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Life cycle assessment of 50 kW_p grid connected solar photovoltaic (SPV) system in India

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Abstract
Life cycle assessment (LCA) of a 50 kW solar photovoltaic (SPV) system which is situated at Bazak (Bhatinda) in Punjab state (India) has been presented. Among all the components in the SPV system, PV modules are energetically and environmentally very expensive elements. The energy pay-back time (EPBT) was found to be 1.85 years and the normalized greenhouse gas (GHG) emissions was evaluated as 55.7 g-CO_2/kWh_e. These results have also been compared with the other SPV electricity generation systems.

Keywords: Energy payback time, GHG emissions, India, Life cycle assessment, SPV.

1. Introduction
High petroleum prices and issue of global warming have created a big question mark on electricity generation through non-renewable energy sources. Environmental problems in present scenario forces to make attention on renewable energy (RE) based electricity generation system. Solar photovoltaic (SPV) system plays a significant role in electricity production for remote areas. SPV based electricity generation is considered to be free from fossil fuel usage and greenhouse gas (GHG) emissions but a considerable amount of non-renewable sources utilized during its manufacturing, installation and transportation of solar PV modules and its components.
LCA (Life cycle assessment) study is called as cradle to grave study of the system/product. It is used to calculate the energy consumption in manufacturing, installation and transportation of SPV systems. LCA studies also aims in comparing and analysis of the environmental impacts of products and services [1, 2]. The EPBT (energy pay-back time) period is used as an indicator to show the amount of energy consumed. EPBT is the time required for the system to generate the equivalent amount of energy which is consumed in the construction, operation, maintenance and decommissioning of the energy generating system. It indicates number of years required to recover the energy consumed in the installation of the plant through energy (electricity) generation by the plant. The total energy requirement of the electricity generating projects and the annual power generated are concerned with the primary energy. To convert the annual power generation (kWh_e) to primary energy, the average efficiency of the electricity generation projects in the studied country is needed. For the present study best average efficiency of electricity generation for India is considered as 0.40. Estimation of EPBT is given as:

$$EPBT\ (years) = \frac{Total\ primary\ energy\ requirement\ of\ system\ throughout\ its\ life\ cycle\ (GJ)}{Annual\ primary\ energy\ generation\ by\ the\ system\ (GJ\ /\ year)}$$

The total life-cycle GHG emissions (Mg-CO_{2eq}) were generally estimated according to the full operational life cycle of each system from the commissioning of the plant to its full operation (cradle to grave). These emissions are found to vary widely within each technology. For the estimation of GHG emissions for the present study, life time of the projects is considered to be 20 years. Estimation of GHG emissions is given as:

$$GHG\ emissions = \frac{Total\ CO_2\ emissions\ throughout\ its\ life\ cycle\ (g - CO_{2eq})}{Annual\ power\ generation\ (kWh_e\ /\ year) \times lifetime\ (year)}$$

Numerous LCA studies have been carried out for SPV systems and a wide range of results in EPBT have been found. Various studies on GHG emission estimation for SPV systems have also been carried out and also a wide range of results have been found [3-7].
SPV system design is very dependent on the geographical location of the system, since the amount of electricity generated varies with the irradiance and temperature. In this article an LCA study has been carried out for 50 kW_p SPV system which is situated at Bazak (Bhatinda) in Punjab state of India.

2. Electricity scenario in India

India is presently the sixth-largest electricity generating country and accounts for about 4% of the world's total annual electricity generation. India is also currently ranked sixth in annual electricity consumption, accounting for about 3.5% of the world's total annual electricity consumption. A summary of current electricity generation scenario in India is shown in Table 1 [8]. Table 1 also consists of their normalized GHG emissions for each electricity generation system. As it is evident from the table that fossil fuel based electricity generation systems are very harmful for the environment (Global Warming). There is an urgent need to generate electricity by some other means which are environment friendly in nature.

