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Multiobjective Optimization of Large Scale Photovoltaic (PV) Systems Design: Technico-Economic and Life-Cycle Assessment Considerations

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Solar energy systems are a source of "clean" energy. Yet, if power generation from photovoltaic (PV) systems is free from fossil fuel use and greenhouse gas (GHG) emissions, a considerable amount of energy is consumed in the manufacturing and transport of the elements of the system. Silicon is currently the most widely used material for solar cell design. In this context, life cycle assessment (LCA) studies play a major role to compare and analyze the environmental impacts of products and services along their life cycle. This work aims at determining a general methodology for designing large scale photovoltaic systems, taking into account both technico-economic and environmental considerations. In this paper, only the environmental issue tackled by Life Cycle Assessment has been implemented to quantify the environmental impacts related to three technology of crystalline silicon for photovoltaic modules (PV) that are monocrystalline, multicrystalline and ribbon silicon.

1. Introduction

The development of sustainable energy systems is a current international priority for response to global warming and depletion of fossil resources. In the past two decades, the photovoltaic has developed into a mature technology (Gong et al., 2004; Solar Buzz, 2010). In recent years, a very high increase in the use of solar energy has been observed under the combined effect of strong incentives taken in Europe because of the energy situation, technological advances and cost reductions (EPIA, 2009; EPIA, 2010; Solar Buzz, 2010). For instance, installed PV capacity in Europe grew from 4941 MWc in 2007 to 9533 MWc in 2008 (+93 %!) (EPIA, 2010). A grid connected photovoltaic system eliminates the need for a battery storage bank resulting in considerable reduction of the initial cost and maintenance cost. A number of studies have been devoted to optimal design of photovoltaic systems (Keoleian et al., 1997; Battisti et al., 2005; Jungbluth et al., 2008), mainly from an economic perspective, taking into account variables related to the inclination or panel design to maximize productivity and benefits.

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It must be yet emphasized that even if power generation from photovoltaic (PV) systems is free from fossil fuel use and greenhouse gas (GHG) emissions, a considerable amount of energy is consumed in the manufacturing and transport of the elements of the system (Gong et. al., 2005). Besides, the amount of energy and emissions from a decommissioning phase of the system must not be neglected. In that context, a supply chain analysis is required in which life cycle assessment (LCA) studies play a major role: they aim at comparing and analyzing the environmental impacts of products and services. There are currently two main technologies for the manufacture of photovoltaic modules (Green, 2001): on the one hand, crystalline technologies that use flat cells from 150 to 200 microns in thickness. The raw material is always silicon. The monocrystalline (sc-Si), multicrystalline (mc-Si) and ribbon silicon technologies belong to this group. On the other hand, thin film technologies use very small amounts of semiconductor materials, which are applied in thin layers to inexpensive glass, metal, and plastic surfaces. The thin-film solar PV cells in use and development include amorphous silicon (a-Si), cadmium telluride (CdTe) and copper / indium / selenium (CIS). This work aims at determining a general methodology for designing large scale photovoltaic systems, taking into account both technico-economic and environmental considerations. The study must combine process and electrical engineering concepts: a keypoint is devoted to the selection of the production technology required for the solar panels, in order to have compromise solutions between cost minimization and environmental impact minimization. The work presented here is only devoted to the study and analysis of crystalline technologies for photovoltaic modules (monocrystalline silicon, multicrystalline and ribbon) from the environmental viewpoint conducted by LCA.

2. Life Cycle Assessment of photovoltaic systems

Life Cycle Assessment characterizes and assesses the total environmental burdens associated with a product system, from raw materials acquisition to end-of-life management. According to the norms ISO-14040-44 (ISO, 1997), LCA is divided into 4 parts: defining objectives and scope of the study, analysis of inventory, impact assessment and interpretation of results (Jolliet et al., 2003).

2.1 Defining objectives and scope of the study

In this work, a standard manufacturing process is considered for the production of the above-mentioned variants of crystalline silicon (see Figure 1) (Alsema and de Wild-Scholten, 2006). Silicon is currently the most widely used material for designing solar cells. It is obtained by reduction from silica. The following step is then the production of Metallurgical-Silicon (MG-Si), only 98 % pure, obtained from pieces of quartz. The Solar Grade-Silicon (SoG-Si) with a purity of 99.9999 %, or polycrystalline silicon (poly-Si) is obtained by the purification of metallurgical silicon (mainly from a chemical route, e.g. Siemens process) for the manufacture of silicon ingots.

