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Research Article

A Life Cycle Assessment Model for Quantification of Environmental Footprints of a 3.6 kW$_p$ Photovoltaic System in Bangladesh

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ABSTRACT. Life cycle assessment (LCA) is an extremely useful tool to assess the environmental impacts of a solar photovoltaic system throughout its entire life. This tool can help in making sustainable decisions. A solar PV system does not have any operational emissions as it is free from fossil fuel use during its operation. However, considerable amount of energy is used to manufacture and transport the components (e.g. PV panels, batteries, charge regulator, inverter, supporting structure, etc.) of the PV system. This study aims to perform a comprehensive and independent life cycle assessment of a 3.6 kW$_p$ solar photovoltaic system in Bangladesh. The primary energy consumption, resulting greenhouse gas (GHG) emissions (CH_4, N_2O, and CO_2), and energy payback time (EPBT) were evaluated over the entire life cycle of the photovoltaic system. The batteries and the PV modules are the most GHG intensive components of the system. About 31.90% of the total energy is consumed to manufacture the poly-crystalline PV modules. The total life cycle energy use and resulting GHG emissions were found to be 76.27 MWh$_{th}$ and 0.17 kg-CO_2eq/kWh, respectively. This study suggests that 5.34 years will be required to generate the equivalent amount of energy which is consumed over the entire life of the PV system considered. A sensitivity analysis was also carried out to see the impact of various input parameters on the life cycle result. The other popular electricity generation systems such as gas generator, diesel generator, wind, and Bangladeshi grid were compared with the PV system. The result shows that electricity generation by solar PV system is much more environmentally friendly than the fossil fuel-based electricity generation. ©2019. CBIORE-IJRED. All rights reserved

Keywords: Life cycle assessment (LCA), solar photovoltaic (PV), energy payback time (EPBT), greenhouse gas (GHG) emissions, electricity generation.

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1. Introduction

With massive effect of fossil fuel use on the environment and the continuous declination of non-renewable energy sources, it has now become an excruciatingly important factor to focus on the renewable energy sources for a sustainable and safe future (Baky *et al*, 2017; Rahman *et al* 2015; Rahman *et al* 2016). Many countries have presented policy to endorse the installation of new renewable source plants in order to reach the Kyoto protocol targets, and in most of the cases greater focus has been on the solar photovoltaic cells (Rahman *et al*, 2016). In 2016, photovoltaic capacity has been increased by at least 75 GW, with a 50% growth year-on-year of new installations. The cumulative installed capacity reached at 302 GW by the end of the year 2015, sufficient to supply 1.8% of the world's total electricity consumption (Masson & Brunisholz, 2015).

Generating power from photovoltaic (PV) systems is free from fossil fuel use and does not emit greenhouse gases (GHGs) during operation. Yet a considerable amount of energy is consumed in the manufacturing and transportation of the solar panels and the balance of plant (BOS) components. In addition, a considerable amount of energy is used in the decommissioning phase of the plant.

Life cycle assessment (LCA) is an important tool used in quantification of energy use and resulting environmental footprints associated with any system or product. The four stages of LCA are goal and scope definition, inventory analysis, impact assessment, and interpretation based on ISO 14040 and ISO 14044.

Numerous LCA studies have been carried out for solar PV systems and a wide variation in the EPBT and GHG emissions is found among these studies. Kannan *et al* (2006) performed an LCA and life cycle cost analysis for a distributed 2.7 kW$_p$ solar PV system operating in Singapore which consists of 36 mono-crystalline silicon modules (12V, 75W$_p$) mounted on a building rooftop with aluminum supporting structures and concrete blocks for the base. The life cycle energy use and the energy payback time (EPBT) were estimated to be 2.2 MJ/kWh and 4.5 years, respectively. Mathur *et al* (2002) estimated the

