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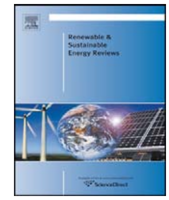

# Life-cycle assessment of a photovoltaic system in Catalonia (Spain)

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ABSTRACT

The life-cycle analysis (LCA) of photovoltaic (PV) systems is an important tool to quantify the potential environmental advantage of using solar technologies versus more traditional technologies, especially the ones relying on non-renewable fossil fuel sources.

This work performs a life-cycle assessment on a 200 kW roof top photovoltaic (PV) system with polycrystalline silicon modules and evaluates the net energy pay-back and greenhouse gas emission rates. The performed life-cycle assessment "upstream" and "downstream" processes are considered, such as raw materials production, fabrication of system components, transportation and installation. The energy pay-back time ratio is determined for the installed technology and two other technologies of PV modules (monocrystalline and thin-film).

The analysed PV system, located in Pineda de Mar (Catalonia, Spain), has an energy pay-back time ratio of 4.36 years. Furthermore, a sensibility analysis on solar radiation has been performed.

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## 1. Introduction

Photovoltaic energy conversion is widely considered as one of the more promising renewable energy technologies which has the potential to contribute significantly to a sustainable energy supply and which may help to mitigate greenhouse gas emissions [10].

Photovoltaic (PV) modules, made of multiple interconnected PV cells of semiconducting materials, convert solar light photons into electricity [1–6,59]. When sunlight hits the modules, photons with a certain wavelength trigger electrons to flow through the materials to produce direct current (DC) electricity [4,6]. Commercial PV materials commonly used for photovoltaic systems include monocrystalline, polycrystalline [7,8] and amorphous silicon and thin film technologies [1–14].

A typical PV system consists of the PV module and the balance of system components (BOS) [15], which includes the structures for mounting the PV modules and the power-conditioning equipment for converting the generated DC electricity to alternate current (AC) with the proper form and magnitude required by the power grid [1,6,16].

The production technology for photovoltaic power plants has constantly been improved over the last decades, e.g. for the efficiency of cells, the amount and production processes for the silicon required, and the actual capacity of production processes [17].

Over the two last decades a number of detailed studies on energy requirements of PV modules or systems have been published [4,5,8–10,18–22]. A vast number of authors from the European Union [4,8–13,18,23–26], the USA [1,5,6,11,27,28], Australia [16], Brazil [1], India [2,29], Singapore [30], Japan [31], etc., have focused on the environmental aspect of future photovoltaic (PV) systems which are assessed through life cycle analysis (LCA), considering mono- and polycrystalline silicon cells, amorphous and ribbon-silicon, CdTe and CIS thin film cells. Most of these studies were concerned with production processes; and their environmental impact assessment was commonly performed from cradle to gate, evaluating the net energy ratio (NER), the EPBT and greenhouse gas emissions, and therefore their mitigation.

Hagedorn [19,32], a pioneer in the field of LCA, extensively analysed material and energy flows in silicon solar cell production facilities in Germany around 1990, covering prototypes of crystalline and amorphous silicon module technologies. Because of its thoroughness and extensive documentation, his work formed the basis for many later studies and, in fact, it was the underlying dataset for the ExternE – (External Costs of Energy) projects – analysis of PV systems [33]. The main aim of the ExternE research projects was to develop a methodology to calculate the external costs caused by energy production and consumption. Later studies partially updated Hagedorn's data on silicon yields and energy consumption [20,32,34–37].

In the past years, the PV sector developed rapidly. Ongoing projects such as *CrystalClear* [38] have investigated the up-to-date life cycle inventory data of the multi- and monocrystalline technologies [13]. CrystalClear was one of the first Integrated Projects to be carried out in the 6th Framework Program of the European Union. The project ran from January 2004 to December 2008 [38]. The aim was to improve the environmental quality of the modules and the corresponding systems, decreasing the energy pay-back time of photovoltaic systems and the $CO_2$ emissions. Moreover, CrystalClear aimed to reduce the environmental impacts of PV modules. This strengthens the position of PV as a clean generator of electricity [38].

In Spain, De la Hoz et al. contributed a critical view of the development of grid-connected photovoltaic systems (GCPVS) during the period 1998–2008 by looking into the different actions that were intended to promote this technology [39]. They also made a special case of the particular promotion of PV systems on roof and goes further to analyse how these actions have affected GCPVS evolution as well as the magnitude of their impact on its performance [39].

Bayod-Rújula et al., described some useful parameters to assess the technology and distribution of modules to be installed in flat roofs and terraces of buildings in Spain, as well as they analysed the effect on the energy parameters of the modules tilt and disposition through a case study, considering different technologies [40].

Concerning to life-cycle analysis in Spain, García-Valverde et al. [41] has assessed, energetic and environmentally, a 4.2 kWp stand-alone photovoltaic system (SAPV) at the University of Murcia (south-east of Spain) in 2009. They found the energy pay-back time and the specific $CO_2$ emissions, and compared the results with other supply options (diesel generator and Spanish grid) [41].

## 2. The life cycle approach

Traditional environmental impact analyses generally focus on a restricted number of life cycle steps. This approach is very narrow because it gives only a restricted picture of the effective environmental performances of the product [42]. Furthermore, in renewable energy plants generally the largest environmental impacts occur during the manufacture and installation steps [42].

The life cycle assessment (LCA) is a methodology able to investigate every direct and indirect impact throughout the life cycle steps of products or services [2,17,32,42–44]. The goal of a LCA is to quantify material and energy resource inputs as well as waste and pollutants outputs in the production of a product or service [1]. The method attempts to systematically quantify the environmental effects of the various stages of a product or process life-cycle: materials extraction, manufacturing/production, use/operation, and ultimate disposal (or end-of-life) [1]. This approach is typically used to compare the environmental impacts for different products performing the same functions [42,45,46]. The LCA is today well defined and also regulated by the international standard series ISO 14040 [18,42,44,46–54], which is divided into 4 steps: goal and scope definition, inventory analysis, impact assessment and interpretation [17]. The results of a life-cycle study applied to a renewable plant can be of great relevance for various aspects [42,46]:

- To compare performances of different system technologies.
- To locate system's components or sub-processes responsible of the highest environmental impacts (hot spots).
- To have useful information in order to reduce the environmental impacts and improve plant's performance.

The construction of the power facilities is an important part, especially in the wind and solar energy, and hence it should be included as part of the required input. When performing a LCA it is a good practice to define proper system's boundaries and a cut-off threshold for impact assessment [8,10]. The analysis should include a detail of all the materials and components employed throughout the life-cycle. The life-cycle analysis was performed from the extraction of the raw materials to the installation of the system and commissioning [6,9,46].

### 2.1. Environmental indexes

The most frequently measured life-cycle metrics for PV system environmental analyses are the energy payback time ($E_{PTB}$) and the greenhouse gas emissions [6,55].

As depicted in Eq. (1), the energy payback time ($E_{PBT}$) is defined as the period required for the PV system to generate the same amount of energy that was used to produce the system itself

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