Development of a Model for Techno-economic Assessment of a Stand-alone Off-grid Solar Photovoltaic System in Bangladesh

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Abstract- Electricity production by solar energy can reduce the emission of greenhouse gases (GHGs) which is a big environmental concern around the globe especially in the countries like Bangladesh. Bangladesh is a small country in South Asia with a huge population. The country has many isolated areas that are not connected to the national grid. People living in those off-grid areas mainly use diesel generators that emit GHGs into the atmosphere contributing to global warming. Electricity production using solar energy can be an attractive alternative from economic and environmental perspective. The present study attempts to conduct a techno-economic assessment by developing a bottom-up data-intensive spread-sheet-based model. The model estimates the unit cost of electricity generated by a 3.40 kW_p stand-alone solar photovoltaic system (PV) for an isolated locality in Char Godagari, Rajshahi. The island has geographical coordinates of 24°28'6"N and 88°19'25"E and is situated in Rajshahi district. The unit cost of electricity by solar energy was found to be $0.72/kWh or 55.47 Bangladeshi Taka (BDT)/kWh with a net present cost of $12,027.83 or BDT 926,142.55 for the selected location, Char Godagari. The results show that battery is the most expensive component of the solar PV system. A sensitivity analysis was also conducted to see the impact of various input parameters on the unit cost of electricity.

Keywords Solar photovoltaic, renewable energy, techno-economic, electricity generation, cost of electricity.

1. Introduction

Bangladesh is a small country in South Asia with a huge population of almost 160 million [1]. The demand of electricity is increasing with the increase in population and development of the industrial sector. For the socio-economic development of a country, supply of electricity is a prerequisite. In Bangladesh, only about 60% [2] of the population is getting electricity from the national grid. In addition to that, 9% of the population is getting solar electricity from 3.6 million solar home systems (SHS) around the country [3]. Electricity generation per capita in Bangladesh is only 371 kWh [4]. Shortage of electricity is a barrier against the sustainable development of the country. Bangladesh has many off-grid areas where people are using mainly diesel generators for a certain period of time. However, some areas are under electrification using solar home systems. To increase the living standard of the people residing in the isolated areas, supply of electricity is essential. But sometimes extending the national grid to the isolated areas is not cost-effective. Using renewable energy (e.g. solar energy) to produce electricity for the remote locations could be an attractive alternative.

The total electricity generation capacity of Bangladesh was 11,877 MW as of October 2015 [4]. About 63% of the electricity is produced by burning natural gas [5]. Natural gas is the main source of energy supply for the electricity and industrial sectors. The country is facing a severe gas crisis; the daily shortage of natural gas is more than 500 MMCF (million cubic feet). The second main source of electricity production is liquid fuels such as HFO (heavy fuel oil) and diesel. Fossil fuel-based electricity generation emits greenhouse gases which is a big environmental concern. Renewable energy especially solar energy can offer convenient solution to these problems. Bangladesh government has a plan to generate 10% of the total electricity by renewable resources by 2020 [6]. Among the renewable energy sources, solar energy has an excellent potential with daily solar radiation of 4.67 kWh/m^2 [7]. The government has already launched "500 MW Solar Power Mission" to promote the use of renewable energy to meet the increasing demand of electricity. Electricity generation by solar energy is comparatively expensive than conventional means of electricity generation. Designing a cost-effective solar photovoltaic system which can meet the electricity demand for a particular location is a challenge.

