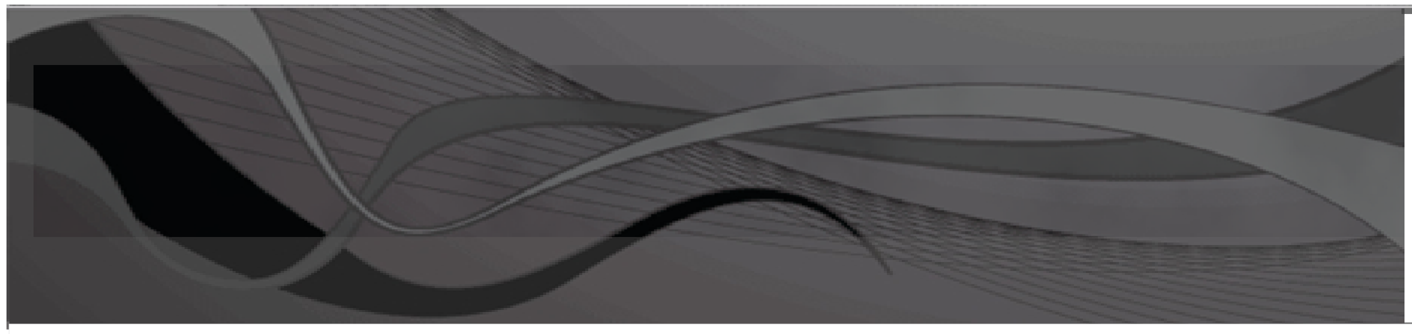

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CONFERENCE MANUAL

November 28th-30th - 2018, Kopaonik
Faculty of Engineering, University of Kragujevac

3rd International conference on Quality of Life

ISBN: 978 - 86 - 6335 - 056 - 4

Editors:
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Publisher:
FACULTY OF ENGINEERING
34000 KRAGUJEVAC
Sestre Janjić 6

CENTER FOR QUALITY
34000 KRAGUJEVAC
Sestre Janjić 6

For publishers:
Dr Dobrica Milovanović, full professor
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No. of copies: 200

Printing: Faculty of Engineering, Kragujevac

Publication of Conference manual and organization of
3rd International Conference on Quality of Life is supported by:
Department of Education, Science and Technological Development of Republic of Serbia

Izdavanje Zbornika radova, organizovanje i održavanje
3rd International Conference on Quality of Life podržalo je:
Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije

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3rd International Conference on Quality of Life
November 2018
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ENERGY PAY-BACK TIME AND CO_2 EMISSIONS OF PV SYSTEMS

Abstract: *Objective of this paper is to review existing knowledge on energy requirements for manufacturing of photovoltaic (PV) systems and to give some representative calculations for the energy pay-back time and the CO2 emissions. Both c-Si and thin film module technologies are analized. In this paper we have reviewed the energy viability of photovoltaic energy technology to answer the question whether PV systems can generate suficient energy output in comparison with the energy input required during production of the system components. The conversion efficiency, material usage, and production energy efficiency of PV systems are improving rapidly. Frequent updates of these analyses are necessary to follow this evolution.*

Keywords: *Photovoltaic systems, Energy pay-back time,* CO_2 *emissions*

1. INTRODUCTION

It is generally believed that our climate is changing, and there is a growing concern about the increase in energy use and its adverse effects on the environment. Today, the renewable energy systems have a significant impact on the environment, so the development of renewable energy resources and the use of renewable energy are essential. One of the most promising renewable energy technologies is photovoltaic (PV) energy conversion. PV energy conversion represents the direct conversion of sunlight into electricity. Commercial PV materials commonly used for PV systems include solar cells of silicium (Si), cadmium-telluride (CdTe), coper-indium-diselenide (CIS) and solar cells made of other thin layer materials. PV systems are still an expensive option for producing electricity compared to other energy sources, but many countries support this technology. Over the last five years, the global PV industry has grown more than 40% each year [1].

Starting from 1990 industry of photovoltaic conversion of solar irradiation shows constant annual economical growth of over 20 %, and from 1997 over 33 % annually. In 2000 total installed capacities worldwide have surpassed 1000 MW, and in developing countries have overreached more than million house-holds which are using electrical energy generated by means of the photovoltaic systems. It is predicted that PV will deliver about 345 GW by 2020 and 1081 GW by 2030. [2]. Silicon is a leading technology in making solar cell, due to its high efficiency. But many researchers, due to its high cost, are trying to find new technology to reduce the material cost for production of solar cells and thin film technology can be seen as a suitable substitution. However, the efficiency of solar cells based on this technology is still low, and researchers are intensively making an effort to enhance the efficiency. [3].

