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Energy Payback Time and CO_2 Emissions of 1.2 kWp Photovoltaic Roof-Top System in Brazil

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Abstract

The energy requirements for the production of photovoltaic (PV) panel and balance of system components are analyzed in order to evaluate the energy payback time and CO_2 emissions of a 1.2 PV roof top system in Brazil. The single crystalline panel technology is investigated by using life cycle assessment methodology. It considers mass and energy flows over the whole production process, starting from metallurgical silicon production to the electric generation. Assuming seven different national geographic conditions, cumulative energy demand (CED), energy yield, energy payback time (EPBT) and CO_2 emissions rates are calculated. As result it is found that the EPBT is 2.47 – 3.13 years and CO_2 emissions rate is 14.54 – 18.68 g de CO_2 eq/kWh for present day roof-top mounted installations.

Keywords: Photovoltaic rooftop system, energy payback time, CO_2 emissions, life cycle assessment

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1. Introduction

The renewable energy has been gaining importance among the public, policy formulators and decision-makers worldwide. In addition to the high cost and insecurity related to fossil fuels, an increasing global awareness about greenhouse gas (GHG) and primary energy supply is acting as the driving force behind the use of renewable of energy.

In this context, photovoltaic energy conversion (PV) is expected to have large potential as an alternative power source without constraint on CO_2 emissions, especially for small distributed thermal and/or electric energy production. For these reasons, there is a growing support from government for photovoltaic R&D program and market introduction schemes [1]-[3].

Particularly in Brazil, with the purpose of promoting the new renewable energy introduction the Ministry of Mines and Energy (MME) established Working Group on Distributed Generation with Photovoltaic Systems (GT-GDSF). The GT-GDSF efforts resulted in nationwide project, namely Development of Competence in Photovoltaic Systems with Distributed Generation Connected in Low Voltage, which aims to define the conditions and impacts for PV systems insertion on Brazilian residential rooftop.

Given that different power systems producing the same gross energy output may differ in regards to energy inputs and it generally have significant environmental implications, the energy accounting is of vital interest and may be a first step towards a more comprehensive environmental assessment [4]. Furthermore, energy analysis results provide a good indication of the CO_2 mitigation potential of the considered technology [2]-[4]. Although several studies on the energy payability (EPBT) and GEE emissions of PV technology were reported in the last 15 years, the potential impacts and benefits must be analyzed carefully, since they depend on efficiency of the module or technology; site of installation

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(latitude, climate); installation type, life time and the country's mixture electricity grid used to material processing [4],[5].

In this sense, we studied the energy payback time (EPBT) and CO_2 potential of mitigation for 1.2 kWp PV rooftop system under different geographic conditions of solar irradiation in Brazil, using Life Cycle Assessment (LCA) methodology. LCA is used in evaluating the potential environmental impacts of energy technologies and its results are increasing used in decisions about R&D funding and energy policies. This paper estimated both EPBT and life cycle CO_2 emission based upon present single crystalline technologies.

Nomenclature

AEO	Annual energy input	GHG	Greenhouse gas
BOS	Balance of system	LCA	Life cycle assessment
CED	Cumulative energy demand	LCE_{input}	Life cycle primary energy input
EPBT	Energy payback time	$LCCO_2$	Life cycle $CO_{2equivalent}$ emission
kWp	Kilowatt peak (PV nominal power)	PV	Photovoltaic

2. Evaluation Method

The analysis, through LCA, is carried out in accordance to the relevant recommendations by International Organization for Standardization (ISO 14044 and updates) and the International Energy Agency (Report IEA-PVPS T12-01:2009). It is performed using the software GaBi 4.0 professional (developed by International PE) the Ecoinvent database v2.1 (Swiss Center for Life Cycle Inventories) and the data from the Solar Energy Laboratory (LabSolar) of the Institute of Electrothenics and Energy (IEE).

The authors estimate the requirements of energy and major materials for life cycle of 1.2 kWp, that is metallurgical silicon production, manufacture and transportation of the system components, including BOS (supporting structure, inverter and cabling), installation and operation. Since the environmental impact is dominated by primary energy use [2],[3] the employed method is Cumulative Energy Demand (CED), calculated by the method describe in Ecoinvent 1.01.