There have been a few studies that conduct the techno-economic assessments to generate electricity from renewables for remotely located areas. Most of the studies worked on the feasibility of hybrid renewable energy systems. A hybrid renewable energy system was designed for a remote community in the Southern region of Ghana whose daily load requirement was 2000 kWh per day [8]. The hybrid system consists of a PV array of 80 kW, a 100 kW wind turbine, and two generators with combined capacity of 100 kW, a 60 kW converter/inverter and a 60 Surrette 4KS25P battery. The cost of electricity was found to be $0.281/kWh [8]. Similarly Rehman and Al-Hadhrami [9] designed a hybrid system of PV/diesel/battery to produce 48.33 MWh of electricity per day at a cost of $0.219/kWh for a village in Saudi Arabia. Rohani and Nour [10] conducted an assessment to compare a hybrid renewable energy system with a conventional diesel generator system. The authors concluded that a stand-alone hybrid system is an expensive electrification system but can reduce greenhouse gas emissions substantially. The techno-economic feasibility of stand-alone renewable energy systems was analyzed by Dalton et al. [11] for a hotel in the coastal area of Queensland, Australia. Wind energy conversion systems, rather than photovoltaics, are the most economically viable renewable energy systems for large-scale operations for the selected location [11]. Kusakana and Vermaak [12] studied the feasibility of stand-alone PV and stand-alone wind systems in the rural regions of the Democratic Republic of Congo. The authors found that a stand-alone PV and a stand-alone wind system can satisfy the load demad for the location at the cost of $0.39/kWh and $0.54/kWh, respectively. Sen and Bhattacharyya [13] did an assessment of hybrid renewable power sources for an off-grid remote village in India. The authors found that combination of photovoltaic-hydro turbine-biodiesel generator is the most cost-effective. Ghasemi et al. [14] analyzed the techno-economic feasibility of stand-alone hybrid PV–diesel energy systems for electrification of remote rural areas in eastern part of Iran. The authors showed that stand-alone hybrid PV-diesel energy systems are more environmentally friendly compared to the diesel generator systems. Research works showed that adding renewable energy resources to the conventional diesel generator system could make a hybrid system more cost-effective and environmentally friendly [15]. To find the cost-effective system for electricity generation from renewable sources, various studies were conducted around the world [16-18]. Chandel et al. [19] conducted a techno-economic assessment of solar power plant in India and the cost of electricity was found to be $0.24/kWh. Rahman et al. [20] considered seven different renewable energy fraction scenarios and designed hybrid energy systems that are capable of producing electricity for a Canadian off-grid community.

There are some studies that conduct assessments of renewable energy systems for applications in Bangladesh. Mondal and Islam [21] studied the viability of grid-connected solar PV system in Bangladesh. The authors found the average cost of electricity as $0.19/kWh at any location of country. The cost of electricity reported by the authors is comparatively lower for PV systems due to the reason that the system does not use batteries to store the energy. Using batteries leads to increase the overall system cost. A PV–diesel generator–battery system was proposed for the decentralized and remote areas by Mondal and Denich [22]. The hybrid system fulfills the requirement of 50 kWh/day primary load with 11 kW peak load for 50 households at a cost of $0.33/kWh. A 19.4 MW hybrid system was designed by Zubair et al. [23] for a coastal region of Bangladesh. A PV-wind-diesel generator system was found to be the most cost-effective. In another study, a PV-wind-diesel generator system was designed to produce electricity for the Saint Martin’s island, Bangladesh at a cost of $0.345/kWh [24]. Salehin et al. [25] conducted a feasibility study of a hybrid renewable energy system for applications in Northern part of Bangladesh.

There is scarcity of research on the assessment of solar PV systems for electricity generation in Bangladesh and specifically in the remote areas. These assessments are very limited in terms of associated costs of electricity generation from small-scale solar PV system. There are some studies that conduct techno-economic assessment of hybrid energy systems but study of stand-alone PV system is very limited. Earlier studies did not consider all the components of the PV systems. Moreover, designing a solar PV system and conducting its techno-economic assessment is location-specific. The objective of this paper is to design a solar PV system and develop a spread-sheet-based bottom-up data-intensive techno-economic model to calculate the cost of electricity generation using solar energy for an off-grid community consisting 50 households in Char Godagari, Rajshahi. A sensitivity analysis was conducted to see the impact of input parameters on the unit cost of electricity.

2. Methodology

2.1. Goal and Scope

The objective of this research is to design a stand-alone photovoltaic system that can meet the electricity demand for an off-grid community of 50 households in the island of Char Godagari in Rajshahi district. The cost of electricity was also calculated for the location by developing a user-friendly data-intensive model. The model was developed using the fundamental engineering principles. The functional unit used in this study is $/kWh of AC electrical energy. Fig. 1

represents the methodology developed for calculating the cost of electricity from solar energy.