A typical PV system consists of the PV module and the balance of system (BOS) structures for mounting the PV modules and converting the generated electricity to alternate current (AC) electricity of the proper magnitude for usage in the power grid [4].

During the last decades a number of detailed studies on energy requirements of PV modules or systems have been published. Most of studies have focused on the environmental aspect of current and future photovoltaic systems which are assessed through life cycle analysis (LCA), considering different technologies, production processes, and evaluation the net energy ratio (NER), the energy payback time (EPBT), greenhouse gas (GHG) emissions, etc [5-8].

This paper is organized in the following way. In Section 2 PV growth today and different PV technologies are considered. In Section 3 life cycle assessment and environmental analysis of PV system are presented. In Section 4 and

Section 5 future PV technology and conclusions are discussed and presented.

2. PV TECHNOLOGY TODAY

2.1 *PV growth today*

The rapid growth of the PV market began in the 1980s. Today, the present PV market grows at very high rates, 30 – 40 %, like the telecommunication and computer sectors.

As can be seen from the Fig. 1, where the annual amount of PV solar systems installed by manufacturers in GW is shown, the solar industry has seen remarkable growth [9].

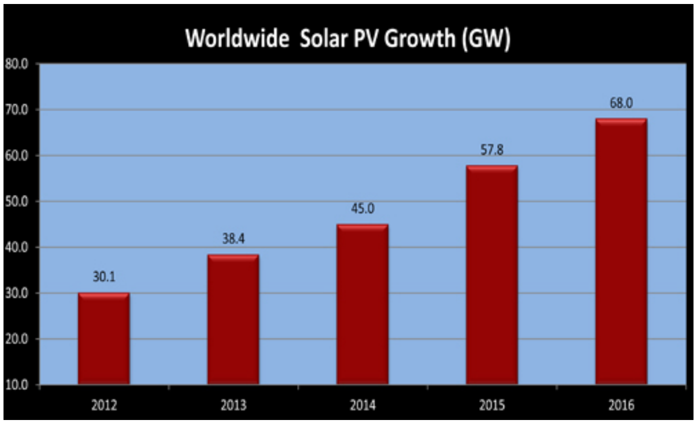

Figure 1 – Evolution of world PV cell/module production [9]

The 5 year average growth rate from 2012 (30.1 GW) to 2016 (68.0 GW) is about 22% per year. The growth in 2013 was 28% and 2014 was 17%, which averages out to be 22.5% for the two years (very close to the 5 year average). The growth in 2015 was also 28% and 2016 is projected to be 18% (slowing down somewhat as the numbers begin to get quite large). The 2013 and 2015 growth spurts of 28% were mainly due to increases in China, Japan and the US which have continued through out this period.

The growth for 2014 was only 17% because of sharp cutbacks in Germany and Italy. Also, China had no growth at all as they were consolidating their tremendous leap from the previous year. However, in 2015 China grew about 60% to 17.0 GW - by far the largest yearly installation ever. After 2016, the long term growth estimates are expected to be roughly 20% per year [9].

At present, the PV market is dominated (more than 40%) by grid-connected residential systems. Module prices are in the range of US$ 3.0 – 4.5/Wp, and the system prices are in the range of US$ 5 – 7/Wp, depending on technology and size. According to the US Department of Energy targets, the cost of energy is US$ 0.06/kWh for utility, US$ 0.08/kWh for commercial, and US$ 0.10/kWh for residential applications by 2015. [10].

2.2 *Materials for PV*

All solar cells require a light absorbing material which is found out within the cell structure to absorb photons and generate free electrons via the PV effect. As the material technology of PV develops, the use of solar power worldwide also increases rapidly year by year. Silicon is a leading technology in making solar cell due to its high efficiency (Fig. 2).