Table 1. Current electricity generation scenario in India [1]

S. No.	Source	Installed Capacity (MW)	Percentage (%)	GHG Emissions (g-CO_2/kWh_e)
1.	Thermal	96,044.24	63.89	922
a.	Coal	78,458.88	52.19	1004
b.	Gas	16,385.61	10.90	543
c.	Oil	1,199.75	0.8	746
2.	Hydro	36,916.76	24.56	41
3.	Nuclear	4,120.00	2.73	25
4.	Renewable Sources	13,242.41	8.82	35
Total*		1,50,323.41	100	

**Till 30/06/2009*

The Indian scientific establishment has been working on the development of various renewable energy systems. In 1981, the Government of India established the Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology (DST). In 1982, CASE was incorporated in the newly created Department of Non-conventional Sources (DNES). After a decade in 1992, DNES became the Ministry of Non-conventional Sources (MNES) [9]. Again, in 2006, MNES was renamed as Ministry of New and Renewable Energy (MNRE).
The Government policy measures have played an important role in development, deployment and commercialization of renewable energy technologies and systems. The country has total estimated renewable energy potential of about 84,000 MW. In addition, India receives sufficient solar radiation that may generate around 20 MW / km^2 by using solar photovoltaic (SPV) systems. The detailed estimated

potential of renewable energy based electricity generation and installed capacity is shown in Table 2 [10].

Table 2. Current renewable energy scenario in India [4]

S. No.	Sources	Approx. Potential (MW)	Potential Harnessed (MW)
1.	Wind Power	45219	9755.85
2.	Small Hydro (up to 25 MW)	15000	2344.67
3.	Biomass Power (Agro residues)	16881	683.30
4.	Cogeneration-bagasse	5000	1033.73
5.	Waste to Energy	2700	58.91
6.	Solar Power	-	2.12
Total		84,776	13,878.58

3. Life cycle assessment

An LCA is performed to evaluate the life-cycle energy usage and GHG emissions from electricity generation from a SPV system. A life time 20 years is considered for the SPV system. However, PV modules are expected to have longer lifetime according to the manufacturer guarantee. India does not have yet extensive life-cycle data base available for general use. Consequently, some data are available for energy as well as CO_2 emissions, much of the data used in this study were based on analyses undertaken in other countries. The life cycle of a solar PV system is considered to be comprised of three phases, namely construction, operation and decommissioning.

The complete methodology which is used here is summarized below:

1. Compilation of the material inventory for the total PV system life.
2. Compilation of the life cycle energy. It is an inventory of the energy inputs. The life cycle energy requirements should be considered initially as thermal and electrical energy separately and then converted to equivalent primary/electrical energy by using conversion efficiency.
3. Compilation of the life cycle GHG emissions which is estimated from the each component of SPV system which is studied.
4. Estimation of the electricity generation by the PV system.
5. Estimation of environmental indicators, i.e. EPBT and GHG emissions.

4. Description of system

There are growing trends in setting up grid interactive power plants worldwide. In grid interactive mode the solar power can be utilized to its full potential.

Under the demonstration of grid interactive solar photovoltaic system program, a 50kW_p capacity, grid interactive power plant had been installed at village Bajak with the help of Ministry of Non-Conventional Energy Sources (MNES) and Indian Renewable Energy Development Agency (IREDA) under World Bank Credit of line and by the State Government’s share. The project was commissioned during October 1999 and still it is operating satisfactorily. The plant has 33 panel assemblies with 21 solar panels each. The plant is installed at Bhatinda because of the fact that high insolation (of nearly equal to 220 kWh/m^2) as compared to other places in India. Other places with high insolation are parts of Rajasthan, Gujarat and Ladakh.

Civil works include pavement, building and boundary. Electro-mechanical equipment includes junction boxes, panel assembly, Alternating (AC) inverter etc. In solar PV systems the material inflow is involved mainly in the construction phase. All the manufacturing, assembly, transportation, installation and recycling of the PV modules and balance-of-system (BOS) such as invertors, charge regulators, supporting structures and accessories. All these components consume energy in their material extraction, fabrication, transportation etc. which is termed as embodied energy. LCA studies for photovoltaic shows a high variation in results. Critical issues during modeling of a life cycle inventory are: few data availability, power mixes assumed for the material production processes and process-specific emissions. Moreover, a LCA is for study for each material should be a site specific study. A life cycle energy analysis for 50 kW_p SPV installation is performed. The LCA boundary of a SPV system is shown in Figure 1. These embodied energies are expressed in the form of primary energy. The last data available is from May 2008 - April 2009. As the complete year data was not available an average monthly electricity generation has been taken based upon the previous data. Based upon this average monthly data, electricity generated for a year has been obtained. The average approximate yearly electricity generated by the system is 95,000 kWh_e.