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energy yield ratio (EYR) and cumulative energy demand (CED) for single-crystalline silicon PV module contributing peak output of 35W and having efficiency of 13%. Battisti & Corrado, (2005) in an LCA of a conventional multi-crystalline silicon PV system, which is grid-connected and retrofitted on a tilted roof in Rome, came up with the findings where EPBT and CO_2 PBT were 3.3 and 4.1 years, respectively. Tripanagnostopoulos *et al* (2005) carried out an LCA study on PV and PV/T system using SimaPro 5.1 software where they calculated EPBT and CO_2 PBT for a 3 kW_p PV system with an active surface of 30 m^2 equipped with multi-crystalline silicon PV modules. The best case is PV/T with glazing, operating at the lowest temperature (25°C) shows payback period of 0.8 years. Pacca et al,(2007) studied the LCA of KC120 multi-crystalline modules including BOS, inverter installations and transportation using the life cycle software Simapro 6.0 where findings suggested that the manufacturing of one KC120 module consumes 1000 MJ of primary energy in materials and 3020 MJ of primary energy as process energy. The lifetime CO_2 emissions were 72.4 g-CO_2/kWh for assumed US conditions whereas 54.6 g-CO_2/kWh by considering European conditions. Ito *et al*, (2008) studied a very large-scale multi-crystalline PV system of 100 MW, which would be installed at Gobi Desert. The EPBT and life cycle CO_2 emission were less than 2 years and 12 g-CO_2/kWh, respectively.

Although there are studies on life cycle assessment of solar photovoltaic systems in various countries around the globe, but the results are not applicable for Bangladesh because conducting an LCA study is location-specific. In addition, there is hardly any article found in the existing literature that worked on quantification of energy use and resulting emissions of a PV system in Bangladesh. Most of the earlier studies evaluated the cost of electricity from solar PV systems. For policy making, it is important to understand the trade off between cost and GHG emissions of the system. In this article, an LCA has been carried out for a 3.6 KW_p stand-alone solar PV system to provide electricity in St. Martin's Island, a small island in the northeastern part of the Bay of Bengal. The specific objectives are: (i) designing a 3.6 kW_p stand-alone photovoltaic system for St. Martin's Island using scientific principles, (ii) quantifying energy usage and GHG emissions for the system based on the LCA framework, and (ii) conducting sensitivity analysis to understand the influence of inputs parameters on the overall GHG emission result.

2. Method

2.1 Load calculation

A small locality in the island has been chosen to provide electricity, which comprises of almost 50 households. For each household a fixed number of electrical components are selected that includes 7 LED bulbs of 3 Watts each, 2 fans of 12 Watts each and a television set of 15 Watts. For the selected locality the entire load was 3 kW and per day requirement of electricity was calculated to be 13.5 kWh. A brief summary of the load calculation is given in Table 1.

Table 1
Electric load calculations for the selected community

Parameter	Unit	Value
Number of LED bulbs	No.	7
Wattage of each bulb	W	3
Number of Fans	No.	2
Wattage of each fan	W	12
Number of TVs	No.	1
Wattage of TV	W	15
Operating hours for lights and fans	Hrs.	5
Operating hours for TV	Hrs.	3
Load of each household	W	60
Load of each household	Wh/day	270
Load of the total community	kW	3
Load of the total community	kWh/day	13.5

2.2 Sizing of components

The photovoltaic system consists of solar panels, battery, inverter, and charge controller. These components were designed to supply 13.5 kWh/day with 3 kW_p electricity for the selected community in St. Martin's Island. The solar panel sizing was estimated using the daily peak load requirement, daily solar hours of 5 per day for Bangladesh, and a derate factor of 75% (Rahman *et al* 2016). Equation 1 shows the formula to calculate the size of solar panels.

$$\text{Panel size in kW} = \text{daily load in kWh}/(\text{solar hours per day})/\text{derate factor} \qquad (1)$$

The installed capacity of the solar panels was estimated to be 3.60 kW_p. In this study, Suntech 280 W_p (24 V) poly-crystalline PV modules were used for the system. While the weight of each panel is 25.8 kg, the length and width are 1955 mm and 982 mm, respectively (Rahman *et al*, 2016). The system considered in this study does not use sun tracking. However, best possible alignment (23° tilt angle for Bangladesh) was assumed.

To regulate the charge between the panels and the batteries, two charge controllers are connected to the PV panels. Maximum charge current is 60 A and the battery voltage operating range is from 0 V to 80 V. Each charge controller weights about 4.8 kg. Battery is an important component of the stand-alone photovoltaic system as it supplies electricity at night when there is no sun light. In this study, lead acid battery is considered. Equation 2 shows the formula for calculating the total size of the battery banks for the 3.6 kW_p PV system.

$$\text{Capacity of battery bank in Ah} = L*A/(D*V*\eta) \qquad (2)$$

where daily load, L, is in Wh/day, autonomy, A, is in days, depth-of-discharge, D is in %, the nominal voltage of battery, V is in volts.

