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ENERGY GENERATION 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 CO_2 emissions. We will also investigate the effects of future enhancements in PV production technology in order to evaluate the long-term prospects of PV systems for CO_2 mitigation. Both c-Si and thin film module technologies are analized. The CO_2 mitigation potential and the importance of PV systems for sustainable development are also highlighted. 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.*

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

1. INTRODUCTION

Photovoltaic energy conversion is widely considered as one of the more promising renewable energy technologies which has the potential to contribute signifcantly to a sustainable energy supply and which may help to mitigate greenhouse gas emissions [1].

Commercial PV materials commonly used for photovoltaic systems include mono-crystalline silicon, multi-crystalline silicon, amorphous silicon and thin film technologies, such as cadmium-telluride (CdTe) and coper indium diselenide (CIS) [2,3,4]. 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 [2].

In these last decades a number of detailed studies on energy requirements of PV modules or systems have been published [5,6,7]. Most of studies have focused on the environmental aspect of future photovoltaic systems which are assessed through life cycle analysis (LCA), considering different tehnologies, production processes, and evaluation the net energy ratio (NER), the energy payback time (EPBT), greenhouse gas (GHG) emissions, etc [8,9] .

This paper is organized in the following way. In Section 2 life cycle assessment, which is a technique for assessing various aspects associated with development of a product and its potential impact throughout a product’s life, is presented. Environmental analysis of PV system is given in Section 3. In Section 4 and Section 5 future PV tehnology and conclusions are discussed and presented.

2. 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.

Table 1 – EPBT and CO_2 emissions of PV systems

Author	Year	Characteristics	gCO_2/kWh	EPBT (years)
Alsema	2000	Monocrystalline grid connected roof top system; insolation of 1700 $kWh/m^2/year$; 30 year lifetime	60.0	3.2
Alsema	2000	Thin film (amorphous) grid connected roof top system; insolation of 1700 $kWh/m^2/year$; 30 year lifetime	50.0	2.5–3
Alsema	2000	Polycrystalline 13% efficiency; insolation of 1700 $kWh/m^2/year$	46.0	2.5
Alsema	2000	Monocrystalline 14% efficiency; insolation of 1700 $kWh/m^2/year$; 30 year lifetime	63.0	3.1
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

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 [6,7]. 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) [5]. 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 [2]. 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 [1,2,3] 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. Accounting for each of them is necessary to create a complete picture of the environmental impact of a technology [2].

Although several published life cycle assessments (LCA) quantify the life cycle energy input of PV installations and their environmental releases, such as CO2 emissions, normalized by electricity output, these studies are difficult to compare [5]. 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 [5]. Thus, the range of values published is quite large. Table 1 shows a compilation of studies that quantified CO2 emissions and EPBT of PV systems [1-8].

3. ENVIRONMENTAL ANALYSES OF PV SYSTEM

The most frequently measured life-cycle metrics for PV system environmental analyses are the energy payback time (EPTB) and the greenhouse gas emissions.

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.

Energy payback time can be obtain by

$$\mathrm{EPBT} = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}}{E_{agen} - E_{aoper}}$$

where:

- E_{mat} is primary energy demand to produce materials comprising PV system;
- E_{manuf} is primary energy demand to manufacture PV system;
- E_{trans} is primary energy demand to transport materials used during the life cycle;
- E_{inst} is primary energy demand to install the system;
- E_{EOL} is primary energy demand for end-of-life management;
- E_{agen} is annual electricity generation in primary energy term and
- E_{aopet} is 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 (E_{agen}) 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. [2].

3.2 Greenhouse-gas emissions

The greenhouse-gas (GHG) emissions during the lifecycle stages of a PV system are estimated as an equivalent of CO_2 using an integrated time horizon of 100 years; the major emissions included as GHG emissions are CO_2, CH_4, N_2O 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. 1 represents Life-cycle GHG emissions from silicon and CdTe PV

