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A PARAMETERIZED MODEL FOR THE ESTIMATION OF LIFE-CYCLE ENVIRONMENTAL IMPACTS OF CRYSTALLINE PV SYSTEMS

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ABSTRACT: As part of global efforts to thwart the climate change challenge, the integration of renewable energy systems, including an increasingly dominant solar sector, would contribute by 36% to the reduction of carbon related emissions. Among current photovoltaic technologies, the focus is on silicon-based technologies dominating the photovoltaic market with a share of 95% of the total production in 2017. Despite nearly-zero emissions during the operation, non-negligible environmental impacts of these systems can be associated with the manufacturing stage, which contributes to 80 – 90 % of the engendered impacts over their lifetime. The electricity mix is a key variable parameter among others affecting the environmental impact in particular manufacturing and recycling phases. In order to tackle this variability, the Life Cycle Assessment method along with comprehensive reviews of latest crystalline-silicon advancements are used in this work to develop a parameterized model. The approach does not only provide a scientific multi-criterion support monitored by more than 25 input variables but also includes updates to current databases for photovoltaic systems, dating from 2005. This parameterization shows the relevance of the model's modular aspect allowing simulations of various scenarios, ensuring up-to-date LCA data, and serving uncertainty and sensitivity analyses in the future.

Keywords: c-Si, CO₂ footprint, photovoltaic, environmental effect, LCA.

1 INTRODUCTION

The electric power sector, responsible of 40% of today's energy-related carbon dioxide (CO₂) emissions, is one of the main contributors to the climate change challenge [1]. Thus, this induced challenge which constitutes one of the main and most complex problems faced by the humanity and the Earth is calling for instant and effective solutions at the global level [2]. These solutions should limit and mitigate the engendered environmental, social, and economic problems [2]. This has led the International Energy Agency (IEA) to encourage and project, by 2050, a significant reduction for the power-sector-resulted emissions in order to reduce them from 13 to 1.4 gigatons of carbon dioxide CO₂ per year [3]. This reduction is interlinked with many substantial steps which should be implemented; one of them is the expansion of the integration of renewable energy systems (RES) such as the photovoltaic (PV) solar energy which is showing a significant development over the past years [2]. RES are expected to contribute by 36% to this reduction by 2040 [1]. However, their quantified contribution to decrease the greenhouse gases (GHG) when compared to other energy sources is debatable with a high level of variability linked with geographical, technological, methodological, and temporal factors [4]. Other potential environmental impacts should also be accounted for to obtain a comprehensive environmental footprint.

It is common that the environmental impacts of the PV systems are considered negligible when addressing the use phase only. On the contrary, the assessment of the raw material extraction and manufacturing as well as the end-of-life stages may involve significant impacts [5]. For instance, 80 – 90 % of the environmental impacts of the PV systems can be associated with the manufacturing stage [6]. Hence, a global analysis accounting for all life cycle stages of the PV system is imperative and Life Cycle Assessment (LCA) methodology is one of the most mature methods to quantify the environmental impacts of products throughout their life cycle stages including the

raw material extraction, the manufacturing, the use phase, the transport, and the end-of-life [7, 8].

Addressing variability of the environmental performance of PV systems is one of the challenges encountered when quantifying the environmental impacts of these systems. For instance, based on a review of 400 LCA studies evaluating PV systems, documented by a report from the Intergovernmental Panel on Climate Change (IPCC) [9], the range of GHG emissions varies between 5 and 217 g-CO₂-eq/kWh. The majority of the studies documented a value between 30 and 80 g of CO₂ eq/kWh. These values express the carbon footprint of the systems in grams-carbon dioxide-equivalent/kilowatt-hour (g-CO₂-eq/kWh). This range is considerably wide due to the variability of the system boundary, the technologies, the applications and the assumptions.

In order to address this variability related to various technological, geographical, and methodological approaches, an explicit parameterized model for crystalline silicon (c-Si) systems is developed. It is based on key variable parameters contributing to this environmental performance variability. The choice of the technology is justified by the dominance of c-Si one among the PV systems: 95% of the total PV production in 2017 [10]. They were extracted from intensive comprehensive review of technological and LCA studies which will be documented in the following paragraphs. These parameters were grouped and modeled within an LCA approach using advanced LCA tools and ecoinvent 3.4 database [11], as explained in the next sections. The results will quantify the impacts and contribution to the carbon footprint expressed in g-CO₂-eq/kWh associated with the chosen parameters. These scenarios are then compared to a baseline scenario representing the original data dated from 2005.