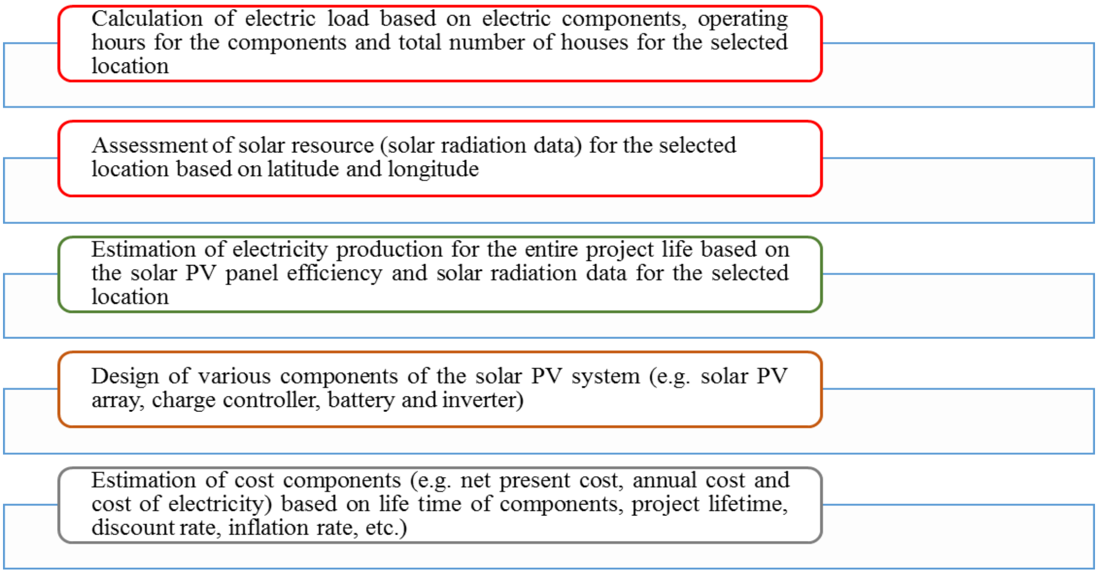


Fig. 1. Techno-economic modelling methodology for this study.

The main components of the solar PV system are solar PV panel, charge controller, battery and inverter. The system boundary is presented in Fig. 2 and shows the scope of the research in terms of the cost calculated for all the components involved.

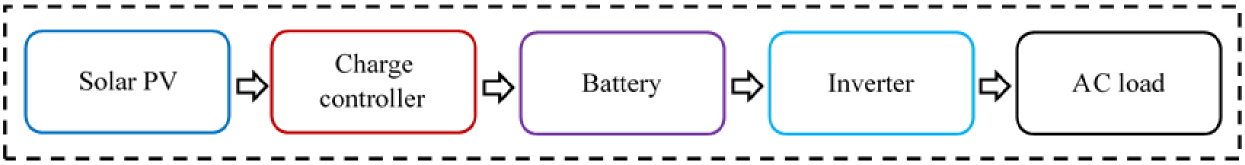


Fig. 2. System boundary considered for this research.

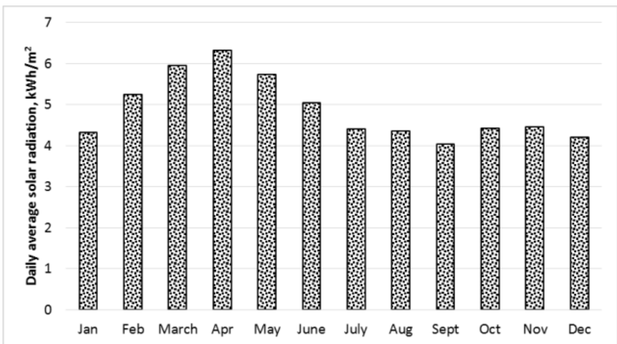
The steel supporting structure, copper cable, installation of components, civil construction and maintenance were also considered within the system boundary of the present study.

2.2. Electric Load Calculation

Char Godagari (24°28'6"N and 88°19'25"E) is an island situated in Rajshahi district, Bangladesh under the Godagari upazila. In this study, a hypothetical model community of 50 households was considered. A typical household in rural areas is simple and hence requires small quantities of electrical energy for lighting and other electrical appliances [21]. A household usually uses few LED bulbs for lighting, one or two fans for cooling and a television for entertainment purpose. The load calculation was based on 7 LED bulbs of 3 W each, 1 ceiling fan of 24 W and a LED television (TV) of 15 W for each household. The daily operating hours for lighting and television were considered as 5 and 2, respectively irrespective of any season. On the other hand, fans are used in summer only at night for 5 hours daily. Two individual load profiles were created for summer (April–October) and winter (November–March) seasons. The peak energy requirement during the summer season is 12.75 kWh/day with a 3 kW peak load, on the other hand the energy requirement during the winter season is 6.75 kWh/day. The yearly electrical load for the community was calculated to be 3.51 MWh.