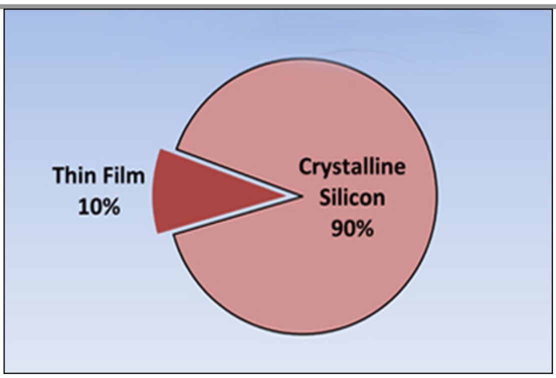

***Figure 2** – Solar cell materials markets in 2015 [9]*

Yet, it has high price, and many researchers are trying to find solution for this high cost problem. Goal is to find new technology, good enough to reduce the material price for solar cell production. To date, thin film technology is recognized as adequate substitute for silicon. The reasons behind the low cost of thin film technology are because it uses less material and the layers are much thinner, compared to mono- and polycrystalline solar cell thus lowering the manufacturing cost. However, this technology conveys solar cells with low efficiency. Three materials that have been given much attention under thin film technology are amorphous silicon, CdS/CdTe and CIS, but researchers are continuously putting in more effort to enhance the efficiency, although all of these materials have some bad impact on the environment. Researchers have carried out another solution for thin film technology by using polymer organic as a solar cell material. Polymer materials have many advantages like low cost, light weight and they are environmental friendly; and low efficiency compared to other materials as the only problem [10].

As can be seen from the Fig. 2, crystalline silicon dominates the solar market. While thin film's share for all thin film technologies was only 10% in 2015 down from 18% in 2009, according, crystalline silicon's share has been rapidly increasing the last few years as Chinese manufacturers became forceful [9].

Chinese suppliers have significantly reduced their costs and prices using multi-crystalline silicon, thus gaining market share. They operate on very thin margins and depend on large volumes to get their unit costs less. Of the ten top PV producers in 2015, seven were Chinese using crystalline silicon. The dramatic decrease in silicon module prices from 2011 to 2015 has almost closed the cost gap between multi-chrystalline silicon and cadmium telluride [9].

3. 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.

Generally, in renewable energy plants the largest environmental impacts occur during the manufacture and installation steps. 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 [6]. 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 [5]. The method attempts to quantify the environmental effects of the various stages of a product or process life-cycle: extraction of materials, manufacturing/production, use/operation, and ultimate disposal (or end-of-life) [7]. The LCA is today well defined and also regulated by the international standard series ISO 14040 which is divided into 4 steps: goal and scope definition, inventory analysis, impact assessment and interpretation.

PV system environmental analysis is based on estimation of energy payback time (EPTB) and the greenhouse gas emissions [4]. The energy payback time (EPBT) 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 [4] including the energy needed for manufacturing, set into motion, maintaining and decommissioning the entire system.

The emissions of criteria pollutants during the life cycle of a PV system are largely proportional to the amount of fossil fuel burned during its various phases, in particular PV material processing and manufacturing. Toxic gases and heavy metals can be emitted directly from the material processing and PV manufacturing, and indirectly from generating the energy used at both stages. Analyzing each of them is necessary to create a complete picture of the environmental impact of a technology [4].

Although several published life cycle assessments (LCA) quantify the life cycle energy input of PV installations and their environmental releases, such as CO_2 emissions, normalized by electricity output, these studies are difficult to compare [6]. Different studies use different methods, with different boundary conditions, rely on different data sources and inventory methods, different PV technologies at different locations, and consider different lifetimes and analytical periods [6]. Thus, the range of values published is quite large.

3.1 Energy payback time

Energy payback time is defined as the period required for a renewable energy system to generate the same amount of energy (either primary or kWh equivalent) that was used to produce the system itself.

Obtaining energy payback time requires knowledge of:

- primary energy demand to produce materials comprising PV system;
- primary energy demand to manufacture PV system
- primary energy demand to transport materials used during the life cycle
- primary energy demand to install the system
- primary energy demand for end-of-life management
- annual electricity generation in primary energy term
- annual energy demand for operation and maintenance in primary energy term

Calculating the primary energy equivalent requires knowledge of the specific of country, energy-conversion parameters for fuels and technologies used to generate energy and feedstock. The annual electricity generation is represented as primary energy based on the efficiency of electricity conversion at the demand side. The electricity is converted to the primary energy term by the average conversion efficiency of 0.29 for the United States and 0.31 for Western Europe. [4].