2 PURPOSE OF THE WORK

The objective of this work is to provide a tool allowing the flexibility to analyze environmental impacts

of a wide range of PV systems. To do so, an explicit LCA parameterized model has been developed to generate environmental results in an automatized way by simply specifying values for a set of key input variables associated with technological hotspots.

The model allows the user, for the first time, to monitor technological, geographical, and methodological parameters to generate tailored life cycle inventories accounting for the current and prospective technological advancements of silicon-based PV systems related to the whole systems' life cycle. One of the potential applications of this work is to provide a solution for the outdated PV data issue while always relying on well-known and developed available databases. The integration of these updates is based on an explicit LCA model with variable input parameters. This parameterization allows a time-effective accessibility to vary the parameters' values across the model in order to elaborate representative environmental assessments. The integration of such parameterization may help the propagation of uncertainties across the model for sensitivity analyses in the future. It also enhances the accuracy and eases the comparisons with other systems and scenarios from an environmental assessment perspective.

3 METHODOLOGY

As the PV market grows, research centers and industries scrutinize the environmental impacts of these technologies. LCA methodology is one of the most widespread techniques to achieve this goal. The adopted cradle-to-grave LCA accounts for the environmental impacts of a product or system over its life cycle stages. In order to represent the models, inventories are used: they consist of lists of inputs and outputs for each unit process included in the life cycle. Then, the Life Cycle Impact Assessment (LCIA) phase translates the inventories into potential environmental impacts using characterization factors that describe the environmental mechanisms behind each impact category [7, 8]. With the LCA methodology as a basis and taking into account the current technological improvements which influence the silicon photovoltaic (PV) industry as well as their prospective evolution, a parameterized modular PV model is developed based on a set of technological, geographical, and methodological parameters (Figure 1). As shown Figure 1, the multi-criteria LCA results are first expressed in terms of impact per kWp of installed capacity then expressed per kWh produced over the whole lifetime. Each of the boxes on the left represents a category of input variables which are exerted to control the modeling according to the user's choice and their system.

The open-source LCA framework Brightway2 [12], relying on Python language, is used to develop the model able to generate the environmental footprint for a large set of PV systems and configurations. The inventories rely primarily on ecoinvent 3.4 database as a basis, then, are modified and updated according to the latest advancements proposed either by the experts of task 12 of the International Energy Agency's Photovoltaic Power Systems Programme (IEA PVPS) or issued from industrial data or other LCA data [13-21].

Regarding the functional unit (FU), the results are expressed per power capacity installed in kilowatt peak

(kWp) or per kWh. In order to calculate the impact per kWh, geographical parameters are added to calculate the electricity production [13]. It is advantageous to separate the impacts related to the technology (manufacturing, end-of-life, etc.) and those related to the geographical aspects of the site inducing a large variability (i.e. irradiation, orientation, etc.) [4]. Hence, the environmental performance is calculated based on the following formula: the environmental Performance is equal to the environmental impacts divided by the electricity generation.

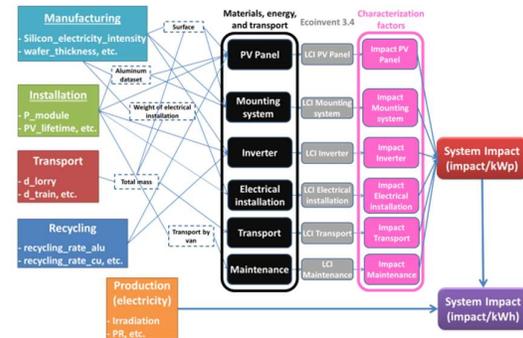


Figure 1: Explicit structure of the parameterized model (4 boxes on the left: technological input variables, dashed white boxes: intermediate parameters, orange box: geographical and production input variables).