2.3. Assessment of Solar Resource and Electricity Production

No measured solar insolation data were available for the selected location. The solar insolation data for Char Godagari were obtained from NASA website [26] based on the latitude and longitude of the location. For accuracy, average data for 22 years were used. Fig. 3 represents the



monthly averaged solar radiation data for the location under study. The average daily solar radiation was calculated to be 4.88 kWh/m^2.

Fig 3. Monthly daily averaged solar radiation for Char Godagari [26].

The useful life of the PV system was taken as 20 years [27]. As the functional unit of this study is 1 kWh of electricity, it was necessary to estimate the amount of electricity the system can generate in its entire lifetime. The system will not be able to generate the same amount of electricity each year. Due to this reason, an annual performance reduction of 0.5% was considered [28]. The amount of electricity generated per day was calculated using the average solar irradiation (kWh/m^2/day), poly-crystalline PV panel efficiency of 13% [29], the total area covered by the solar panels (m^2) and inverter efficiency of 95%. The total AC electricity was estimated to be 100.15 MWh for 20 years lifetime. Fig. 4 represents the electricity production over 20 years lifetime of the PV system.

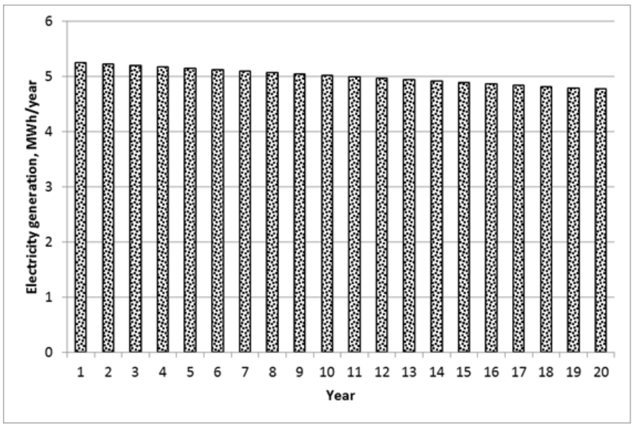


Fig 4. Estimated energy production during the life cycle of the PV system.

2.4. Design of the Solar Photovoltaic (PV) System

The main components of the PV system are photovoltaic panel, charge controller, battery and inverter. All the components were designed to satisfy the load requirement of 3.51 MWh/year for the selected location. PV panel sizing was done using the daily peak load requirement during summer season to avoid any shortage of electricity, daily solar hours of 5 per day [30] for Bangladesh and an assumed derate factor of 75% [31]. Eq. (1) [31] was used to estimate the PV panel sizing.

Array size (kW) = (Daily kWh usage in summer)/(solar hours/day)/0.75 (1)

The power rating for the PV array was calculated to be 3.40 kW$_p$ with the help of Eq. (1). Suntech 290 W$_p$ poly-crystalline PV modules were selected for the PV system. Characteristics of the PV module are presented in Table 1. The 3.40 kW$_p$ solar PV system consists of 12 poly-crystalline silicon modules (24 V, 290 W$_p$ each). The assembly of PV modules is shown in Fig. 5. The PV modules are mounted on the ground with steel supporting structures. No sun tracking was considered for this study, but the best possible alignment of the panel was assumed (23° tilt angle for Bangladesh). A total 23.28 m^2 area is covered by the PV modules. The assembly of PV modules is connected to a charge controller which regulates the charge of a bank of batteries from the PV panels. Two charge controllers are required for the system. Each charge controller is connected with six PV modules offering a nominal voltage of 48 V (see Fig. 5). The technical specifications of the charge controllers are presented in Table 1. Batteries are required to store the energy and supply at night when there is no solar radiation is available. For cost-effective design of a system, appropriate sizing of battery is important. Battery capacity required for the system was calculated using Eq. (2) [32], where the peak electric load, D, is in Wh/day, days of autonomy, E, is in days, depth of discharge, DOD is in %, efficiency of charging, η_c is in % and the nominal voltage of each battery, V is in volts.

