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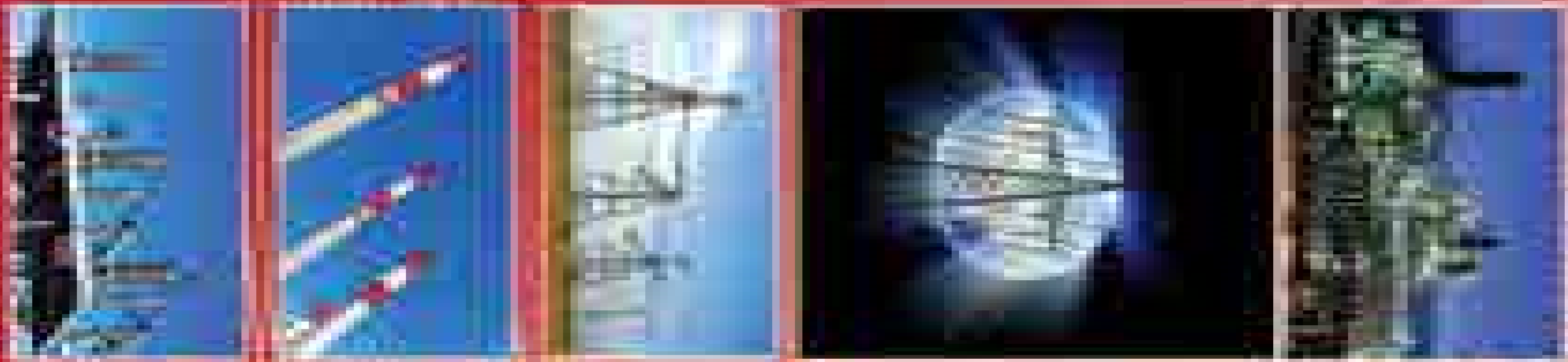

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Life cycle analysis of silicon photovoltaic panels

ABSTRACT

Although photovoltaic (PV) systems in their work do not require the use of conventional energy sources (fossil fuels), a considerable amount of energy obtained from such sources is needed for their production. Life Cycle Analysis (LCA) is an analytical method that is used to assess the impact of a PV system on the environment. This paper presents a theoretical overview of the life cycle analysis of the PV panels, with special emphasis on silicon PV cells and amorphous silicon PV cells. Assessment of the energy needs for the production of photovoltaic systems, energy payback period and greenhouse gas emissions are also presented in paper.

Key words: life cycle analysis, photovoltaic cells, silicon PV cells, amorphous silicon PV cells, energy payback time, CO_2 emission

ANALIZA ŽIVOTNOG CIKLUSA SILICIJUMSKIH FOTONAPONSKIH PANELA

REZIME

Iako fotonaponski (FN) sistemi pri svome radu ne zahtevaju korišćenje klasičnih izvora energije (fosilnih goriva), znatna količina energije, dobijene baš iz takvih izvora, potrebna je za njihovu proizvodnju. Analiza životnog ciklusa (Life Cycle Analysis - LCA) je analitički instrument koji se koristi za procenu uticaja jednog FN sistema na životnu sredinu. U ovom radu dat je teorijski pregled analize životnog ciklusa fotonaponskih panela, sa posebim osvrtom na silicijumske fotonaponske ćelije i fotonaponske ćelije od amorfnog silicijuma. Date su i procene energetskih potreba za proizvodnju fotonaponskih sistema, energetski period otplate kao i emisija gasova staklene bašte.

Ključne reči: analiza životnog ciklusa, silicijumske FN ćelije, FN ćelije sa amorfnim silicijumom, energetski period otplate, emisija CO_2

1. INTRODUCTION

Everything around us is based on the use of energy. The number of people on the planet is increasing every day and therefore the consumption of resources and energy increase, as well as the negative impact on the environment. The fact is that today's production of energy is based largely on obtaining from non-renewable sources, such as oil, coal, gas... These sources are the most accessible but they are not inexhaustible. Not to mention their negative impact on the environment, because emissions of CO_2 is constantly growing. Therefore there is a need for the use of renewable energy sources.

Solar energy is one of the most important renewable energy sources. It is inexhaustible and, at the same time, the cleanest of all renewable energy sources. Of the total solar energy on Earth arrives 1.75×10^{11} MW [1]. The photovoltaic effect is one of the best ways to use solar energy. In fact, it is a method of direct conversion of solar energy into electrical energy by creating potential differences in the material.

