Study of a PV system energy generation including the aspects and impacts in the manufacture of monocrystalline silicon PV modules

Léa Beatriz Dai Prá
Environmental Engineering, UNISINOS, Av. Unisinos, 950. São Leopoldo - RS, Brazil
biadaipra@gmail.com

João Batista Dias
Graduate Program in Mechanical Engineering, UNISINOS, Av. Unisinos, 950. São Leopoldo-RS, Brazil.
joaobd@unisinos.br

Amanda Gonçalves Kieling
Environmental Engineering, UNISINOS, Av. Unisinos, 950. São Leopoldo - RS, Brazil
amandag@unisinos.br

Abstract: Due to the fact that the consumption of electrical energy is growing and is necessary to improve the technologies related to this, is proposed a study about environmental impacts and solar photovoltaic energy. It was taken into account the generation of environmental aspects and impacts in the manufacture of monocrystalline silicon PV modules (consisting of three components: silicon cell, flat tempered glass and aluminum frame). And an analysis of a grid-connected PV system using an energetic alternative in residences was considered. Results show that this kind of renewable energy is really clean and can be considered as a way to change the energy technology.

Key words: *manufacturing of PV modules; generation of environmental impacts; grid-connected PV system.*

1. Introduction

With the advances in society in the matter of sustainability, the use of renewable energy is more and more frequent, mainly because they are considered clean energy. The generation of electricity, through PV modules, has become increasingly recognized in this area.

In a matter of use, solar PV energy is really clean. However, during the manufacturing of its components, many environmental impacts can be generated. These, in turn, should be studied in order to improve processes, especially as it relates to energy costs, taking into account the energy consumed in the manufacturing of a module and the energy that it produces during its lifetime.

The main objective of this study is to analyze the manufacturing processes of monocrystalline silicon photovoltaic modules, environmental aspects and impacts at each stage of manufacturing as well as the energy generation in a residential grid-connected system during its use.

2. Review

Photovoltaic solar energy is obtained by direct conversion of solar radiation into electricity (photovoltaic effect). The PV effect is the appearance of an electrical potential difference in the extremes of a semiconductor material structure, produced by part absorption of the solar radiation spectrum [1].

A PV module is composed of individual cells connected in series, tempered glass with low iron content, on the side that faces the sun and an aluminum frame [2].

Figure 1 shows a schematic composition of a standard photovoltaic module, of monocrystalline silicon.

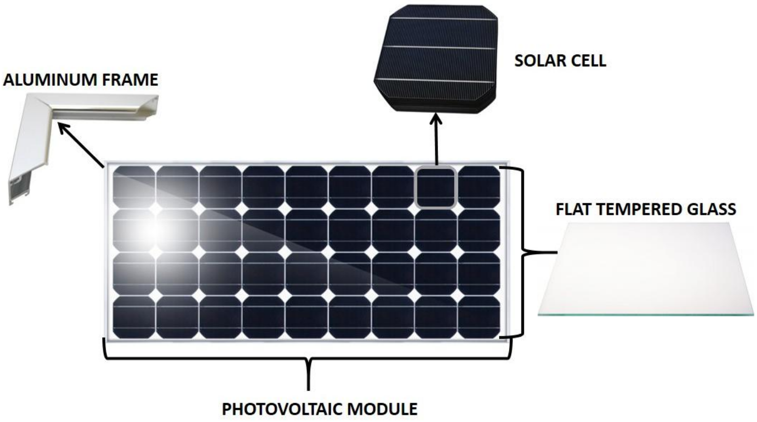

Fig. 1 - Components of a standard photovoltaic module

According to the type of semiconductor material that forms the solar cells, they are classified into different groups. The most common types of PV modules are manufactured with cells formed of monocrystalline silicon (m-Si) and multicrystalline (c-Si) [3].

The efficiency of a PV module composed of m-Si cells, in converting solar radiation into electricity, is higher than 12% [2].

Because they have an efficiency of 12%, the modules with m-Si cells are better suited for the production of electricity [4].

The classical method of manufacturing m-Si cells uses a method known as Czochralski Method (Cz), which gets the silicon from the processing of silica [3]. The method consists of introduce a seed crystal in molten silicon, then slowly lowering the temperature, to give crystallization. After obtaining the monocrystal, it passes by mechanical machining, cutting, thinning, rounding of the edges, cleaning and polishing, obtaining finally the monocrystalline silicon wafers [5].

Energy consumption in this process is extremely intense and complementary steps to the monocrystal growth have considerable material losses, in the order of 50% of the original billet [6].