On the other hand, an important environmental effect is the global warming potential(GWP), this is calculated by using GWP 100 years according to the characterization fator CML 2001 method. For further details on each individual method, the reader is asked to refer to cited literature. The indices of energy yield, EPBT and CO_2 emission rate estimated here are defined by the following equations:

$$E_{yield} = PR \times P_0 \frac{H}{I_{std}} \tag{1}$$

where E_{yield} is the amount of electricity producing in kWh/year, PR is the performance ratio, P_0 is the nominal power of the PV system in kWp, and H means the solar radiation on the unit-surface under consideration(kWh/m^2) analysed during the period (year) and I_{std} is reference irradiance equal to 1kW/m^2.

EPBT is defined as ratio of the total energy input during the system life cycle compared to the yearly generation during system operation and is expressed in years.

$$EPBT = \frac{LCT_{input}(MJ)}{AEO(MJ/year)} \tag{2}$$

where LCT_{input} is the life cycle primary energy input and AEO is the annual energy output or energy yield in their primary energy equivalent. EPBT means years to recovery primary energy consumption throughout its life cycle by its own energy production. Acording to Ito [5] CO_2 emissions rate is useful index to know to what extent the PV is effective to the global warming.

$$\mathrm{CO}_{2\text{(emission rate)}} = \frac{LCCO_2(\text{kg CO}_2\ \text{equivalent})}{AEO(\text{kWh/year}) \times PV_{\text{lifetime}}(\text{year})} \tag{3}$$

where $LCCO_2$ is the total $CO_{2\ \mathrm{equivalent}}$ emissions on life cycle.

2.1. Major assumptions

The chain for current PV system has been decomposed into the following step, each modelled separately: metallurgical silicon grade (MG-si) processing, production mix of silicon solar grade (SoG), former process of single crystalline silicon, wafer manufacture and panel fabrication. To describe the entire 1.2 kWp PV system, additional elements have been included in the assessment. One is the BOS, i.e., the inverter and electric installation and other electric components required to connect the system to the grid. The decommissioning stage is not including in this study.

As mentioned before it is assumed that a 1.2 kWp PV system is installed in Brazilian residential rooftop connected in low voltage. The LCA of this study consider on following below and material process data which is show in Table 1.

- A LCA study takes a reference value “functional unit” as a basis and it specifies the reference flow to enable comparison. As functional unit for the purpose of this study is 1.2 kWp.
- Many manufacture process for PV rooftop system take place all over the world. Since the Brazil is one of the major supplies of silicon metallurgical grade, this process count upon the national electricity mix as source of energy supply. The other manufacture process such as silicon solar grade, solar cell and panel, as well as inverts and cabling were modeled based on the European and US production.
- Nowadays the majority of silicon used in PV industry is made specifically for this sector with a modified Siemens process. Off grade silicon has a decreasing share in PV industry supply, it is estimated in 2006 at only 5% of total PV supply [5]. In this study it is assumed that the share of purified silicon PV supply is 80.2% silicon solar grade and 9.8% off grade and electronic silicon grade (production mix for silicon purified).
- The type of solar cell technology is single crystalline and the panel is aluminum framed, with 15.3 % and 14% efficiency, respectively. The type of installation is residential slanted roof mounting system. The panel capacity rate is 140 Wp/m^2 and the amount of panels per 1.2 kWp is 8.57 meter square (7.85 m^2 active surface).
- The inverter is produced with an efficiency of 93.5%. The device mass is about 18.5 kg, with more than 50% w/w steel (from the casting) and about 35% of transformers.

Table 1. Major requirement data for 1.2 kWp PV system evaluation

Material/Process/Equipment	**Description**	**Data**
Silicon to metalurgical silicon grade (MG-si)	Carbothermic reduction	9.8654 kg
Silicon solar grade (SoG)	Modified Siemens Process	8.9240 kg
Off grade and electronic grade (EG) silicon	Conventional purified chemical process	1.9589 kg
Single crystalline silicon (Sc-si)	Czochralski process	10.171 kg
Sc-si wafer	Thickness (270µm)	9.4636 m^2
Sc-si cell	Cell area (0.0243 m^2)	8.9257 m^2
Sc-si panel	Aluminum framed	9.5751 m^2
Construction of mounted system	Aluminum and steel support	9.2966 piece
Inverter	Inverter (2500 W)	1.0412
Land transport in Brazil (installation)	Van < 3.5 t,(distance average)	100 km
Land transport in Brazil (installation)	Lorry >16 t, (distance average)	1175 km
International marine transport from Europe to Brazil	Freight ship,(distance average)	9610 km
Electrical installation	Cabling	0.43834 piece

The values used for irradiation have been calculated on the optimal angle or on maximum annual energy availability. Here we studied seven different Brazilian locations: Belém, Belo Horizonte, Florianópolis, Porto Alegre, Rio de Janeiro, Salvador and São Paulo. The Table 2 shows the values of the irradiation, latitude and climate of each place.