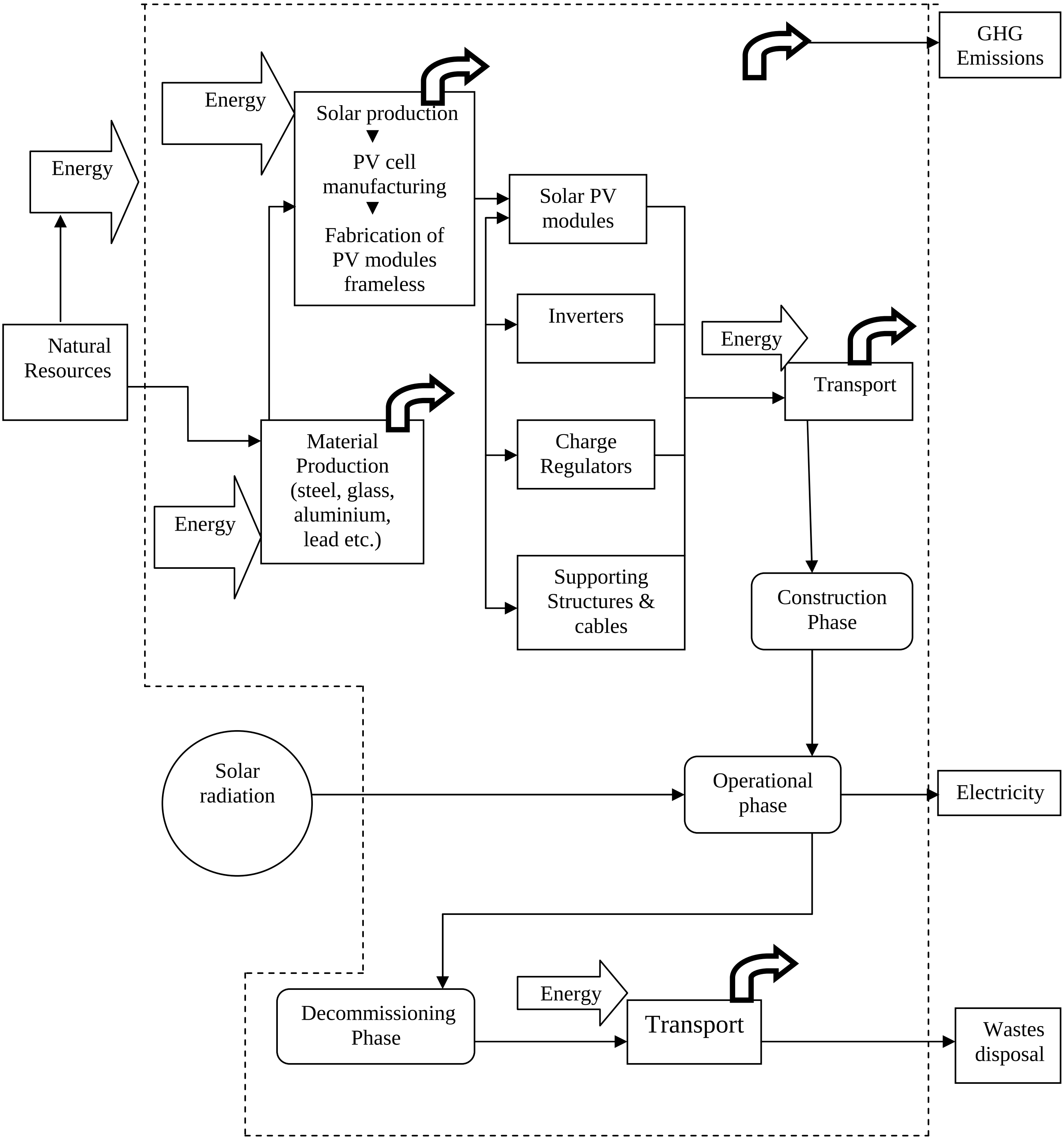

Figure 1. LCA boundary of the SPV system

4.1 Material inventory

Numerous studies have been carried out to estimate the energy consumption in the manufacturing of amorphous solar PV modules [4, 7]. Since the selected plant was established in 1999 and amorphous SPV modules based study carried out by Alsema et al. in 2000. Hence for energy consumption for amorphous SPV modules has been taken from the above mention study. The energy consumption for module is considered 17 MJ/W_p. The amorphous PV cell having an efficiency of 7% is considered. In the present study, 10% of the module weight is considered to be the weight of the frame. Frame has been made up of aluminium. There are few available data about energy requirements for change regulators and inverter manufacturing, especially for small and medium size facilities. Kato et al. [11] estimated a 0.5 MWh for energy requirements. No significant material inflow is involved during operation and decommissioning phases [2]. A list of components and materials that were used in considering the SPV system is given in Table 3.

Table 3. Technical Specifications of the PV Plant

S.No.	Component	Specification	Material	Numbers
1	Solar cell	l:10, b:10	Amorphous Silicon	24948
2	Panel	l:120, b:55, t:2	Aluminum	693
3	Main junction box	l:46, b:31, h:19	Copper, iron	1
4	Panel Assembly	l:360, b:385	Steel	33
5	Array Junction box	l:46, b:31, h:19	Copper	33
6	Inter-junction box	l:46, b:31, h:19	Copper	9
7	Foundation of PA	l:160, b:34, h:28	Steel, Bricks, Cement	66
8	Wire	l:1750	Copper, Plastics	43
9	Structural column	d: 5.73, h: 130, t: 1	Steel	132
10	Power wire	d: 0.6, l:180	Copper	66
11	Building	l:1200, b:600, h:600	Steel, Bricks, Cement	1

l=length; b=breadth; t=thickness; h=height and d=diameter; All dimensions are in cm.

4.2 Life cycle input energy

