ELSEVIER

Energy Policy 34 (2006) 3144–3152

ENERGY POLICY

www.elsevier.com/locate/enpol

Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level

I. Nawaz[a], G.N. Tiwari[b,*]

[a]Department of Mechanical Engineering, Faculty of Engineering and Technology, Jamia Millia Islamia, New Delhi 110025, India
[b]Center for Energy Studies, IIT Delhi, Hauz Khas, New Delhi 110016, India

Available online 25 July 2005

Abstract

In this paper the energy payback time and CO_2 emissions of photovoltaic (PV) system have been analyzed. The embodied energy for production of PV module based on single crystal silicon, as well as for the manufacturing of other system components have been computed at macro- and micro-level assuming irradiation of 800–1200 W/m^2 in different climatic zones in India for inclined surface. The energy payback time with and without balance-of-system for open field and rooftop has been evaluated. It is found that the embodied energy at micro-level is significantly higher than embodied energy at macro-level. The effect of insolation, overall efficiency, lifetime of PV system on energy pay back time and CO_2 emissions have been studied with and without balance of system. A 1.2 kW$_p$ PV system of SIEMENS for mudhouse at IIT, Delhi based on macro- and micro-level has been evaluated. The CO_2 mitigation potential, the importance and role of PV system for sustainable development are also highlighted.

Keywords: Embodied energy; Photovoltaic system; Energy payback time

1. Introduction

At the global level, the generation of electrical energy mostly depends on fossil fuels. Fossil fuels are however diminishing due to extensive and continuous use prompted by increasing population and rising level of development. Moreover, burning of fossil fuels is the principal cause of CO_2 emissions leading to air pollution and environmental degradation. Hence, there is a need to conserve fossil fuels and to explore possible alternatives. In this perspective, awareness about the utilization of renewable energy sources (such as solar energy) has gained acceptance globally. Most of Indian territory is blessed with a high potential of solar radiation, which is most suitable for development of solar photovoltaic (PV) system for power generation.

Energy conversion through PV system is one of the most important, more reliable and environment friendly renewable energy technology which has the potential to contribute significantly to a sustainable energy system. It also plays an important role to mitigate CO_2 emissions. Alsema and Niluwlaar (2000) have evaluated the energy requirement for manufacturing of PV system, energy payback time (EPBT) and CO_2 emissions. But they have not considered: (a) support structure, (b) interval of battery replacement and (c) efficiency of balance-of-system (BOS). They have considered the system efficiency to 14% uniformly throughout the lifetime of PV system. Krauter and Ruther (2004) have evaluated only the energy requirement for manufacturing the PV system and CO_2 emissions without considering the above-mentioned parameters. Frankl et al. (1998) have considered support structure for open field mounted and on rooftop to evaluate the energy requirement for manufacturing PV system. They have also considered the same lifespan for battery and PV system.

*Corresponding author. Tel.: +91 11 26591258; fax: 91 11 26862037, 26581121.
E-mail address: gntiwari@ces.iitd.ernet.in (G.N. Tiwari).

0301-4215/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2005.06.018

In this paper, an attempt has been made to calculate EPBT by evaluation of energy requirement for manufacturing a single crystalline silicon PV system for open field and rooftop conditions with BOS. Mitigation of CO_2 emissions at macro and micro-level of the PV system has also been studied.

2. Solar energy technology

Solar energy can be used in two forms: (i) thermal form and (ii) PV form.

(i) *Thermal form*: In this form, solar energy is absorbed directly or through concentrators and then converted into thermal energy for various applications such as water heating, space heating, cooking, drying and water purification, etc.
(ii) *PV form*: In photovoltaic form, solar energy is converted into electricity using PV cell and can be used for various applications (e.g. as a source of electricity in refrigeration, water pumping, electrical and electronic equipment, lighting, etc). This has significant result in saving of fossil fuels and also saving of electricity and minimizing the emissions of CO_2.

3. Energy analysis

In energy analysis, a comprehensive study has been made for energy input and output involved in products. The overall energy performance of such products is determined by accounting all energy flows in the life cycle from resource extraction through manufacturing and product use. In case of PV system, the gross energy requirement (E_{in}) is determined by adding together the energy input during resource winning, production, installation, operation and maintenance of the PV system and the other system components. This gross energy requirement is then compared with the energy output (E_{out}). The classification of energy is broadly expressed as:

(i) Embodied energy: It is the amount of energy required to produce the material in its products form. It is also known as energy input (E_{in}). It can be classified into two groups: (a) macro-level and (b) micro-level.
   a. *Macro-level*: If lifetime of battery (consumables) and PV system are same.
   b. *Micro-level*: If lifetime of battery (consumables) and PV system are not same.
(ii) Energy output: It is the amount of energy obtained per year in kWh from the system (E_{out}).

Table 1
Specifications of PV system

Size of a cell	12.5 cm × 12.5 cm
Area of a cell	156.25 cm^2 (square shape) 142 cm^2 (pseudo square)
Thickness of a cell	0.035 cm
Density of silicon	2.3 gm/cm^3
Mass of a single cell	12.578 gm. (square shape)
No. of cells in a module	36
No. of cells in an array	576
Total mass of cells	7245 gm (7.245 kg)
Size of module	120 cm × 52 cm
Area of module	0.6240 cm^2 (0.6240 m^2)
Area of cells in module	36 × 142 cm^2 (0.5112 m^2)

4. Specification of PV system

A 1.2 kW_p PV system of SIEMENS make has been installed at IIT, Delhi. Each module has an effective area 0.6240 m^2 and produces 75 W_p power. There are 16 modules connected in series and parallel combination and total effective area of PV system is 10 m^2. The system was installed by m/s Advanced Electronic Systems. The specifications of PV system are given in Table 1.

5. PV system

The installation of PV system can be divided into the following sectors:

(i) Energy required in purification and processing of material (silicon dioxide) to produce Czochralski silicon (solar grade) ingot per kg.
(ii) Energy required for production of silicon wafers form Czochralski silicon ingot for cell fabrication per m^2.
(iii) Energy required for module assembly per m^2.
(iv) Energy required for support structure per m^2 (for open field and for rooftop).
(v) BOS components: Battery, inverter, electronic components, cables, miscellaneous, etc. (defined later in Section 9).

6. Embodied energy of silicon purification and processing

Material (silicon) required for preparing a PV module of 1 m^2 is 0.724 kg.The energy and material requirements for module production are area dependent. Metallurgical grade silicon (MG-Si) is created by carbothermic reduction of silicon dioxide (SiO_2), 'Quartz sand'. It is a process in which coal, coke and wood chips are heated together with SiO_2. The energy required to produce 1 kg of (MG-Si) is 20 kWh, Dones and Frischknecht (1998),