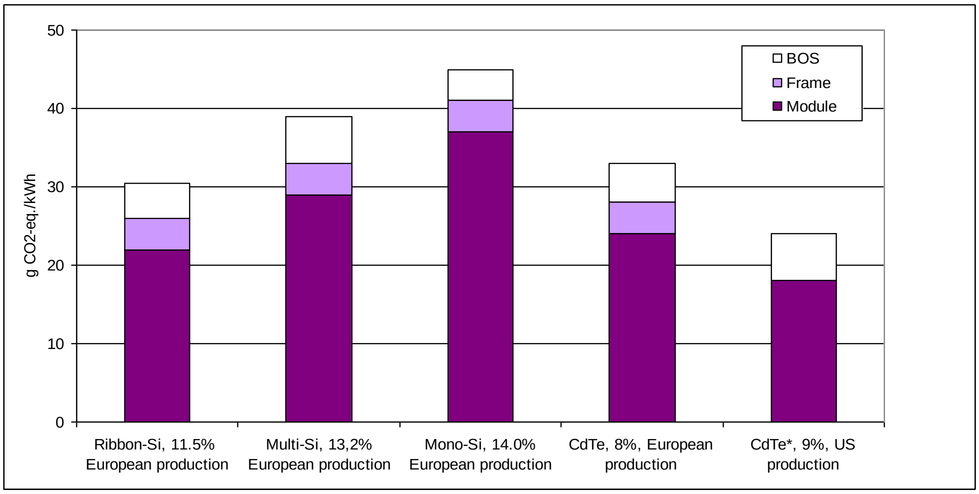

Fig. 1. *Life-cycle GHG emissions from silicon and CdTe PV modules*

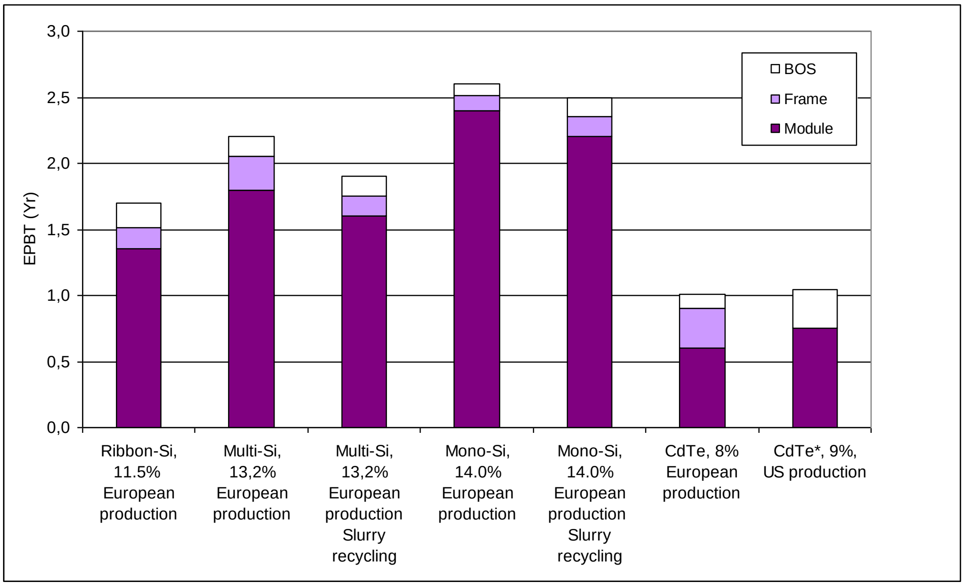

Fig. 2. *Energy payback time for silicon and CdTe PV modules*

modules, where BOS is the balance of system, that is the module's supports, cabling and power conditioning [1-8]. The estimates are based on rooftop-mount installation, Southern European insolation of 1700 kWh/m^2/year, a performance ratio of 0.75, a lifetime of 30 years. One exception, denote by * at Fig. 1, represents a case based on ground-mount installation, average US insolation 1800 kWh/ m^2/year, and a performance ratio of 0.8.

Fig. 2 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 [1-8]. The estimates are also based on rooftop-mount installation, insolation of 1700 kWh/m^2/year, a performance ratio of 0.75, and a lifetime of 30 years. The same exception, denote by * at Fig. 2, represents a case based on ground-mount installation, average US insolation 1800 kWh/m^2/year, and a performance ratio of 0.8.

4. FUTURE PV TEHNOLOGY

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 [8]. 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.