The embodied energies for different components and transportation of SPV system are shown in Table 4. To convert primary energy into its equivalent electrical energy, a best average efficiency is considered to be 40%. The value has been calculated for present PV modules is 8,50,000 MJ_{pri}. For the estimation of concrete structures, the studies of Reddy & Jagadish [12] and Shukla et al. [13] are used which has been carried out for India. The energy adopted for inverter and aluminium is based on its energy consumption presented by GEMIS [14]. The distance (by road) between Bhatinda (Punjab) and Central Electronics Limited (nearest PV module centre from Bhatinda) is approximately 420 km. The energy value for transportation is taken as 0.1 MJ/km. The maximum amount of primary energy used is consumed by PV modules which are 53.8%. The component wise distribution of primary energy of Bazak SPV plant is shown in Figure 2.

Table 4. Component wise distribution of embodied energy for SPV system

S. No	Component	Material	Embodied Energy (MJ_{pri})	Embodied Energy (kWh_{e})
1	PV module	amorphous	850000.0	94444.44
2	Frame	Aluminium	214825.0	23869.44
3	Support structure	Steel	67701.9	7522.433
4	Power wire	Copper, Iron	83006.386	9222.932
5	Inverter	Electronic	49860.0	5540
6	Concrete	-	298423.068	33158
7	Transportation	-	15820.0	1757.778
	Total		1579636.354	175515.2

4.3 Life cycle GHG emissions

GHG emissions are normally occurs during manufacturing, installation and transportation phases of solar PV modules. The GHG emissions pertaining to non-renewable and renewable electricity generating sources for India are given in Table 1. Among all the electricity generation sources, the coal has highest value of GHG emissions while nuclear based electricity generation has the maximum value. The GHG emissions for all components of Bazak solar PV system is given in Table 5. Among the renewable energy based electricity generation, wind has the highest potential and then there is a potential for small hydropower. An average value of 35 has been taken as GHG emission factor for the renewable based electricity generation sector. As wind and small hydro have the lesser (near by) value than the 35 and in the electricity generation.