$$\text{Battery capacity (Ah)} = D\times E/(DOD\times \eta_c \times V) \quad (2)$$

For this study, DOD and η_c were assumed as 80% [33] and 85% [32], respectively. To store the electricity required to satisfy the load demand, 24 batteries (130 Ah, 12 V each) are required. 130 Ah, 12 V batteries were chosen as these batteries are available and largely used in PV systems in Bangladesh. The system was designed for 2 days of autonomy. Six battery strings will be required for the PV system. Each battery string will have 4 lead-acid batteries connected in series offering 48 V of nominal voltage. Fig. 5 shows the circuit diagram of the stand-alone PV system. Solar PV modules produce DC electricity which is stored in the batteries. An inverter is required to convert the DC electricity of 48 V to AC electricity of 220 V which can be used in the appliances. The peak load for the location was calculated to be 3 kW. The inverter should be designed 25-30% bigger for safety. Considering 30% safety factor, the inverter was designed to be 3.9 kW. In this study, an inverter of 4 kW was considered for its availability in the market. The technical specifications of the inverter are presented in Table 1. The inverter is connected to the AC load.

2.5. Techno-economic Assessment

After designing the components of the PV system, a techno-economic assessment was conducted to find the cost of electricity for the community under study. The base year for the cost calculation were considered 2015 unless otherwise mentioned. The key assumptions and input parameters of the model are shown in Table 2. The effect of the key assumptions and input parameters used for the model was investigated with the help of a sensitivity analysis. The interest rate and inflation rate were assumed to be 10% [23] and 7.3% [34], respectively. The conversion rate was used as 1 USD to 77 Bangladeshi Taka (BDT). All the capital costs were amortized over the lifetime of the components of the PV system. The testing and installation cost, and the yearly maintenance cost (including the cost of lease for the land on which the system is mounted) were assumed to be 3.75% and 2.00% of the total capital cost, respectively based on personal communication with an expert of Infrastructure Development Company Limited (IDCOL) [30].

Table 1. Technical specifications of the components of the PV system

PV module	**Suntech**	**Battery**	**BD-Tech**
Nominal power (W_p)	290	Type	Open Lead-acid
Operating Temperature (°C)	-40 to +85	Nominal voltage (V)	12
Short circuit current (A)	8.65	Capacity (Ah)	130
Maximum System Voltage (VDC)	1000	Depth of discharge (%)	80
Optimum Operating Current (A)	8.20	Charging efficiency (%)	85
Weight (kg)	25.8	**Inverter**	**Tripp-Lite**
Length (mm)	1956	Frequency Compatibility (Hz)	50/60
Width (mm)	992	Output (W)	4000
Charge controller	**Schneider Electric**	Output Nominal Voltage (V)	220/230/240
Nominal battery voltage (V)	12, 24, 36, 48, 60	DC System Voltage (VDC)	48
Max. charge current (A)	60	Efficiency (%)	95
Battery voltage operating range (V)	0-80		
Weight (kg)	4.8		