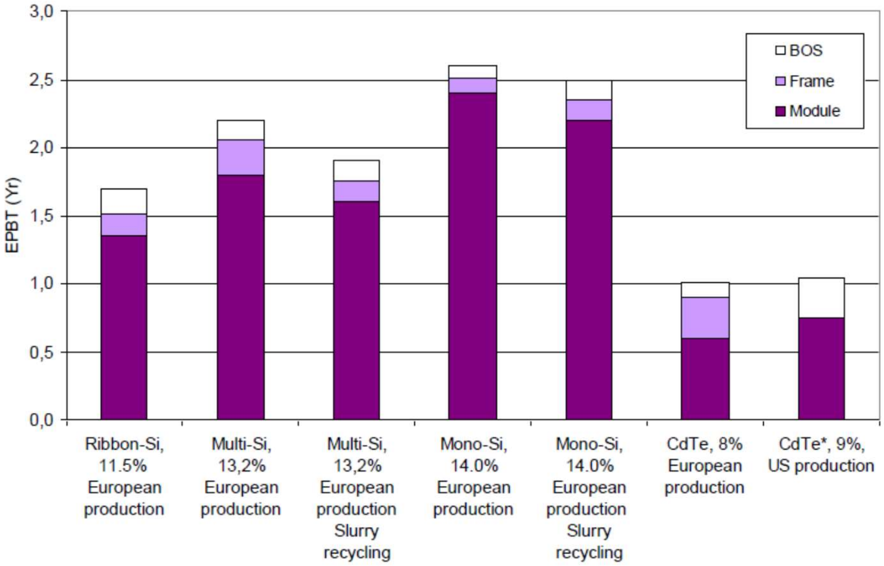

Figure 3 – Energy payback time for silicon and CdTe PV modules

Fig. 3 represents Energy payback time for silicon and CdTe PV modules, where BOS is the balance of system that is the module supports, cabling and power conditioning [4-8]. The estimates are based on rooftop-mount installation, insolation of 1700 kWh/m^2/year, a performance ratio of 0.75, and a lifetime of 30 years.

3.2 Greenhouse-gas emissions

The greenhouse-gas (GHG) emissions during the lifecycle stages of a PV system are estimated as an equivalent of CO2 using an integrated time horizon of 100 years; the major emissions included as GHG emissions are CO2, CH4, N2O and Chlorofluorocarbons. Electricity and fuel use during the PV materials and module production are the main sources of the GHG emissions for PV cycles. Upstream electricity generation methods also play an important role in determining the total GHG emissions.

For instance, the GHG emission factor of the average US electricity grid is 40% higher than that of the average Western European (UCTE) grid although emission factors of fossil-fuel combustion are similar, resulting in higher GHG estimates for the US - produced modules [2].

Fig. 4 represents Life-cycle GHG emissions from silicon and CdTe PV modules. The estimates are based on the same conditions as for the Fig. 3.. One exception, denoted by * at Fig. 3 and Fig. 4, represents a case based on ground-mount installation, average US insolation 1800 kWh/m^2/year, and a performance ratio of 0.8.

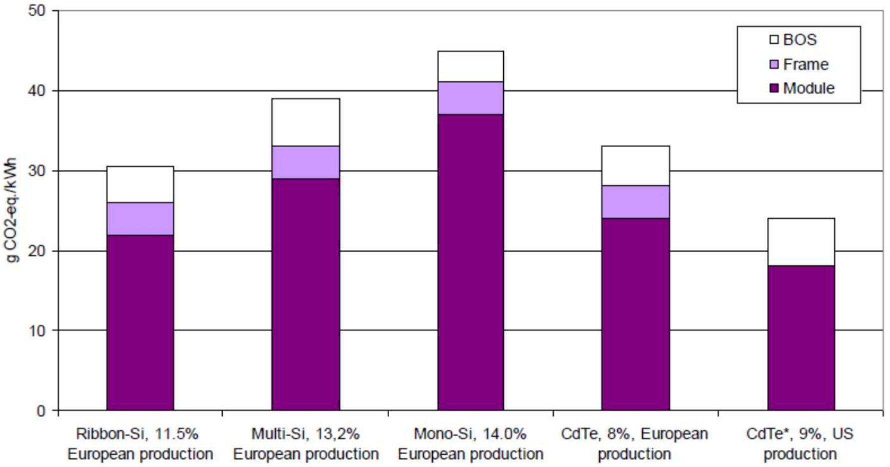

Figure 4 – Life-cycle GHG emissions from silicon and CdTe PV modules

4. OUTLOOK ON PV

The major improvements in materials and energy consumption as well as conversion efficiencies which expected to be realized within a few years in the crystalline-Si PV sector are outlined [6]. They forecast that the efficiency of ribbon, multi and mono-Si module will improve to 15%, 17%, and 19%, respectively, in near future, in accordance with the target established by the Crystal Clear project.