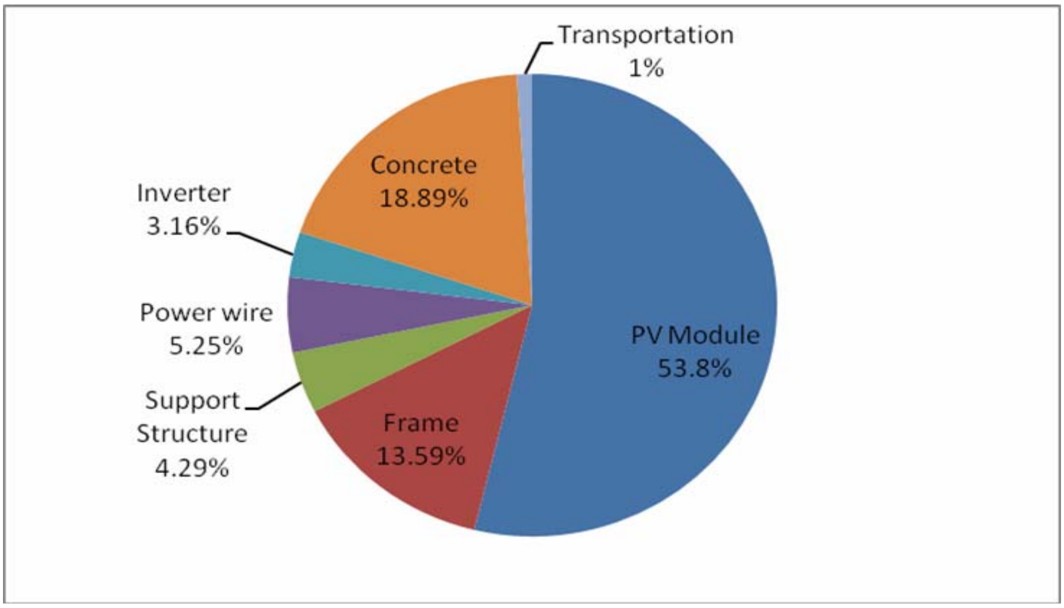

Figure 2. Component wise life cycle energy use in Bazak solar PV system

Table 5. Component wise GHG emission of Bajak solar PV system

S. No	Component	GHG Emissions ($kg\text{-}CO_2/kWh_e$)
1	PV module	56941.02
2	Frame	14391
3	Support Structure	4535.312
4	Power wire	5560.551
5	Inverter	3340.093
6	Concrete	19991.12
7	Transportation	1059.773
	Total	105818.87

5. Results

The total primary energy requirement for the Bazak solar PV electricity generation system is 15,79,636.354 MJ_{pri} (175515.2 kWh_e). The EPBT is calculated and it comes out to be 1.85 years which is very less if we compare this value with the other studies related to PV based electricity generation system. As the amorphous solar cells are very less energy intensive elements as compared to crystalline (mono or poly) but their conversion efficiency is also very less as compared to crystalline solar cells.

The total normalized GHG emission for the Bazak SPV system is 105818.87 $kg\text{-}CO_2/kWh_e$. The estimated life time for this system is considered to be 20 years. The GHG emission for one kWhel is calculated as 55.7 $g\text{-}CO_2/kWh_e$. The results obtained from this study have also been compared with the previous studies on SPV based electricity generation system as shown in Table 6.

Table 6. Comparison of energy pay-back time and GHG emission for different solar amorphous PV systems

S. No.	Year	Capacity	Life Time (Years)	EPBT	GHG Emission (g-CO_2/kWh_e)
1	1996 [3]	30 m^2	20	na	47
3	2000 [4]	na	30	2.7	50
4	2007[5]	33 kW	20	3.2	34.3
5	2008 [6]	100 MW	30	2.5	15.6
6	Present Study	50 kW_p	20	1.85	55.7

6. Conclusions

LCA study is performed for Bazak solar PV electricity generation system in Bhatinda (India). The use of solar PV modules for electricity generation is environmental friendly as compared to fossil fuel based energy generation. It was found that highest energy consumption and GHG emissions are in manufacturing of PV modules. Inverter and power wire accounts for 8.4% of the total embodied energy and GHG emissions. Also, transportation accounts for 1% of the total embodied energy and GHG emissions. The initial cost of installing this type of system is quite high and having less efficiency. Now a good amount of work has been going on in the area which leads to efficiency improvement and cost reduction in this type of systems.

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