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Carbon footprint of polycrystalline photovoltaic systems

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ABSTRACT

The environmental and energy parameters of Photovoltaic (PV) systems play a very important role when compared to conventional power systems. In the present paper, a typical PV-system is analyzed to its elements and an assessment of the material and energy requirements during the production procedures is attempted. A Life Cycle Analysis (LCA) is being performed on the production system of photovoltaics. Energy and environmental analyses are extended to the production of the primary energy carriers. This allows having a complete picture of the life cycle of all the PV-components described in the present study. Four different scenarios are examined in detail providing every possible aspect of scientific interest involving polycrystalline PV systems. In order to obtain concrete results from this study, the specific working tool used is the Eco-Indicator '95 (1999) as being reliable and widely applied and accepted within LCA community. A process that relates inventory information with relevant concerns about natural resource usage and potential effects of environmental loadings is attempted. Large-scale PV-systems have many advantages in comparison with a conventional power system (e.g. diesel power station) in electricity production. As a matter of fact, PV-systems become part of the environment and the ecosystems from the moment of their installation. Carbon Footprints of various PV-systems scenarios are greatly smaller than that of a diesel power station operation. Further technological improvements in PV module production and in the manufacture of Balance-of-System components, as well as extended use of renewable energy resources as primary energy resources could make Carbon Footprint of PV-systems even smaller. Extended operational period of time (O.P.T.) of PV-systems determined by system reliability should be given special attention, because it can dramatically mitigate energy resources and raw materials exploitation.

1. Introduction

Photovoltaic systems convert light energy directly into electricity providing an interesting bundle of abundant energy source and at the same time environmental preservation, for the good of humanity and our planet (Pacca et al., 2007). Modern solar photovoltaic technology of the last decade is expected to resolve world energy sufficiency and environmental issues due to definite advantages of PV systems (Varun et al., 2009). Complicated PV systems provide electricity for pumping water, powering communications equipment, lighting homes and running appliances. In an extensive use of this technology, it is possible to produce a great amount of electricity through large-scale PV systems (Peng et al., 2013).

A grid-connected large-scale PV system consists of the photovoltaic modules, inverters (with all the necessary electronic components), batteries for the autonomy of the system, and other components such as cables, support structure and foundations (see Fig. 1) (Bernal-Agustín and Dufo-López, 2006).

Photovoltaic modules consist of a number of solar cells relevant to the module area. The most important part of a solar cell is the semiconducting layers, where the electron current is created. There are a number of different materials suitable for manufacturing these semiconducting layers, and each has benefits and drawbacks. There is no ideal material for all types of cells and applications. The main types of solar cells are (Peng et al., 2013; Şengül and Theis, 2011):

1) Polycrystalline silicon cells (poly-Si, also called semi- or multicrystalline silicon)
2) Amorphous silicon cells (a-Si)
3) Cadmium Telluride cells (CdTe)
4) Copper Indium Selenide cells ($CuInSe_2$; also shortened to CIS)

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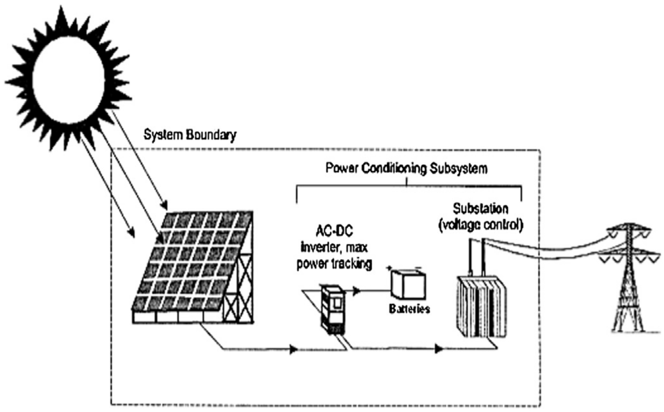

Fig. 1. A large-scale grid-connected PV system schematic.

In the current study, the life cycles of Polycrystalline silicon solar cell modules are analyzed, due to the advantages they present (Swanson, 2006). The most important advantage is that silicon is so readily abundant, since it is actually the second most abundant element in the Earth's crust-second only to oxygen. Many research institutions and manufacturers have an extensive research program in the area of Polycrystalline silicon solar cells. Their main objective is to make solar photovoltaic technology a beneficial solution for producing electricity (Raugei et al., 2007b; Jungbluth, 2005; Pacca et al., 2007).

2. Materials and methods

2.1. System definition

A system is defined as a collection of materially and energetically connected operations (e.g., manufacturing processes, transport process, or fuel extraction process) which perform some defined function (de Haes et al., 1999).