Table 2. Irradiation, latitude and climate of Brazilian locations

Location	**Irradiation (kWh/m^2/year)**	**Latitude (^{o})**	**Climate**
Belém	1884	-1.45	equatorial tropical
Belo Horizonte	1643	-20.08	high altitude tropical
Florianópolis	1690	-27.50	humid subtropical
Porto Alegre	1581	-30.09	humid subtropical
Rio de Janeiro	1758	-22.5	humid tropical
Salvador	1935	-12.41	humid tropical
São Paulo	1506	-23.43	subtropical

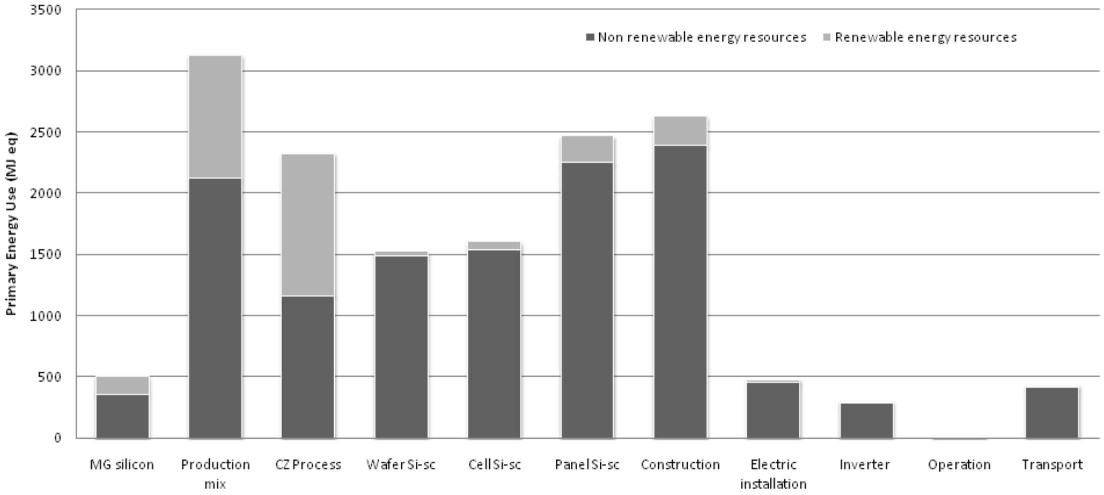

Fig. 1. Cumulative energy demand of .1.2 kWp PV roof -top system in Brazil

The performance ratio assumed in this study is 75%, according to IEA Task 12's recommendation for rooftop mounted PV system. The lifetime of PV panel, structure and cabling for roof top mounting system is 30 years, while the inverter lifetime is 15 years. Also for the panels a 2% replacement of damaged modules during the lifetime plus production loss during handling of 1% is assumed here.

3. Evaluation Results

Briefly the most important results of the analysis are calculation of cumulative energy demand measured in MJ equivalent of primary energy consumption, EPBT and global warming potential concerning the contribution of the process to climate change. Fig. 1 shows the share of primary energy required in each phase of the PV system studied. More than 80 % of energy input is related to the use of non-renewable sources. The contribution of renewable energy has great share of hydroelectric energy mainly due to the consideration of location-specific electricity mix.

The total CED for the 1.2 kWp PV system, expressed in MJ of primary energy per meter square of panel area, is 1619 MJ/m^2. The critical phases in terms of CED (normalized results) are the metallurgical silicon process into purified silicon, (3133 MJ), the mounting construction (2632 MJ) and the panel assembling (2468 MJ). The Si purification is characterized by the great electricity consumption, even if the most efficient technologies have been considered. The use of aluminum and solar glass (low iron), which are very intensive energy materials is also a large a contributor for energy requirements in the panel assembling. In fact, aluminum and also steel low alloyed used as support contributes for the CED in the construction phase.