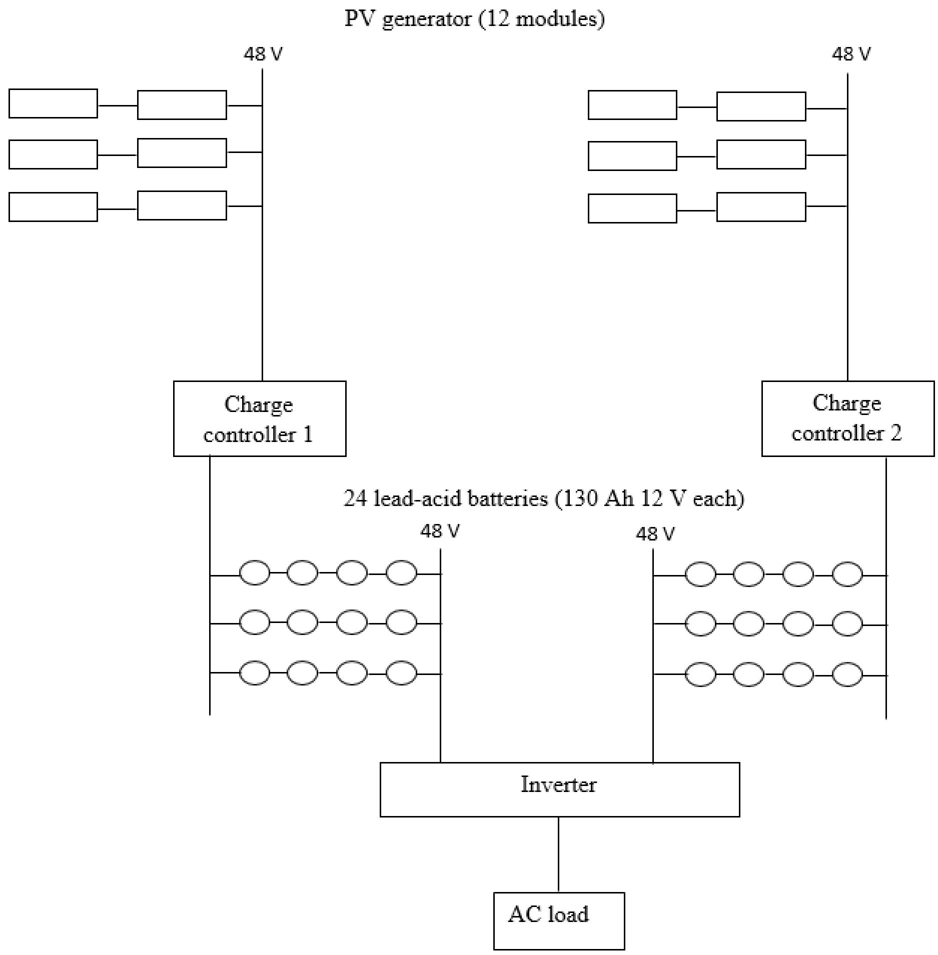


Fig. 5. Circuit diagram of the stand-alone PV system.

Table 2. Key assumptions and input parameters for the techno-economic modelling [all costs are in 2015 USD]

Parameter	Unit	Value	Source/comment
Interest rate	%	10	[23]
Inflation rate	%	7.3	Based on the annual average inflation rate for the year of 2014 found in Bangladesh Bank website [34]
Solar panel			
Lifetime	years	20	[27]
Capital cost	$\$/W_p$	1.27	The cost number was inflated for the base year of 2015 [35]
Battery			
Charging efficiency	%	85	[32]
Depth of discharge	%	80	[33]
Capital cost (130 Ah 12 V each)	$	155.84[a]	[36]
Lifetime	years	2	Based on personal communication with an expert from IDCOL [30]
Charge controller			
Capital cost	$	1370.00	Two charge controllers are required. Cost of each controller is $685 [37]
Lifetime	years	5	Based on personal communication with an expert from IDCOL [30]
Inverter			
Capital cost	$/kW	258.23	The cost number was inflated for the base year of 2015 [21]
Lifetime	years	10	Based on personal communication with an expert from IDCOL [30]
Supporting structure (steel)			
Material requirement[b]	MT	0.45	
Capital cost	$/MT	740.26[a]	[38]
Lifetime	years	20	
Copper cable			
Capital cost[c]	$\$/kW_p$	50.24[a]	Based on personal communication with an expert from IDCOL [30]
Lifetime	years	20	
Testing and installation cost	%	3.75	Testing and installation cost was assumed to be 3.75% of the total capital cost [30]
Yearly maintenance cost (including the cost of lease of land)	%	2.00	Maintenance cost was assumed to be 2.00% of the total capital cost [30]
Civil works			
Capital cost	$	636.36	A room of 7 ft*7 ft was considered to keep the batteries, charge controlllers and inverter based on personal communication with an expert from IDCOL [30].
Lifetime	years	20	

[a] A factor 0.013 was used to convert BDT to USD.
[b] Calculated from the numbers (562 kg steel for 4.2 kW_p system) reported by Valverde et al. [27].
[c] Calculated from the numbers ($854.03 for 17 kW_p system) suggested by the IDCOL expert [30].
MT– Metric ton

The unit cost of electricity (COE) was calculated using Eq. (3), where annualized cost of the system (after amortization), A is in $/year and annual average electricity production, E, is in kWh/year.