Today there are several materials that are used for the production of photovoltaic cells: mono-crystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, cadmium sulphide, hybrid solar cells...

Life cycle analysis (LCA) is an analytical instrument that is used to assess the impact of a particular product on the environment. The basic goal of impact assessment is to identify and establish links between the life cycle of a product or service and the potential environmental impact during the entire life cycle, starting from raw materials extraction, production, distribution and transport, use, repair and maintenance all the way to recycling and final disposal.

International Organization for Standardization (ISO) has established the basic principles of life cycle analysis [2]. LCA consists of four steps:

- Goal and scope definition
- Inventory analysis - data collection and processing (Life cycle inventory)
- Assessment of impacts on human health and the environment (Life cycle impact assessment)
- Interpretation

In recent years, a lot is invested in the technology of photovoltaic cells for maximum utilization of the huge amount of solar energy that reaches the Earth. Photovoltaic systems are increasingly used as part of households, residential and commercial buildings, and therefore it is necessary to have insight into the impact of such system on the environment and human health. Precisely life cycle analysis (LCA) can help in that area very much.

2. THE LIFE CYCLE ANALYSIS OF PHOTOVOLTAIC PANELS

Although photovoltaic systems in their work do not require the use of conventional energy sources (fossil fuels), a considerable amount of energy obtained from such sources is needed for their production. The quantity of used energy during the manufacturing process is associated with the problems about the use of inexhaustible, non-renewable energy sources and pollution which occurs as a byproduct of the production process.

Each life cycle analysis has its typical boundaries and the same thing is when it comes to the PV system. Boundaries include products and services related to each stage of life cycle analysis for a PV system, starting from excavation and procurement of raw materials to final disposal or recycling (*Figure 1*).

In addition to the PV panel, which consists of a PV cell, the frame and glass, each PV system contains also the components for system balance. These components are necessary to provide structural support and to deliver electricity to the facility or a to the grid. The BOS includes wiring, cables, switches, mounting system, battery, battery charger... [3].

Producing electricity by using PV cells emits no pollution and greenhouse gases and uses no fossil fuels. The advantages of these systems in terms of environmental protection are really great. But even though in their work PV systems do not consume large amounts of energy and do not pollute the environment, the question is how long it takes the system to compensate for the energy that went into making the system in the first place and how much pollution is created in the process. By using LCA the energy payback time of a PV system can be assessed, as well as the negative impact on the environment through emissions of carbon dioxide (CO_2).

Energy payback time (EPBT) is defined as the period required for the system to generate the same amount of energy that was used to produce the system itself. It is calculated as:

$$EPBT = \frac{(E_{mat} + E_{manu} + E_{trans} + E_{inst} + E_{EOL})}{(\frac{E_{agen}}{\eta} - E_{aoper})}, \qquad [4]$$

where:

E_{mat} – Primary energy demand to produce materials comprising PV system

E_{manu} – Primary energy demand to manufacture PV system

E_{trans} – Primary energy demand to transport materials used during the life cycle

E_{inst} – Primary energy demand to install the system

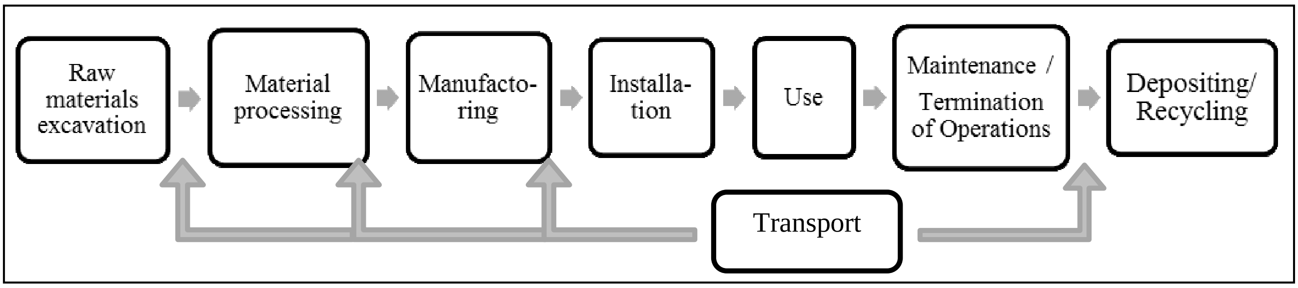

Figure 1 - *Stages of the life cycle of PV system*

E_{EOL} – Primary energy demand for end-of-life management

E_{agen} – Annual electricity generation

η – PV efficiency

E_{aoper} — Annual energy demand for operation and maintenance in primary energy terms