The depth-of-discharge and the efficiency of charging were assumed to be 80% (Verma *et al,* 2015) and 85% (Rahman *et al.*, 2016), respectively. The number of days of autonomy has been considered 2 days. The total capacity of the batteries was calculated 5294.12 Ah. Each battery has a capacity of 130 Ah (1.56 kWh). A total of 42 batteries were required for the system. An inverter converts the DC power to AC power. It is always better to have inverter wattage about 20-25% more than that of appliances connected. Power factors of inverter vary from 0.85 to 0.99. An average of 0.92 has been considered. The inverter size has been selected to be 3.26 kW.

2.3 Life cycle assessment

The first stage in life cycle assessment is the goal and scope definition. The goal of this study is to quantify the energy consumption and resulting GHG emissions from manufacturing and transportation of various components of the PV system. The decommissioning phase is not included within the system boundary of the analysis. The primary service of the system is delivering electricity and that is why the functional unit of the study is chosen as 1 kWh of AC electricity. Figure 1 shows the system boundary of this study.

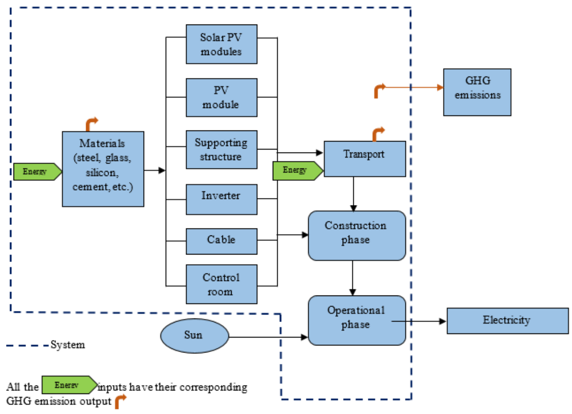

Fig. 1 System boundary considered in this study

2.3.1 Construction phase

2.3.1.1 Solar PV modules

Several studies have been carried out to estimate the energy consumption in the manufacturing of polycrystalline solar PV modules. The variations in results have occurred due to technological assumptions and different system boundaries. In this study, three different cases have been outlined for the solar cell production technology. The worst case scenario represents present-day production technology, the base case scenario describes the technology which will most probably be commercially available within 10 years and the best case represents an optimistic view on production technology available within the next 10-15 years (Phylipsen & Alsema, 1995). In Table 2, total energy requirement for the PV module excluding and including the aluminum frame has been shown for three different cases. While Phylipsen and Alsema estimated 970 kWh_{th}/m^2 energy requirement PV panel excluding aluminum frame (see Table 2), according Sharma & Tiwari, (2013) the energy requirement is 980 kWh_{th}/m^2. In this study, the average of these two values was used for the calculations.

2.3.1.2 BOS components

The availability of data about the manufacturing energy requirements for charge controllers and inverters for small facilities is very limited. Both for the inverter and the charge regulator, we have assumed 0.277 MWh_{th}/kW energy is required in the manufacturing phase (Rydh & Sandén, 2005a, 2005b).

Table 2
Energy required (kWh_{th}/m^2) in solar panel manufacturing

Parameter	Worst case	Base case	Best case	Ref
Total Energy Requirement excluding Al Frame	970	400	180	(Phylipsen & Alsema, 1995)
Energy Requirement for Al Frame	175	120	80	(Phylipsen & Alsema, 1995)
Total Energy Requirement including Al Frame	1145	520	260	(Phylipsen & Alsema, 1995)
Total Energy Requirement excluding Al Frame		980		(Sharma & Tiwari, 2013)

The life time of components has a huge impact on the LCA results. The life time for inverter and charge regulator was taken as 10 years (Rydh & Sandén, 2005b). For this study, the batteries were considered lead acid batteries since in developing countries like Bangladesh, lead acid batteries are used at a large scale. Recycling network of lead acid batteries are quite widespread in Europe and Asia, especially in developing countries. According to (García-Valverde et al., 2009), around 50% of the battery materials come from recycled materials and for a realistic hypothesis we have considered so. The lead acid batteries that we considered have a lifetime of 10 years. The energy required to manufacture new and recycled materials were assumed to be 331 and 242 kWh_{th}/kWh battery output (García-Valverde et al., 2009).