In the framework of the PV module, there are two glass functions: to protect the solar cell and provide the transparency necessary for the transmission of solar radiation. In this case, the glass appears to be the most efficient and versatile option. It should be able to withstand bad weather (rain, wind, hail and snow), sudden changes in temperature and smaller mechanical impacts [7].

The glass can be classified as flat, hollow or special. Flat glass is produced in the form of plates (which can later be cut and processed). This is the material suitable for use in photovoltaic modules, as it has the characteristics needed for this function [8].

As it needs to be robust, flat glass is tempered. Its production occurs through a horizontal or vertical tempering furnace. After being undergone a rapid heating and cooling process, it starts to have a resistance up to five times higher, compared to its natural state. Once tempered, the glass cannot be benefited, cut or punctured. Therefore, any process of transformation must be done before the tempering process. Tempered glass is resistant to thermal shock, bending, buckling, twisting and weight. When broken, it breaks into small pieces, also reducing the risk of accidents involving cuts [8].

In a study of Lifetime Analysis (LA), inherent impacts in the glass manufacturing process were identified, particularly in relation to the high temperature required for melting the raw material, which results in a big emission of dioxide carbon and harms human health. [9].

The aluminum is a rigid and conductive material that serves as PV module enclosure structure and for its fixing. The primary aluminum is produced in three stages: extraction of bauxite, obtaining of alumina by the Bayer process and obtaining the aluminum by casting [3].

Although aluminum has a low financial cost, the environmental costs of its mining and refining, can be high. The environmental impact extends from forest degradation and water contamination with their combings, to the direct influence of contamination in ecosystems. It is necessary to extract from four to five tons of bauxite to produce two tons of alumina that, in turn, results in the production of one tone of primary aluminum [3].

One of the main attributes of aluminum is that it can be recycled numerous times, both of used products, such as slag from its casting [10].

The energy requirement for the production of a standard photovoltaic module, of approximately one meter long, half a meter wide and 32 cells, is 1373.72 kWh [3].

Considering the module power of 74 Wp, daily use of six hours and an approximate service lifetime of 25 years, it is able to generate 4051.50 kWh in this period, in other words, 162.06 kWh/year. The time required of the module operating, so it can repay its energy production spending, is 8.48 years. Consequently, 16.52 environmentally useful years of lifetime would remain after the module achieves its energy balance in relation to the energy costs of its production [3].

As the PV system does not emit pollutants during its operation, it is very promising as a sustainable alternative energy. However, it generates environmental impacts to be considered. The most significant environmental impact of photovoltaic system for electricity production is caused during the manufacturing of its materials and construction and, also, related to the area of deployment [11].

Environmental aspect is "an element of the activities or products or services of an organization that can interact with the environment", and environmental impact is "any change of the environment, whether adverse or beneficial, resulting in whole or in part, of the environmental aspects of the organization" [12].

3. Methodology

The methodology is to qualitatively analyze the manufacturing processes of the components of monocrystalline silicon PV modules, pointing out the steps of the process and making the survey of environmental aspects and impacts involved. Also, study the energy generation in a residential grid-connected system.

First, a literature review about the components of the PV module and its manufacturing characteristics was performed. From this research, a detailed flowchart of the processes was obtained and, based on the flowchart and the theoretical evaluation, a complete analysis of environmental aspects and impacts, generating a simplified table was performed. After this, was made the calculation of the energy generated by the system in its use.

3.1 PV system

In order to accomplish the PV system dimensioning, the consumption of a house with four people was estimated. The simulation was made in a simulator of the COPEL (Companhia Paranaense de Energia). Was obtained a monthly consumption of 166 kWh, around 2000 kWh per year.

The assembly of the system is shown in Fig. 2. The system contains a 1700 W inverter to grid-connected photovoltaic power systems and twenty 100 Wp modules. The PV arrangement is composed of two parallel strings, each one with ten modules connected in series. The total installed capacity is 2 kWp. The system was dimensioned to a residence in the city of Porto Alegre, Brazil.