A fluidized bed reactor (FBR) currently being deployed will be able to reduce the energy demand for polysilicon by 70–90% from the popular Siemens process although it is unconfirmed if this new reactor type is capable of producing the same high-purity polysilicon as the latter. At the same time, Si wafers will become thinner: 150 µm for multi- and mono-Si and 200 µm for ribbon-Si. Table 1 presents compilation of studies that quantified CO$_2$ emissions and EPBT of PV systems.

Table 1 – EPBT and CO2 emissions of PV systems

Author	*Year*	*Characteristics*	*gCO_2/kWh*	*EPBT (years)*
Fthenakis and Alsema	2005	Polycrystalline; 13.2% efficiency; roof top PV systems under an insolation of 1700 kWh/m^2/year	37.0	2.2
Fthenakis and Alsema	2005	Monocrystalline; roof top PV systems under an insolation of 1700 kWh/m^2/year	45.0	2.7
Pacca et al.	2007	Amorphous PV system—20 year life time; efficiency 6.3%		
Pacca et al.	2007	Polycrystalline modules; 20 year life time; efficiency 12.92%	54.6	7.5
Fthenakis et al.	2006	CdTe; efficiency 8%/9%; 30 year lifetime;	21/25-18	1.0/1.1
Raugei et al.	2007	CdTe; efficiency 9%; 20 year lifetime;	48	1.5

The future of life-cycle GHG emissions from CdTe PV is exposed in [4], and in previous research of authors.

The US manufacturer of CdTe PV predicts:

- a linear increase in electrical-conversion efficiency;
- a reduction of electricity requirements by about 25% within a couple of years through optimization of the deposition processes in CdTe lines;
- about 20% of the manufacturing requirement will be satisfied via on-site solar electric generation.

The prediction is that the EPBT would fall to 0.4 years and the GHG emissions to 10 g CO2-eq./kWh for the life cycle of installed CdTe PV under the average US insolation, 1800 kWh/m^2/year [4].

5. CONCLUSION

In this paper the current commercial and potential future of PV technologies is analyzed, with a special focus on their related prospective and challenging manufacturing issues. Commercial c-Si cells have efficiencies in the range of 15–22%, so any TF PV still have to compete with this technology.

The PV system is promising source of electricity generation for energy resource saving and CO2 emission reduction, even if current technologies are applied. Further the development in efficiency of solar cells, amount of material used in the solar cell system and the system are designed for maximum use of recycled material will reduce the energy requirement and GHG emissions.

The PV industry is striving for cost savings simultaneously for advanced performance, which largely translates into life-cycle energy savings and emissions abatement. The conversion efficiency, material usage, and production energy efficiency of both Si and CdTe PV systems are improving rapidly. Frequent updates of these analyses are necessary to follow this evolution.

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Acknowledgment: This paper is a result of project TR33015, Investigation and development of Serbian zero-net energy house, supported by the Ministry of Science and Technological Development of Republic of Serbia.

CIP - Каталогизација у публикацији - Народна библиотека Србије,
Београд

316.728(082)
006.015.5(082)

INTERNATIONAL Conference on Quality of Life (3 ; 2018 ; Kopaonik)
Conference Manual / 3rd International Conference on Quality of Life,
November 28th-30th - 2018, Kopaonik ; [editors Slavko Arsovski,
Miladin
Stefanović, Danijela Tadić]. - Kragujevac : Faculty of Engineering, Center
for Quality, 2018 (Kragujevac : Faculty of Engineering). - VIII, 242 str. :
graf. prikazi, tabele ; 27 cm

Tiraž 200. - Napomene i bibliografske reference uz tekst. - Bibliografija
uz svaki rad.

ISBN 978-86-6335-056-4
1. Arsovski, Slavko [уредник], 1952- 2. Tadić, Danijela [уредник], 1967-
3. Stefanović, Miladin [уредник], 1971-
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COBISS.SR-ID 270130700