2.3.1.3 Supporting structure, concrete, and cables

The PV modules were installed over a galvanized steel structure that supports the entire system. The amount of steel required for the supporting structure was assumed as 133.81 kg/W_p and the specific energy consumption for steel was considered to be 9.72 kWh_{th}/kg of steel (García-Valverde et al., 2009). Concrete was used to create the base structures. The specific concrete requirement and specific energy consumption for concrete were assumed to be 62.96 kg/kW_p (Kannan et al., 2006) and 1.63 kWh_{th}/kg of concrete (" Wang M. GREET 2; 2013. Argonne National Laboratory: Argonne (IL),"), respectively. It was considered that the necessary wirings were done using copper cables which weighted around 37.71 kg for the entire module. With reference to (Hammond & Jones, 2008), if the cables were considered to be made from new materials the specific energy consumption was presumed 19.44 kWh_{th}/kg.

2.3.2 Transportation

The Solar PV modules are imported from Germany to Bangladesh through sea ways by Handy Size ships of 10000 DWT (Rahman *et al.*, 2015). The distance from Bonn Port, Germany to Chalna Port, Bangladesh is 9158 miles. The average speed of the ship is 20 miles/hour and the fuel is residual oil (" Wang M. GREET 1; 2013. Argonne National Laboratory: Argonne (IL),"). The origin to destination load factor was taken as 0.83 as obtained from GREET 2013. The lower heating value (LHV) of residual oil is 140352 Btu/gallon and density is 3752 gm/gallon (" Wang M. GREET 1; 2013. Argonne National

Laboratory: Argonne (IL),"). The mass share for solar PV is 0.004% of the ship which gives the same amount of energy intensity share for solar PV. The transportation distance for the BOS components, cables and supporting structures was assumed to be 50 miles using an ACE Ex-truck. The ACE Ex- truck has a gross vehicle weight of 1.71 tons and a fuel economy 42.27 miles/gallon. The energy intensity is considered 1778.07 Btu/ton-mile (" Wang M. GREET 1; 2013. Argonne National Laboratory: Argonne (IL),").

2.3.3 Operational and decommissioning phase

There is no external source of energy supply required for PV modules and BOS components in the operational phase. The necessary control systems that are installed draw energy from the module itself. The facility has no mobile parts and all the components apart from the batteries require very less maintenance, therefore required energy for maintenance may be ignored.

At the end of the life cycle, the entire solar PV system produces a certain amount of waste. According to Müller *et al*, (2005), the PV modules if recycled could save two third of the necessary energy for wafer production. However, the possibility of recycling of PV modules in Bangladesh is very less due to technological deficiencies. Therefore, it was presumed that the solar PV modules would be land filled. Due to lack of data in the public domain, energy required in the decommissioning phase is not considered in the analysis.

3. Results and discussion

3.1 Electricity production

According to the Atmospheric Science Data Center's website of NASA, the daily average solar insolation for the selected location is 4.80 kWh/m^2/day. For supplying 3.60 kW$_p$, 13 PV modules of 280 W$_p$ each are required according to equation 1. The total area covered by these panels are 1.92 m^2. With an efficiency of 13% (Graebig *et al*, 2010) for polycrystalline modules and 90% (Islam *et al* 2012) inverter efficiency, the total electricity generation from solar energy for a 20 years of project life time was estimated to be 100.03 MWh. It is important to mention that we have assumed 0.5% reduction in electricity generation each year starting from year 2 of the project (Desideri *et al*, 2012). Figure 2 shows the amount of electricity generation each year.