The environmental profitability of PV system refers to the impact that the system has on the environment in terms of global warming and greenhouse gas emissions. The most important among them is carbon dioxide.

$$CO_2\ emission\ rate = \frac{Total\ CO_2\ emission\ during\ life\text{-}cycle\ [g\ CO_2]}{Annual\ power\ generation \times Lifetime\ [kWh/god]}, \quad [5]$$

For each type of PV panel materials and input / output amount of energy are different. Therefore, in this study it will be analyzed the photovoltaics with different solar cells:

- Mono-crystalline silicon PV cell
- Polycrystalline silicon PV cell
- Photovoltaic cells from amorphous silicon

1.1. *Crystalline silicon PV cells*

The first phase of the life cycle represents the extraction of raw materials. In this case, quartz sand ore (SiO_2) which is processed through certain processes to obtain crystalline silicon. The silica in the quartz sand is reduced in an arc furnace to metallurgical-grade silicon, which must be purified further into solar grade silicon, in order to become suitable for the manufacture of solar cells.

To obtain mono-crystalline silicon PV cells Czochralski process is applied [6]. In this process from the melted silicon doped with boron, with adding grains of single crystals, mono-crystalline wafers thickness 0.3 mm were obtained. PV cells obtained in this way have the highest efficiency and the best quality.

Polycrystalline PV cells are obtained by purification of metallurgical silicon with modify Siemens process. Melted silicon is cast into molds, forming a rectangle and then cut into very thin sheets - wafers. This process yields very high silica purity (99.999%) [7].

The efficiency of most mono-crystal silicon solar cells is about 22%, they have a nice uniform color and have a more circular cell shape. Polycrystalline silicon