On the other hand, the energy and associated emissions during operation are practically negligible compared with the requirements during the various steps of PV manufacturing. The relative magnitude of CED for 1.2 kWp PV system is clearly similar to relative impact scores of global warming potential. The major contributor to GWP is the panel production phase (159 $kgCO_{2\ equivalent}$), while the construction phase is 151 $kgCO_{2\ equivalent}$. Indeed, most of the emissions associated with current PV systems originate from the energy requirements; the rest is from materials production and, to a minor extent, directly specific process of the PV chain. Emissions not related to energy use only are found in steel and aluminum production for the support and frames. Fig. 2 shows the results of $CO_{2\ equivalent}$ emissions for the entire 1.2 kWp PV system life cycle.

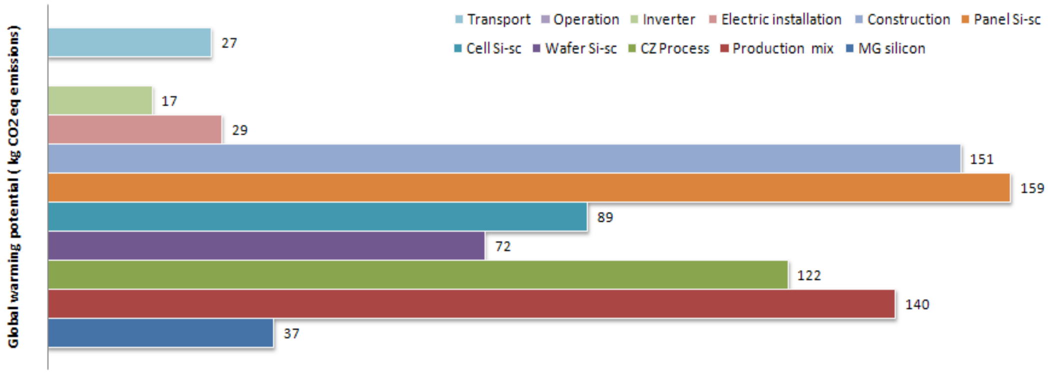

Fig. 2. Global warming potential of 1.2 kWp PV roof-top system in Brazil

The energy generated per year calculated according to Equation 1, EPBT (Equation 2) and CO_2 emissions rate (Equation 3) for the different Brazilian locations are presented in Table 3. For the average Salvador and Belém solar irradiation the EPBT for complete installed system is 2.47 and 2.60 years, respectively. The highest values of EPBT (about 3years) are found in São Paulo and Porto Alegre. The specific CO_2 emissions rate in each Brazilian location is about 14.54 kg/kWh to 18.68 kg/kWh, which is considerably lower than the emissions from existing fossil-fuel electricity system (400 kg/kWh to 1000 kg/kWh).

Table 3. Energy yield, EPBT and CO_2 emissions rate

Location	Energy yield (kWh)	Energy yield (MJ)	EPBT (years)	CO_2 emissions rate (kg/kWh)
Belém	1660	5975	2.60	15.26
Belo Horizonte	1479	5323	2.91	17.12
Florianópolis	1521	5476	2.83	16.65
Porto Alegre	1423	5122	3.03	17.79
Rio de Janeiro	1582	5669	2.72	16.00
Salvador	1742	6229	2.47	14.54
São Paulo	1355	4879	3.13	18.68

These results show that the present PV roof-top system is able to produce the energy required for its existence from 10 to 12 times during life cycle of 30 years and can contribute significantly to the mitigation of CO_2 emissions. It means that PV roof-top system would be very promising for the energy and environmental issues in Brazil.

4. Conclusions and Further Work

The EPBT and CO_2 emissions rate have been investigated for roof-top crystalline silicon PV system under different geographic conditions of solar irradiation in Brazil. As a result of our life cycle assessment, we show that a residential 1.2 PV system in Brazil may recover the energy input within its lifetime and with lower CO_2 emissions. At the present sensitive analysis of PV panel transport from factory to utilization on EPBT and CO_2 emissions is being studied, this could be interesting to evaluate the real impact of different types of fuel and distances. Multi objective evaluation of environmental performance, cost and regulatory policies issues over the life cycle PV system will ultimately provide the most complete bases for design, planning and implementation. This full set of information and data offers a more powerful means for promoting PV technology as an effective source of sustainable energy in Brazil.

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