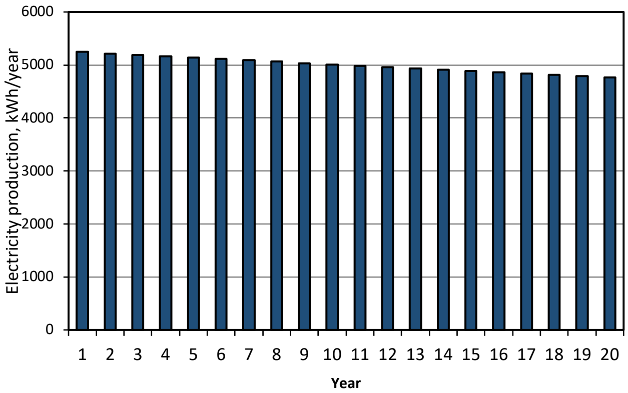

Fig. 2 Life time electricity generation from the PV plant

3.2 Energy requirements

With specific energy requirements of 975 kWh$_{th}$/m^2 and 175 kWh$_{th}$/m^2 for PV modules and aluminium frame, respectively, the total energy requirement for production of PV panels was calculated to be 28.69 MWh$_{th}$. The batteries are the most energy intensive component of the system due to large quantity of material use. The total energy consumption in battery production is 37.54 MWh$_{th}$. 1.81 MWh$_{th}$ and 1.99 MWh$_{th}$ energy are required for the inverters and charge controllers. The amounts of copper for cables, steel for supporting structure, and concrete for the base were estimated to be 37.71 kg, 481.71 kg, and 226.67 kg, respectively. The energy consumption for each component of the system is represented by figure 3. The total energy requirements for these materials were calculated from the mass and specific energy requirements of each material mentioned in section 2.3.1.3. The thermal energy was converted to electrical energy with a thermo electric conversion efficiency of 35% (García-Valverde *et al*. 2009). The energy payback time for the system was found to be 5.34 years which means, 5.34 years will be required to recover the amount of energy that is used to produce the components of the system.

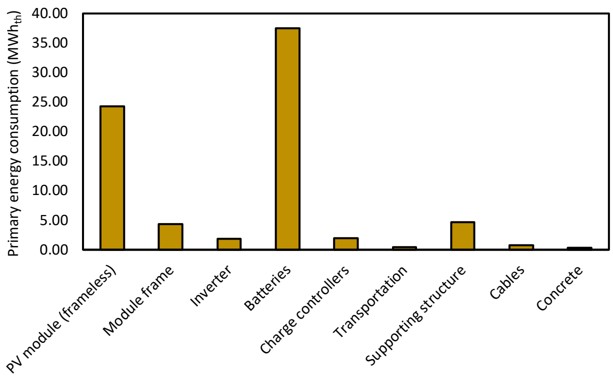

Fig. 3 Component wise energy consumption

The total energy requirement for the system is 76.27 MWh$_{th}$. The batteries and the PV modules are the most energy intensive components with 49.23% and 31.90% of the total energy consumption, respectively. The contributions of supporting structure and aluminium frame are 6.14% and 5.73%, respectively. Figure 4 shows the contribution of each component to the total energy requirements.

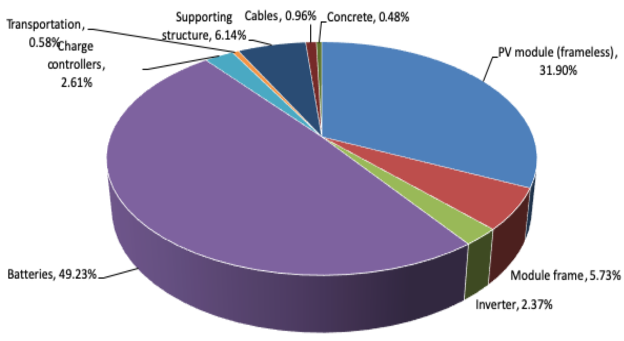

Fig. 4 Percentage contribution of each component to the total energy requirements

3.3 Impact assessment

The solar PV modules that may seem to be totally clean having no environmental impacts, but this system also has GHG emissions which basically results from the manufacturing, transportation and installation of solar PV modules, BOS components, supporting structures, cables in the construction phase. During operational phase since there is no inflow of material and energy into the system, no such GHG emission is observed. The emissions were calculated from the energy requirements or the total mass of various components and the related emission factors. Table 3 shows the emissions factors for various components of the system. The emissions of CO_2, CH_4, and N_2O are converted to CO_2 equivalents. It was assumed that the PV panels were manufactured in Germany. With an emission factor of 675 g-CO_2eq/kWh (or 236.25 g-CO_2eq/kWh$_{th}$) for the German grid, the emissions from manufacturing the panels and the aluminium frames were calculated as 67.78 g-CO_2eq/kWh. The batteries, inverters, and charge controllers were assumed to be manufactured in Bangladesh. With an emission factor of 637.87 g-CO_2eq/kWh (or 223.25 g-CO_2eq/kWh$_{th}$), the emissions for batteries, charge controllers, and inverters were found to be 83.79, 4.45, and 4.03 g-CO_2eq/kWh, respectively. The transportation of components using ocean tanker and local trucks emits 1.46 g-CO_2eq/kWh. Considering all the aspects of the system, the total well-to-wheel life cycle GHG emissions were estimated to be 173.42 g-CO_2eq/kWh.