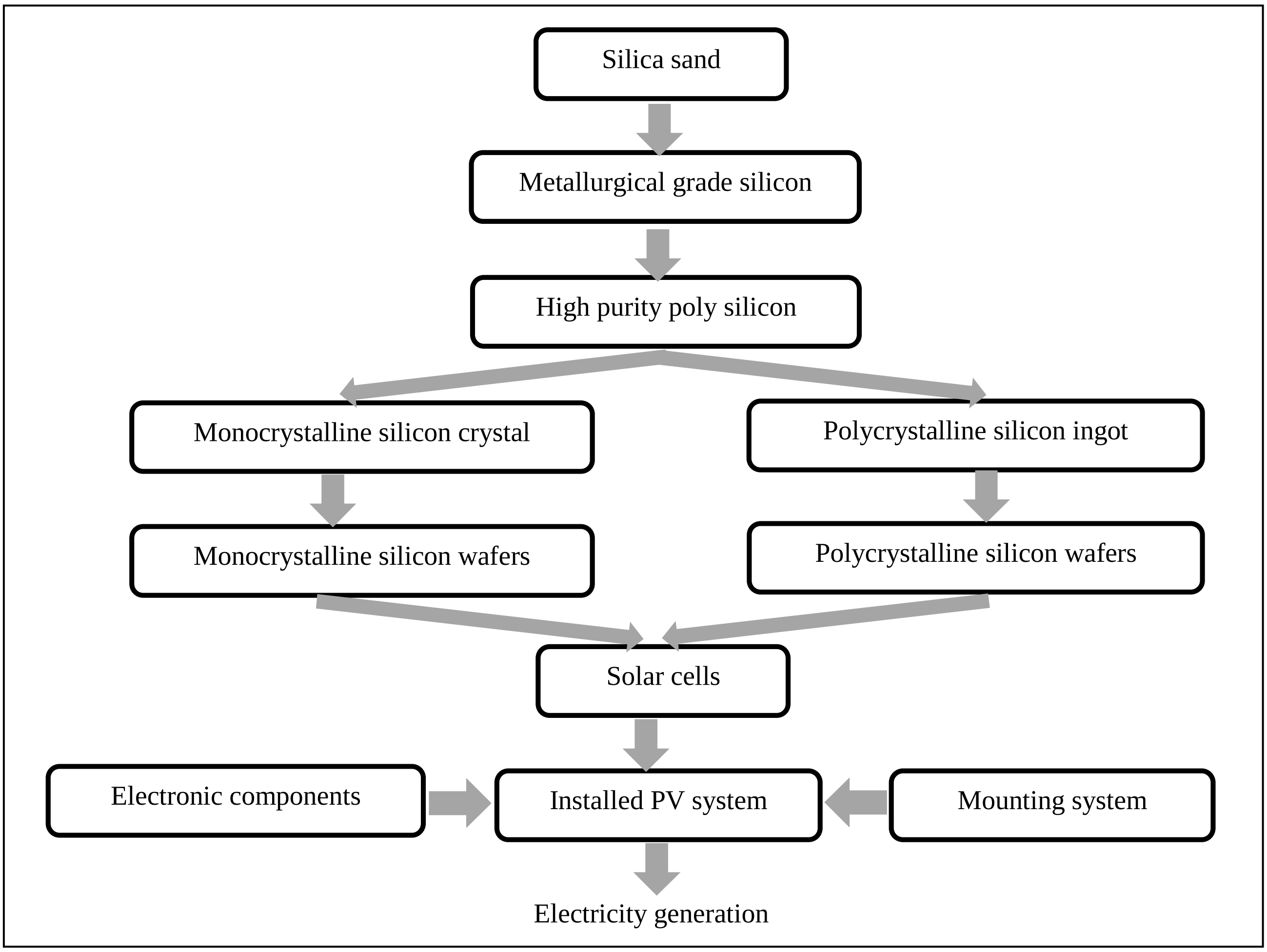

Figure 2. – *Life cycle stages of crystalline silicon PV cells*

wafers are manufactured with a lower cost process than mono-crystalline silicon and therefore the price of polycrystalline solar cells is lesser than mono-crystalline. The size of both types of crystalline cells is similar but the efficiency of polycrystalline solar cells is slightly lower, 14-18% [8]. *Figure 2* illustrates life cycle stages of crystalline silicon PV cells.

1.2. PV cells from amorphous silicon

Amorphous silicon represents a non-crystalline form of disoriented structure silicon and if it is applied as a thin film on glass or some other material it is discussed about the thin film PV cells. This thin-film technology is the most popular technique used.

The production technology for thin-film modules differs significantly from the one for crystalline silicon modules. The deposition of a thin layer of semiconductor material on the substrate (usually a glass plate) may be carried out in various ways and depending on the selected mode power consumption in the production process will vary [9].

There are several benefits for the production of solar cells made from amorphous silicon. Coefficient of absorption of solar radiation is higher than the crystalline silicon's and so they require significantly smaller amounts of material. With smaller amounts of material comes lower cost of production. Since this technique does not use any toxic heavy metals, such as lead or cadmium, it represents a technique with the least environmental impact. The disadvantage is lower cells efficiency (5-7%) [10].

3. EXAMPLES OF LCA FOR PV CELLS

- Erik Alsema in his papers [9] and [11] gave an overview of the energy requirements for crystalline PV cells and cells from amorphous silicon. For the polycrystalline silicon cells the total energy require-

Table 1. - *Energy requirements for a typical polycrystalline silicon PV module*

Process	Energy requirements (MJ/m^2)
Silicon winning and purification	2200
Silicon wafer production	1000
Cell/module processing	300
Module encapsulation materials	200
Overhead operations and equipment manufacturing	500
Total (without frame)	**4200**
Module frame (aluminum)	400
Total	**4600**

Table 2. - *Energy requirements for a typical amorphous silicon PV module*

Process	Energy requirements (MJ/m^2)
Cell material	50
Module encapsulation materials	350
Cell/module processing	400
Overhead operations and equipment manufacturing	400
Total (without frame)	**1200**
Module frame (aluminum)	400
Total	**1600**

Table 3. - *Energy requirements, Energy Pay Back Time and CO$_2$ emission for different types of PV modules [9]*

Type of PV module	Energy requirement (total) (MJ/m^2)	EPBT (year)		CO$_2$ emission (g/kWh)
		Rooftop	Ground-mounted	
mc-Si	4600	3,1	4	50
a-Si	1600	2,4	4	40

Table 4. - *Energy requirement and Energy Pay Back Time according to Bankier and Gale*

Type of PV module	Energy requirement (total) (MJ/m^2)	EPBT (year)
sc-Si	7900	/
mc-Si	6400	3,8
a-Si	3400	3,8

Table 5. - *Energy requirement for crystalline silicon PV modules*

Type of PV module	Energy requirement (total) (MJ/m^2)	EPBT (year)	CO$_2$ emission (g/kWh)
sc-Si	5200	2,2	45
mc-Si	4000	2,7	35

ments is 4600 MJ/m^2 (*Table 1*). Most of the energy is required for initial production processes, such as production of pure silicon and silicon wafer production. For the production of mono-crystalline silicon modules, Alsema states that energy requirements are higher, more precisely with an additional 1500 MJ/m^2 because of the more elaborate crystallization process.