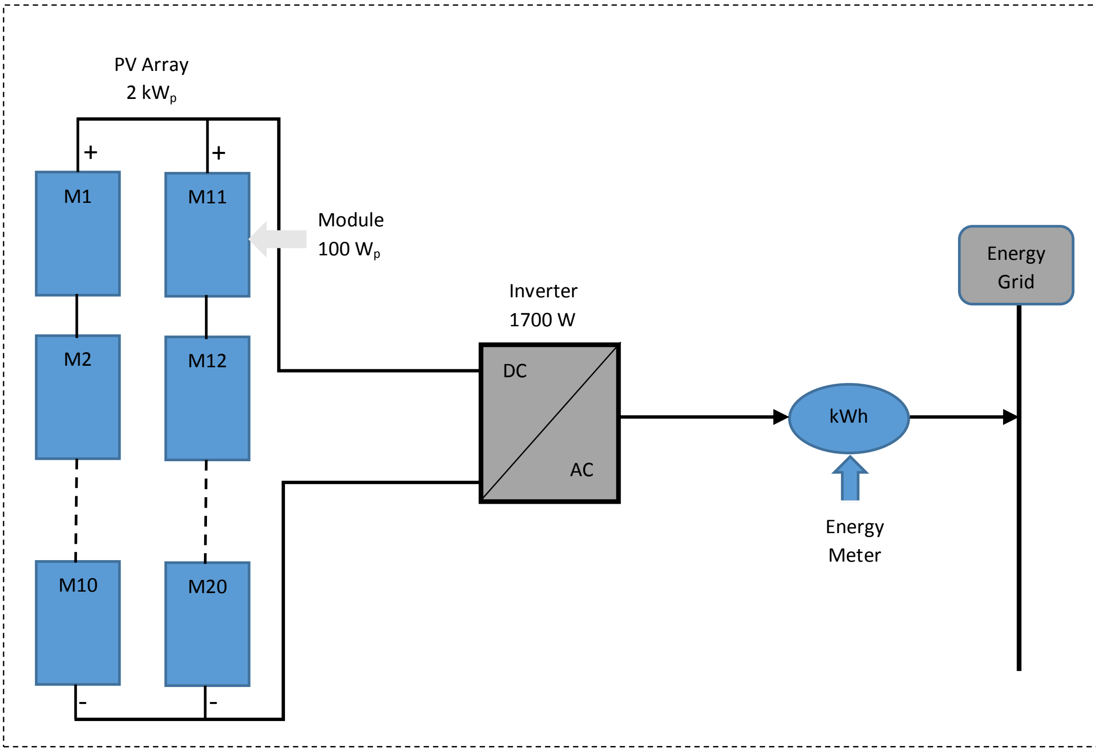

Fig. 2 - PV system diagrame

4. Results

Part of the results was obtained according to the studied literature and the qualitative analysis of environmental aspects and impacts. Which made possible to generate a flow chart of the steps of each process involved in the production of monocrystalline silicon photovoltaic modules; to construct a table that lists the environmental impacts related to the relevant stages of the process; the other part of the results was obtained with a simulation of energy generation, considering a PV system. That provided the quantification of the energy consumption in a residence and the produced energy by the PV system, enabling the study between the generation of impacts in the manufacturing of a module with its energy produced.

4.1 Simplified flowchart of process steps

In the flowchart shown in Fig. 2, the different type of lines of the frames differentiate the module components. In complete line, is the solar cell; in dashed line, is the flat tempered glass; and in dotted line, is the aluminum frame. Boards having more than one type of line boundary are part of both processes.