A multi-criteria approach is considered based on 4 impact categories selected for this particular study after international standards and initiatives such as the Product Environmental Footprint (PEF) Guide, the ILCD 2011 Handbook, and IEA PVPS reports [21-24]. The main characteristics of the analyzed case studies can be summarized as follows:

- Technological scope: 3 kWp PV installation roof-mounted with modules of multi-Si technology.
- Geographical scope: A South European case study (corresponding to specific energy production of 1300 kWh/kWp) with an electricity mix representative of the world electricity mix.
- Temporal scope: 2005 and 2019 technology horizon.
- Methodological scope: the greenhouse gas (GHG) emissions are addressed using the IPCC 2013 global warming potential (GWP) 100a method as recommended by the Product Environmental Footprint Category Rules (PEFCR) and Task 12 [23, 25, 26]. Additionally, 3 of the impact categories recommended by the PEF were integrated to assess the impacts of PV cells which will be explained in Section 5. They include the cumulative energy demand (CED), the respiratory effects inorganics, and the freshwater ecotoxicity impact categories.

4 SCIENTIFIC INNOVATION AND RELEVANCE

This parameterized LCA model is the first PV model allowing such a vast flexibility and accessibility to operational parameters for the silicon technology where enormous advancements have been achieved lately. While Marini and Blanc (2014) PV parameterized model focused on the Cadmium Telluride (CdTe) technology based on 8 input parameters including both technological and site-specific aspects, this model accounts for more than 25 input parameters able to characterize the

technological, geographical, and methodological aspects of the silicon PV technology. These parameters can be divided into subcategories such as PV manufacturing, electricity production, transport and end-of-life. The proposed model also allows the user to monitor a large number of operational parameters and to either specify their own values or use the default set values to calculate the environmental impacts using the LCA method without being limited to a set of less recent inventories. Such model is especially relevant for industrial stakeholders and academic researchers to face the time-consuming modeling and accuracy limitations encountered using traditional LCA tools.

5 RESULTS AND DISCUSSION

By modifying some of the input variables of the parameterized model, represented in Table I, the impacts engendered by 1 m² multi-Si PV cell, are compared at the level of 4 chosen impact categories.

Table I: Input variables related to PV cell manufacturing.

Parameter	Original value (ecoinvent 3.4)	Adjusted value	Unit or Type
Silicon electricity intensity	110	30	kWh / kg
Wafer thickness	240	200	μm
Silver amount	10.2	9.6	g / m ²
Cutting Process	LAS	DW	Boolean
Kerf loss	0.5	0.29	fraction
Electricity dataset	RER	RoW	dataset

As shown in Table I and Figure 2, two scenarios were compared: the original dataset of the multi-Si PV cells extracted from ecoinvent 3.4 (represented in red) and the adjusted multi-Si PV cell resulted from the variation of the input variables of the parameterized model (represented in green). The choice of showing the impacts of PV cells, among many other components, is encouraged by the significance contribution of the cells to the system's impacts and the numerous advancements, found in the literature, at this level, such as: the reduction of the electricity consumption between the modified Siemens process (110 kWh / kg of silicon) and the Fluidized bed reactor (FBR) (30 kWh / kg of silicon) for the silicon processing [13, 28]; the tendency to reduce the thickness of the wafer; the reduction of the amount of silver used for the metallization paste; the shift from the Loose Abrasive Slurry (LAS) towards the diamond wiring (DW) cutting process for the wafer [28]; the reduction of cutting losses during processing; and the dependency of the impacts on the electricity mix used for the manufacturing [27, 28].

The results show a reduction of 40-50 % of GHG emissions, cumulative energy demand, and human health respiratory effects, along with a reduction of 21-22% of the freshwater ecotoxicity impact. This is justified by the reduced amount of material (silver, silicon, etc.) involved in the manufacturing phase because of the reduction of the initial amount and the less cutting losses associated to the manufacturing phase. Additionally, the reduction of the electricity amount largely contributes to an impact reduction in the 4 impact categories, even after changing the mix from a European context to a less favorable RoW context. The electricity mix is changed from a European

(RER) to a rest of the world (RoW) context for a better representation of the cell manufacturing market. This analysis reflects the altered impact associated with a component of the system: the cells. It helps to identify the main hotspots at the level of manufacturing.

