiation, represented in red in ENVI-PV v2.0, result in low values for the environmental performance (impact per kWh), which correspond to locations in green in ENVI-PV v1.0. On the contrary, locations in red in ENVI-PV v1.0 correspond to high impacts and low solar irradiations and are set in blue in ENVI-PV v2.0. In this way, relative differences between locations are the same for both parameters and therefore, the new format preserves all the relevant information and only modifies the color code.

The main improvement of ENVI-PV v2.0 is the possibility of the user to specify, for 3kWp and 570kWp mono- and multi-Si systems, the region of module manufacture. As previously mentioned, European and US average supply inventories are fixed by default in the corresponding countries, while Chinese production is considered as the baseline for the rest of the countries. Nevertheless, the user is given the option to select another origin by changing the default supply by one of the available manufacture regions, namely Asia-Pacific, China, Europe or US.

To illustrate the importance of considering region-specific inventories, Figure 4 presents the environmental performance (impact per kWh) of PV systems of the same technology and power output. In particular, results were obtained for a 3kWp mono-Si laminate produced in different countries based on the inventories from IEA PVPS Task 12 [7]. The categories of climate change, human toxicity (cancer effects) and particulate matter were evaluated. The red bar shows the single value obtained in ENVI-PV v1.0 based on the original European average supply, regardless of the selected installation location. All scenarios available in ENVI-PV v2.0 are depicted next to it. For each location, the default scenario available in the Web service is shown in blue, and corresponds to the European average supply for Marseille, the Chinese production for Beijing and the US average supply for Los Angeles. The average solar irradiation in Marseille is 1827 kWh/m^2, 1489 kWh/m^2 for Beijing and 2144 kWh/m^2, for Los Angeles. The four alternative manufacturing regions are available for all locations.

In most cases, the default scenario gives the most similar values compared to ENVI-PV v1.0 average supply. Results for the Chinese production are in a similar range, although slightly higher than those of the European and US supply. Both findings can be explained by the predominance of China as a key actor involved in the supply chain of both European and US market, with about 80% share of mono-Si in European supply and 56% in US supply [7].

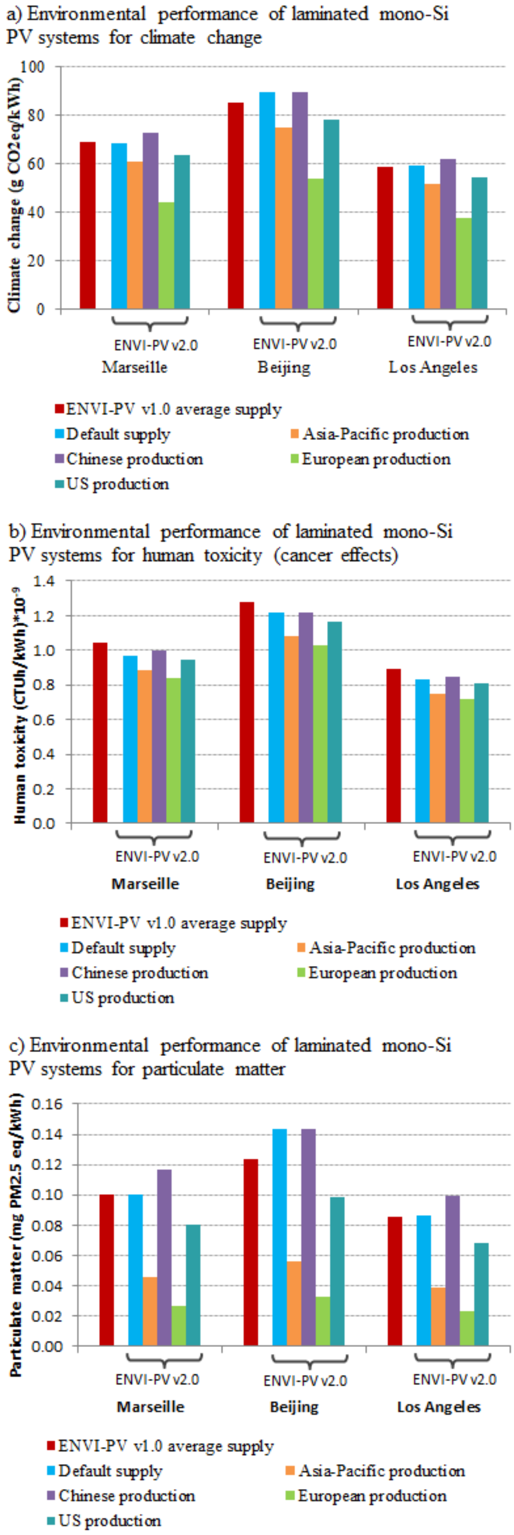


Figure 4: Comparison between ENVI-PV v1.0 and v2.0 results for a 3kWp mono-Si laminate in the impact categories of: a) climate change, b) human toxicity and c) particulate matter.

ENVI-PV v1.0 results neglect, however, remarkable differences between manufacturing origins for a given PV system, which are especially significant in the cases of Asia-Pacific and European production. The comparison of ENVI-PV v2.0 manufacturing regions shows that these differences range between 12% and 58% for climate change, 5% and 40% for human toxicity and 18% and 84% for particulate matter. Differences between the European or US supply and the Chinese production are, in general, lower than differences of the specific manufacturing regions, especially in the cases of Asia-Pacific and European production. This is explained by the predominance of China as the main supplier of both European and US markets. The lowest environmental impact per kWh is observed for the European production, followed by the Asia-Pacific production. This result is explained by specificities of the corresponding country electricity mixes involved in raw materials' transformation and module manufacturing processes, including lower shares of fossil energy sources and higher rates of renewable sources. The new feature allows users to obtain results for a range of possible manufacturing countries, including crystalline silicon PV systems produced from different electricity mixes.

5 CONCLUSIONS

The analysis of these results, which are a good reflect of the comparisons obtained for the other mono- and multi-Si systems, indicates that the choice of the manufacturer location can play a decisive role in the environmental performance of PV systems. Thus, the LCA results should account for the geographical dependence of both PV installation (as solely considered in ENVI-PV v1.0) and the manufacture of the PV module. The combination of these two features has therefore been at the root of ENVI-PV v2.0 development.

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