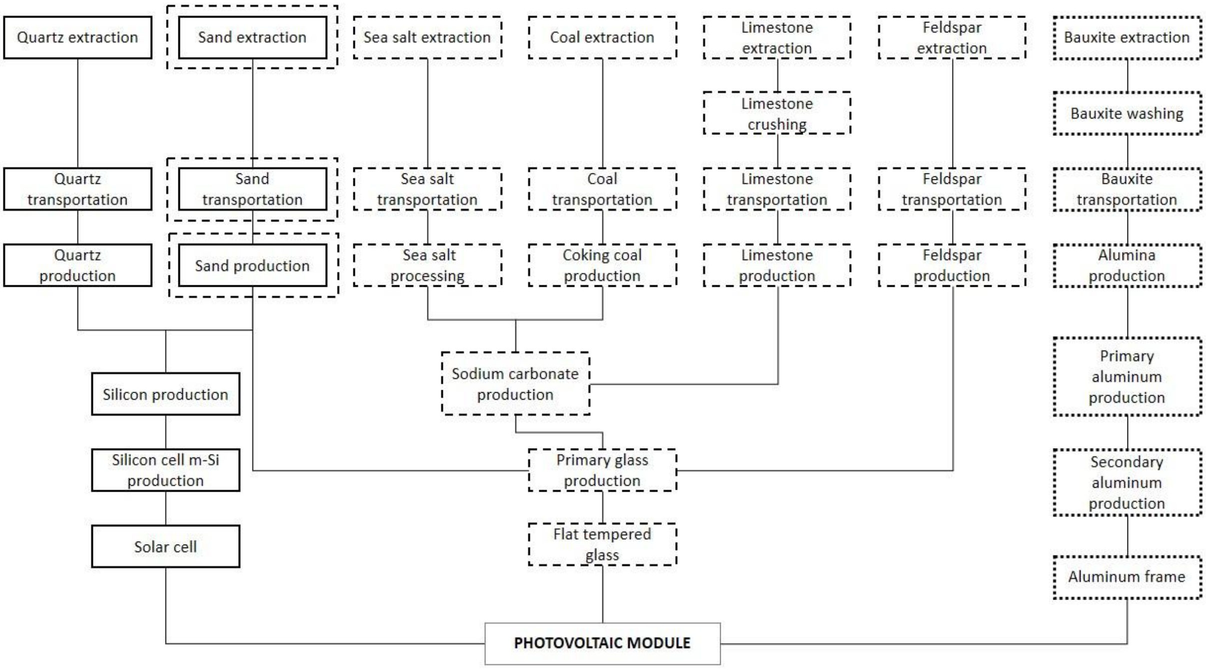

Fig. 2 - Flowchart of manufacturing processes of a m-Si photovoltaic module

4.2 Environmental impacts at each stage

Based on the flowchart and with the survey of environmental impacts, it was possible to draw up the Tab. 1, composed of the relevant steps to each process and the impacts generated in the module manufacturing as a whole. Each component has a corresponding letter and in the second and third columns, it is possible to identify the relationship of each component in the module manufacturing steps. The environmental aspects and impacts are for all the steps.

Table 1: Generation of environmental aspects and impacts in the manufacture of photovoltaic modules

COMPONENT			RELATED COMPONENTS	STEPS	ENVIRONMENTAL ASPECTS	ENVIRONMENTAL IMPACTS
PV Module	A	Silicon Cell (m-Si)	A, B, C	Raw materials (RM) extraction	Energy consumption Water consumption Materials consumed Generation of effluents Emissions generation Residue generation	Reduced availability of natural resource Change in soil quality Change in water quality Change in air quality (gas and dust) Discomfort to the neighborhood
			A, B, C	Raw materials transportation		
			B, C	Raw materials processing		
			A, B, C	Production derived from the RM		
	B	Flat Tempered Glass	A	Silicon production (m-Si)		
			A	Silicon cell production		
			B	Primary glass production		
			C	Primary aluminum production		
	C	Aluminum Frame	A	Solar cell assembling		
			B	Flat tempered glass production		
			C	Secondary aluminum production		

4.3 Energy production

The PV system dimensioning was performed in the program Sunny Design by SMA Solar Technology AG [13]. The installation angle of the PV array is 20^{o}. With a monthly consumption of 166 kWh or approximately 2000 kWh per year, was obtained the following results shown in Tab. 2.

Table 2: Simulation results

ANNUAL SIMULATION	
Energy produced by the PV system	2201.50 kWh
Energy injected on the grid	1469.81 kWh
Energy available from the grid	1268.31 kWh
Own residential consumption	731.69 kWh
Own consumption (%)	33.2 %

4.4 Energy consumption x Energy produced

Using the literature as a base, the energy consumption costs in the manufacture of a module are approximately 1373.72 kWh. The quantity of energy produced by the system of 20 modules, obtained at the annual simulation is 2201.50 kWh. Multiplying the energy consumed to produce one module per 20 (system), is obtained the approximate value of 27475 kWh, that is the energy cost for producing all the modules of the system. Considering a medium lifetime of 25 years, the total generation of the system is approximately 55040 kWh. Analyzing the data and discounting the energy consumed in the manufacturing, there are still approximately 27565 kWh to use as completely clean energy. Specifically, the system will take approximately half of his life to compensate for the energy demand, but it will still be self-sustaining for over 12.5 years.

6. Conclusions

The process analysis of the monocrystalline silicon PV module components enabled the raising of environmental aspects and impacts. That is an effective tool for qualitative studies. However, the proposed PV system enabled a quantitative study, relating the energy consumed in the modules manufacturing processes with the energy produced by the system and delivered to the electrical energy grid of the residence.

Results show that if taken into account the energy used in the manufacture of a module, as quantified in the literature, and the energy that a module system produces, this technology proves to be sustainable due to the fact of having many years of really clean energy production, even if in the first years the system equals the energy spending in manufacturing, with gains in use.

Studies like this prove that renewable energies are becoming, more frequently, an alternative way to develop our countries in the sustainable area. There are many kinds of energy alternatives that can be used to reduce the environmental impacts; the photovoltaic energy is one of them. With directed researches to this area and the right support, the manufacturing processes may be improved and this can reduce even more the environmental impacts, turning it on a complete sustainable way to generate energy.

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