For the monocrystalline type, the basic manufacturing method is the Czochralski (Cz) process, in which solid cylindrical ingots of single-crystal silicon are grown (typically 400 mm in diameter and 1 or 2 m long). Monocrystalline silicon photovoltaic cells have the best energy conversion rates of any silicon photovoltaic technology. In addition,

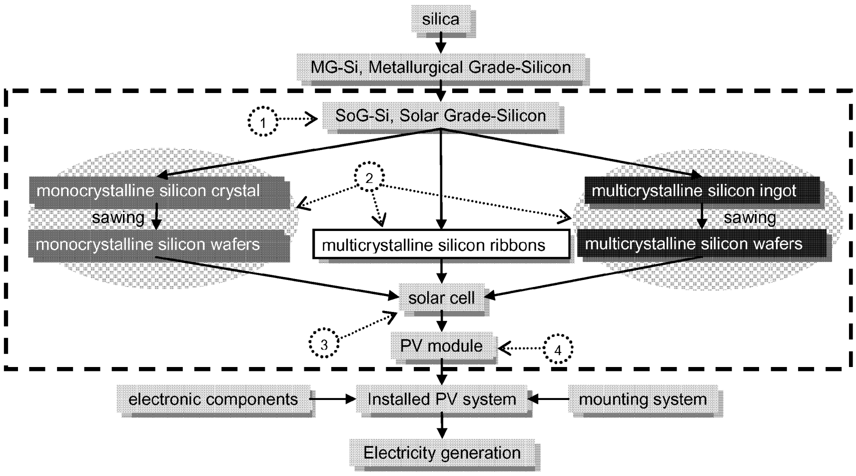


Figure 1: System boundary for LCA study

when the crystals are grown, the photovoltaic components must be cut from cylindrical ingots. The resulting circular shapes do not match the standard square cell module and cutting creates a lot of waste. As an alternative, circular slices of the crystal can be attached to square solar cell modules, leaving gaps at all four corners. Here the price is paid in efficiency. The vast majority of silicon photovoltaic cells are yet produced using a monocrystalline process.

In multicrystalline silicon, molten silicon is poured into a large molding container and then carefully cooled and solidified. The cells start out as cast square ingots, so when sliced into wafers, they readily fit the solar cells. Multicrystalline cells are less expensive to produce than single-crystal cells. Yet, the finished product is not as efficient as with single-crystal cells.

Ribbon silicon, manufactured using a variety of solidification (crystallization) methods, offers a multicrystalline structure with lower production costs and less waste than monocrystalline production. Most of the energy used to slice the wafers in the single- and multicrystal processes is eliminated. Moreover, the ribbons can be stretched to the desired thickness. However, ribbon silicon cells are generally less efficient than multicrystalline cells.

LCA is conducted on these three types of technologies from the solar grade silicon to module construction (see Figure 1). We consider that the other steps are identical regardless of the technology used. The manufacture of the other system components (electrical equipment such as cables and inverters) will not be detailed here. Initially, the functional unit used is the production of 1 kWp for a module. Watt peak is the power delivered by the panel at the point of maximum power and solar irradiation of 1,000 W/m² with a cell at 25 °C.

2.2 Inventory analysis and data collection

The analysis was performed according to the data published by de Wild-Scholten and Alsema (2005). In this work, an effort was made to collect inventory data from standard production data of crystalline silicon modules (material balances). Alsema and de Wild-

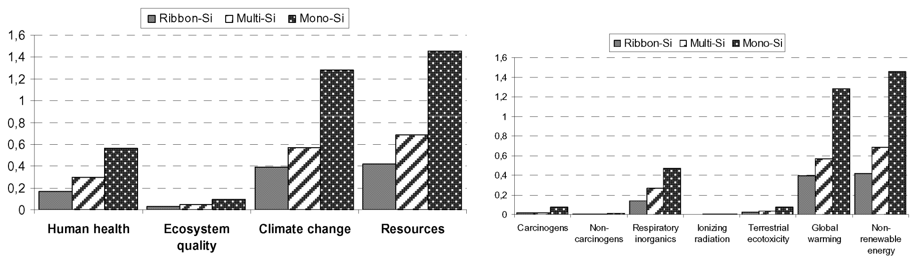
Scholten (2006) propose a single type of standard module with 72 cells and 1.25 m². The conversion efficiency of the modules is based on classical characteristics of each technology (see Table 1). We used the IMPACT 2002+ (Jolliet et al., 2003) database which is a combination between IMPACT 2002, Eco-indicator 99, CML and IPCC (Guinée et al., 2002; Michigan University, 2010).