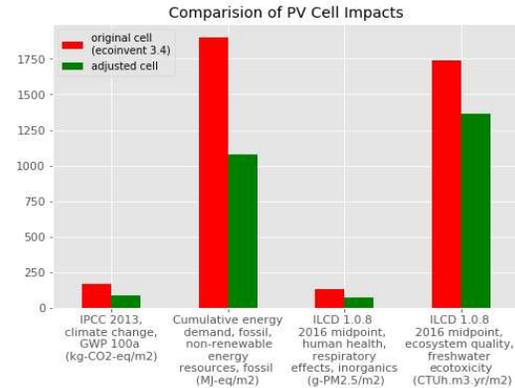


Figure 2: Comparison of the impacts of the original PV cell dataset (ecoinvent 3.4) and the adjusted one (produced by the parameterized model).

Moreover, in order to address the carbon footprint with respect to the chosen FU (1 kWh), Figure 3 represents the carbon footprint of the full system expressed in g-CO₂-eq/kWh. The first bar represents the impact of a 3 kWp multi-Si PV system extracted from ecoinvent 3.4 [11]. The second bar represents the impact of the same system when analyzed using the parameterized model. It can be noticed that both have an impact of around 60-61 g-CO₂-eq/kWh which validates the modeling aspect. Since a 210 Wp panel is not representative of the current technologies, a 280 Wp considered as a representative current panel is analyzed [13, 29]. This is equivalent to a better efficiency of 17.5%. As a result, the impact of such system with 280 Wp panel would reduce the impacts to around 47 g-CO₂-eq/kWh. As presented previously in Table I, since the silicon processing rely more on the FBR process which consumes less energy than the modified Siemens process, the impacts are to around 38 g-CO₂-eq/kWh when FBR process is selected. Finally, in order to emphasize the impact associated with the electricity mix used for manufacturing, a low carbon mix is tested and represented in the bottom bar. This low carbon electricity mix can result in 31-32 g-CO₂-eq/kWh carbon footprint. This significant overall reduction highlights the necessity to adopt an up-to-date database with representative technological data to avoid the over-estimation of the systems' impacts and accommodate for the rapid technological enhancement of the PV field with a time-effective way.

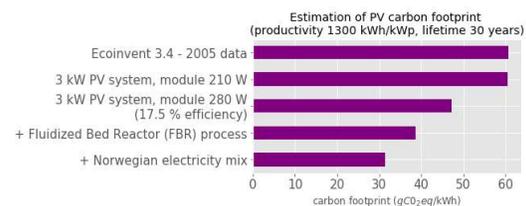


Figure 3: Comparison of various scenarios for the PV system carbon footprint with an assumed productivity of 1300 kWh/kW_p and a 30-years lifespan system.

6 CONCLUSION

With the emergence of photovoltaic-based electricity generation systems and its competitiveness with other conventional systems and RES, it is important to have an easy, transparent, and explicit model allowing the users, researchers, and industrial stakeholders to better model and compare their systems in terms of their environmental performance. The proposed parameterized model answers this need and provides estimates of the impacts of a 3 kWp multi-Si PV cell and system, as an example, accommodating for the latest technological trends in the PV sector within a European context. Among the studies' finding, the following key points can be highlighted:

- There is a significant decrease (21-50%) in the environmental impacts of the PV silicon cell resulting from the latest technological advancements associated with the electricity consumption, silicon manufacturing process, cutting processes, silver use, source of electricity, etc.
- This explicit parameterized model enabled to monitor 4 different multi-Si PV systems' scenarios which showed a significant reduction of the carbon footprint from 60-61 g-CO₂-eq/kWh to 31-32 g-CO₂-eq/kWh by directly modifying a set of input parameters. This overcomes the limitations of some traditional LCA software and less recent inventories that might reflect misconceptions in the environmental analyses.
- If users, aside from industries and researchers, are not aware of certain specifications of their system, there is a possibility to use the proposed default values based on the current industrial data and recommendations.
- An optimization could be integrated to the model, in the future, to address the uncertainties associated with these systems and the robustness of resulted LCA impacts.

It is worth mentioning that, although a 3 kWp multi-Si PV system is analyzed, this explicit model allows the user to investigate the environmental performance for representative systems ranging from few kilowatt to several Megawatt (MW) silicon-based PV systems along with different options of installations, balance of system (BOS), electricity mixes, etc.

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