Table 3
Emission factors for various components of the system

Element	Emission factor
Al frame	834.56 kg-CO_2eq/ton
PV modules	0.236 kg-CO_2eq/kWh$_{th}$
Charge controllers	0.223 kg-CO_2eq/kWh$_{th}$
Inverter	0.223 kg-CO_2eq/kWh$_{th}$
Lead-acid batteries	0.223 kg-CO_2eq/kWh$_{th}$
Supporting structure	3115.47 kg-CO_2eq/ton
Cables	396.85 kg-CO_2eq/ton
Concrete	367.52 kg-CO_2eq/ton

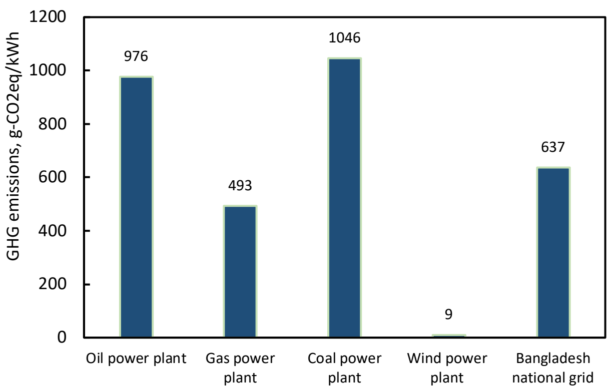

Fig. 5 Comparison of GHG emissions from various power plants (Rahman et al 2017)

We have compared GHG emissions from stand-alone PV system with the environmental footprints of other renewable and fossil fuel-based electricity generation systems. Figure 5 depicts the comparison of GHG emissions from various electricity generation systems. The GHG emissions from wind power plant is the minimum due to low material requirements and higher efficiency and life time than the efficiency and life time of solar PV plants. On the other hand, coal power plants emit the maximum GHG emissions (1046 g-CO_2eq/kWh) due to combustion of coal which is a dirty fuel. The GHG emissions from oil and gas power plants are 976 and 493 g-CO_2eq/kWh, respectively.

3.4 Sensitivity analysis

A sensitivity analysis was carried out to see the impact of various inputs on the total GHG emission result. The input parameters, days of autonomy, depth of discharge of battery, solar radiation, and module efficiency were varied from -20% to +20% of the base case value. The base case values for days of autonomy, depth of discharge of battery, solar radiation, module efficiency, and daily load are 2 days, 50%, 4.80 kWh/m^2/day, 13%, and 13.5 kWh/day, respectively. The sensitivity analysis shows that if the days of autonomy is increased, the GHG emissions are also increased due to the increase in battery requirement for the system. On the other hand, increasing the depth of discharge, solar radiation, and module efficiency will lower the GHG emissions. If the solar radiation is increased by 20% from the base value, the GHG emissions will be reduced to 144.51 g-CO_2eq/kWh. An increase in depth of discharge by 20% will result in about 8% overall GHG emission reduction. The daily load requirement has negligible impact on the overall GHG emissions.

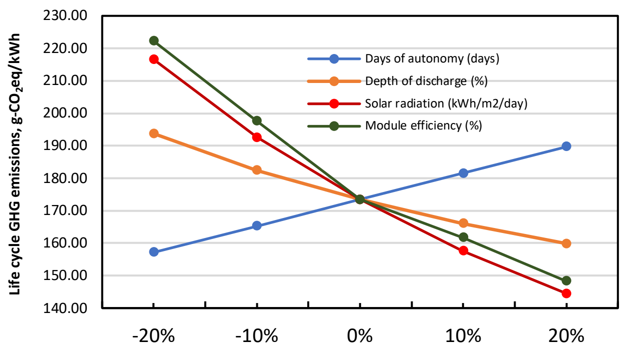

Fig. 6 Sensitivity analysis for the total GHG emissions

4. Conclusion

A life cycle analysis of a stand-alone polycrystalline solar PV system located in Saint Martin's Island, Bangladesh has been performed evaluating the greenhouse gas emissions and energy payback time. Improving the technological aspects of the modules achieving better solar irradiation can help reduce the existing primary energy consumption with a higher electricity generation and a limited cost. The energy payback time came out to be 5.34 years and the total GHG emissions from the system were calculated to be 173.42 g-CO_2eq/kWh. To conclude, it is obvious the PV technology offers a significant amount of energy savings and GHG emission mitigation despite of the fact that the energy payback time is still relatively high; but with the advancement of technology, this kind of systems will prove to be an irreplaceable source of energy in remote locations in the upcoming future.

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