3. Typical results of LCA

Figures 2a and 2b show the normalized results for the three types of modules (functional unit 1 kWp). Not surprisingly, it is observed that mc-Si technology has the highest score for all impact categories, while the silicon ribbon modules have the lowest impact. When comparing the categories of damage (see Figure 2a), it can be seen that the resource depletion and climate change have the largest contributions in terms of impacts. Figure 2b indicates that the categories relating to non renewable energy and global warming lead to higher scores.
A more realistic comparison to evaluate different technologies for PV is to consider the number of panels required to meet a given amount of energy. Using the same considerations as above, we calculated the minimum number of panels required to meet a demand of 1 kWh (see Table 2) with an average daily irradiance of 1 kWh/m². Figure 3 shows the results of the LCA. A similar trend relative to the impact of each technology assessed (Figure 3) is observed. A closer look is to identify the steps of the manufacturing process that generate the highest impact. The manufacturing process for the three technologies based on silicon is divided into 4 stages (silicon [1], solar wafer [2], solar cell [3], and PV module [4]) according to the diagram in Figure 1. For the sake

Table 1: Efficiencies of the modules and cells by technology

	Si en ruban	Multi-Si	Mono-Si
Cellule	12.8 %	14.7%	15.5%
Module	11.5 %	13.2 %	14%



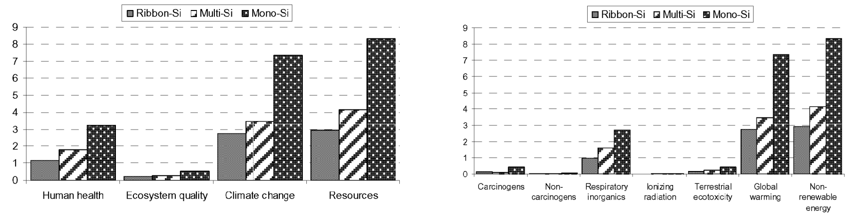
(a) Damage categories

(b) Midpoint categories

Figure 2: Normalized results of LCA for the three technology modules

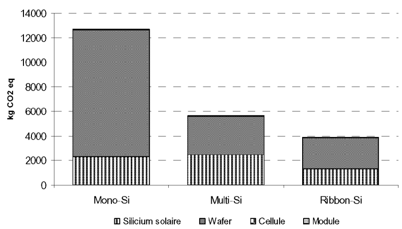
Table 2: Number of modules required to meet a demand of 1 kWh

Si en ruban	Multi-Si	Mono-Si
7	7	6



(a) Damage categories (b) Midpoint categories

Figure 3: Normalized results of LCA for the three technology modules



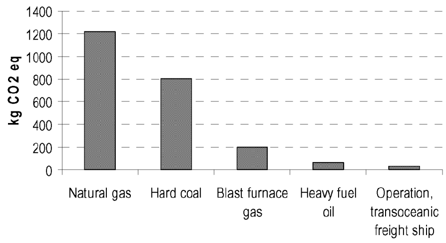


Figure 4: Result Global Warming category by technology

Figure 5: Score of the main resources that contribute to the intermediate characterization for mc-Si wafer

of illustration, the results of the analysis are presented for the global warming indicator. Figure 4 shows that the largest contribution comes from the first two stages of module manufacturing (i.e., silicon wafer and solar cell) for the three technologies. It can be clearly pointed out that for the monosilicon module, the wafer manufacturing process generates more than half of the total impact of the category, because of the higher energy consumption of Cz crystal growth. The main causes are related to the emissions corresponding to the energy needs of the process as it can be highlighted through the analysis of the resources involved in the manufacturing process of mc-Si wafers (see Figure 5).

4. Conclusions and perspectives

Life Cycle Assessment is positioned as an essential tool to evaluate and guide the development of PV technology. It is used to quantify the environmental impacts associated with for photovoltaic systems (global impacts like greenhouse gases and depletion of natural resources, but also more local impacts such as ecotoxicity, human toxicity) and to identify critical steps. The next phase of the work is now to extend the approach to the other components of the system and also to the production technologies of thin films such as amorphous silicon and cadmium telluride (CdTe).

Another incentive is to take into account the solar PV recycling policies (McDonald et al., 2010) by analyzing the recycling protocols for the major types of commercialized PV materials: unlike other industries, PV waste is unique because of its long lag time from production to decommissioning time (First Solar, 2010). The simultaneous consideration of these criteria is essential to develop a global design methodology for large-scale photovoltaic systems and make energy efficient strategies.

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