In the present analysis the basic elements of the PV-system (see Fig. 2) are the PV-modules, the inverters, the batteries and the steel foundations. PV-modules, which are the main PV-system's components, are fully analyzed to their materials and full inputs-outputs analyses have been implemented (GaBi Software, 2011). The term "various materials" in Fig. 2 defines materials like aluminum, steel, copper, zinc and plastics, which are parts of the inverters, batteries and ECCS steel foundations.

2.2. Life cycle inventory

The life cycle of a Polycrystalline silicon PV module starts with the mining and refining of silica (quartz) (Stoppato, 2008; Raugei et al., 2007a). Silica is reduced with the use of carbon and the reduction step is either followed or preceded by a purification step. The resulting high purity silicon is melted and cast into blocks of Polycrystalline silicon. The blocks are portioned into ingots (lump of metal, cast in a mould), which are subsequently sliced into wafers. The wafers are processed into solar cells by etching, texture, formation of the emitter layer, application of back surface layer and contacts, passiveness and antireflective coating. The solar cells are tested, interconnected and subsequently encapsulated and framed into modules (Aulich and Schulze, 2002; Jungbluth et al., 2009).

At this point, it is crucial to note that the modes of transportation of raw materials that are necessary for the production of PV-module components (aluminum, glass, EVA, Tedlar, Si), taking into account travel distances to Nisyros island have been included in the inventories (Ecoinvent, 2011; GaBi Software, 2011). Same procedure has also been followed for the BOS-components (GaBi Software, 2011; Du Pont, 2013; Franklin Associates, 2010). In more detail, raw materials and necessary chemical compounds for the production of PV-modules have been exported from China to Japan, where production processes of the assumed modules take place. The delivery of PV raw materials to the japanese manufacturer has been made by cargo ship to cover a distance of 2100 km, and another 300 km have been covered by road transport using a 40 tonnes truck. Then, PV-modules have been exported from Japan to Greece traveling 9400 km by cargo ship. On the other hand, inverters, batteries and steel foundations are imported from Germany to Greece assuming road transport covering a 1650 km distance by a 40 tonnes truck. All PV-system components have been transhipped to a freighter traveling 470 km from port of Piraeus to the island of Nisyros, where the assembly procedures of PV-systems take place.

The module fabrication processes diagram is shown on Fig. 3. In this Figure the flow charts of the basic PV-module elements are included (Jungbluth, 2005). The polycrystalline solar modules manufacturing flow chart is a conjunction of studies stemming from the same database, thus ensuring reliability of inventory data (Ecoinvent, 2011).

The rest of the system's components other than PV-modules, namely inverters, batteries and Steel foundations, have been included in the evaluations of energy and materials requirements, as well as calculations of emissions in order to secure a complete overview of system's carbon footprint (Hischier et al., 2010; Mason et al., 2006).

In this study, four discerned cases are examined, which represent the present and future of PV-technology: the base case, the improved case, the forward case and an application based to the KC-65T PV-module, which is a product of Kyocera Corporation (2013). Table 1 summarizes the most important tasks, which determine the technological cases.

The base case is chosen in such a way that it represents a good estimate of the present state of production technology and environmental control measures (Stoppato, 2008). The improved case is defined as the technology, which has been already reached and will be commercially available widely within next couple of years. The forward case represents an optimistic view on production technology available within the next 5 years (Swanson, 2006). Finally,

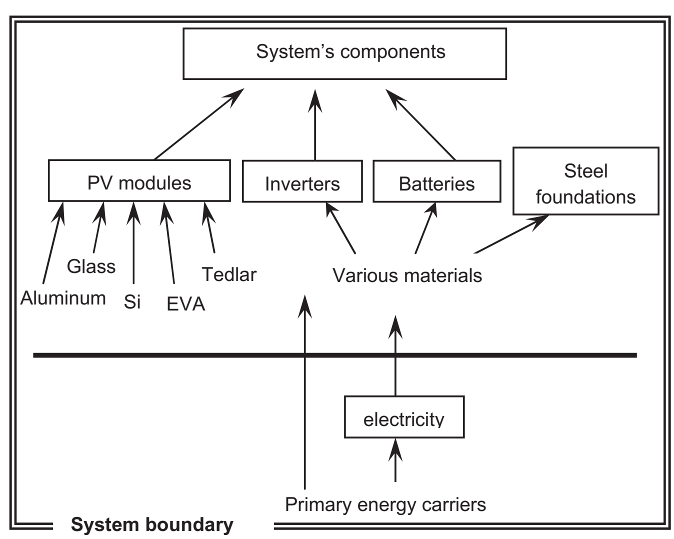

Fig. 2. Basic elements of the grid-connected PV-system with energy storage.