The corresponding GHG emissions

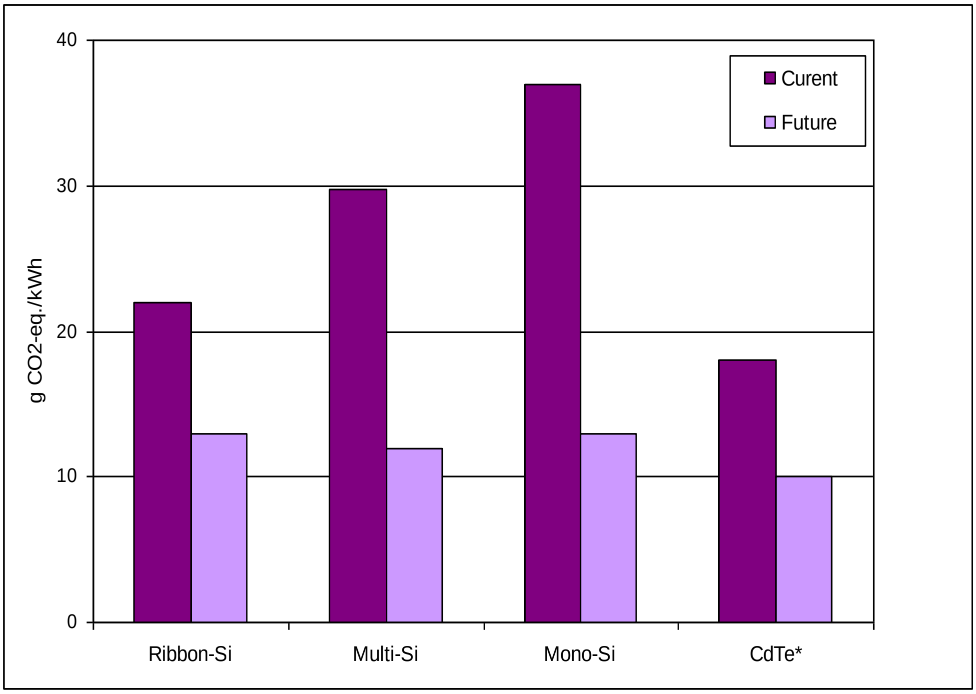

Fig. 3. *Future prediction for Life cycle GHG emissions from silicon and CdTe PV modules*

and EPBT are presented in Fig. 3 and 4 respectively. The future of life-cycle GHG emissions from CdTe PV is exposed in [2], and in previous research of authors.

The US manufacturer of CdTe PV predicts:

- a linear increase in electrical-conversion efficiency from the current 9% to 12% by 2010;
- 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 CO_2-eq./kWh for the life cycle of installed CdTe PV under the average US insolation, 1800 kWh/ m^2/year, [2].

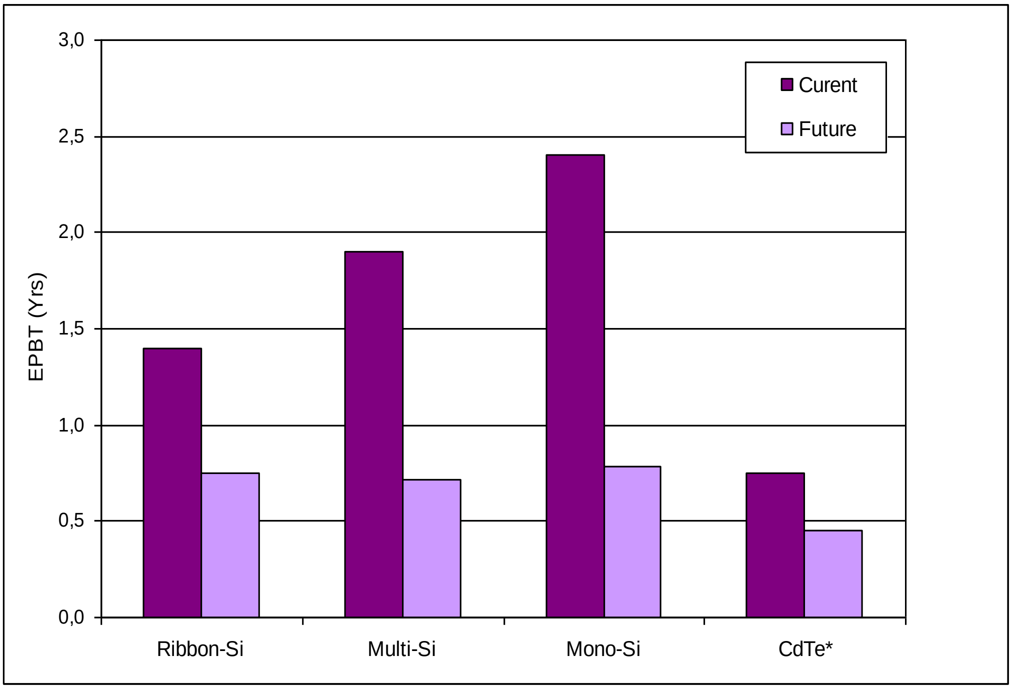

Fig. 4. *Future prediction for Energy payback time from silicon and CdTe PV modules*

5. CONCLUSION

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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