As for the PV cells from amorphous silicon, in *Table 2* it can be seen that the material for the actual solar cell requires relatively little energy. This is primarily due to the small cell thickness [9]. On top of that it is necessary to add energy requirement for the balancing of the system.

Table 3 represents the data obtained on the basis of Alsema's research from the 2000s, for polycrystalline silicon PV system and for thin-film PV systems installed on the rooftop or ground-mounted, with medium irradiation of 1700 kWh/m2/year.

Given that, according to Alsema, expected life time of PV systems is 25-30 years and maximum energy payback time in low radiation exposure is 6 years. Even though it seems like a long time, it leaves plenty of room for a significant net production of energy.

- Bankier and Gale [12] give their assessment of the viability of PV system in 2006. According to their research the energy requirements of PV systems are slightly higher (*Table 4*). These differences occur because of different assumptions about the parameters of the process, especially for the production and purification of silicon. In this case energy payback time increases to 8 years.
- In their paper [13], Alsema and de Wild-Scholten collected data from several companies in America and Europe in order to fully cover the process of obtaining crystalline silicon PV modules. They gave information on the total energy requirements, as well as CO$_2$ emissions and energy payback period, in the middle irradiation of 1700 kWh/m$_2$/year (*Table 5*).
- Pacca in his study [14] gave an assessment of the impact of the life cycle of PV system with cells from amorphous silicon mounted on the roof of the building in Michigan, United States. At this location, solar radiation is 1359 kWh/m^2/year, CO$_2$ emission is 34.3 g/kWh for PV cell efficiency of 6.3%. The life time is estimated at 20 years.
- Mason's paper [15] published in 2006, shown the detailed life cycle analysis of the plant with a polycrystalline silicon PV panels capacity of 3.5 MW, mounted in Arizona. The system is set up on the ground and the modules are frameless. Radiation intensity is 2100 kWh/m^2/year. CO$_2$ emission amounts to 29 kg/kWh, while the energy payback time is 0.21 year. If you take the average value of radiation for America (1800 kWh/m^2/year) energy payback time will be 0.37 years.

2. CONCLUSION

In this work theoretical consideration of life cycle analysis of photovoltaic systems, with special emphasis on crystalline silicon PV cells and PV cells from amorphous silicon, is presented. As the output data of this analysis it is necessary to get the energy payback time of a PV system and CO$_2$ emissions as a useful index for determining the efficiency of PV systems in terms of global warming.

At the same time, a brief literature review of studies that have been done on this subject is shown, as well as example of PV power plant in Arizona. In order to draw a conclusion, only data for medium irradiation (1700 kWh/m^2/year) is shown. Average energy payback period for rooftop crystalline silicon PV systems ranging from 2-3 years, and for ground-mounted systems around 4 years. Energy payback period for PV cells from amorphous silicon is slightly lower, primarily because their production requires less primary energy. Balancing the system is very important because its share in primary energy consumption is significant, which could be seen from the tables above. The energy payback period is inversely proportional to the intensity of solar radiation, so in areas with high levels of radiation (2200 kWh/m^2/year) energy payback period of PV systems is lower. Emissions of CO$_2$, according to the research, for crystalline silicon PV systems ranging from 35-50 g/kWh and for PV systems from amorphous silicon 25-40 g/kWh.

Since the lifetime of PV system exceeds 20 years, according to some goes up to 30 years, low energy payback period means that the system can relatively quickly restore energy invested in its development. Value data related to greenhouse gas emissions, primarily CO$_2$, are significantly lower than the values that come from combustion of fossil fuels. Therefore it can be concluded that PV systems have significant potential to mitigate global warming. New PV technologies are more profitable from the energy side and negative impact on the environment is getting smaller. Bearing in mind how much is done to improve PV system, by 2020 according to Alsema [9] can be expected that the energy payback time for silicon crystal system is going to be 1-2 years and CO_2 emissions around 20 g/kWh or 0-1 and about 10 g/kWh for PV system with cells from amorphous silicon.

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