Cost of electricity, COE ($/kWh) = A/E (3)

3. Results and Discussion

3.1. Economics of the Solar PV System

The techno-economic model provides the capital cost distribution of the solar photovoltaic system and the unit cost of electricity for the selected community in Char Godagari. All cost numbers were calculated in 2015 USD. The total load for the community was found to be 3.51 MWh/year. To satisfy the load demand, total capacity for solar panel was calculated to be 3.40 kW_p. Considering $\$1.27/W_p$ for solar panel, capital cost for solar panel was calculated as $4305.97. There is no data available in the public domain for testing and installation, and maintenance cost. With an expert's opinion, 3.75% and 2.00% of the capital cost were assumed to be testing and installation cost, and yearly maintenance cost, respectively batteries, charge controllers, inverter, supporting structure, copper cable, testing and installation and civil works were estimated to be $3740.26, $1370.00, $1032.90, $336.78, 170.81, 434.74 and $636.36, respectively. The model [30]. Fig. 6 shows the capital cost distribution of the various system components. The capital costs of lead-acid

determines the total capital cost of the system to be $12,027.83 or 926,142.55 BDT (conversion factor 1 USD = 77 BDT).

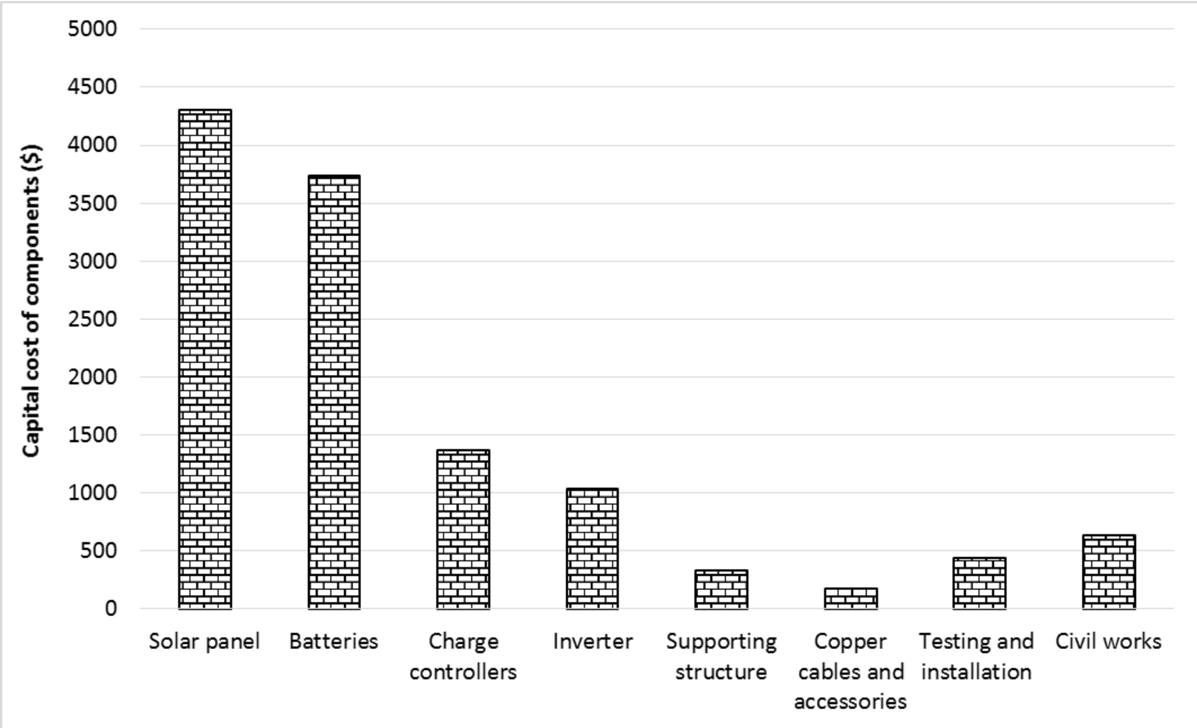


Fig. 6. Capital cost distribution for the solar PV system.

Table 3 represents the annual cost of various components of solar PV the system. The capital costs of the components were amortized over the lifetime of the components to get the annual cost numbers. For the amortization, the interest rate was assumed to be 10% with an inflation rate of 7.3% (see Table 2). Battery is the most expensive component of the system with a cost of $2155.10/year is because of its high capital cost and comparatively lower lifetime than other components. The yearly maintenance cost of the system was calculated as $231.86. The total annualized cost of the system was found to be $3607.68.

Table 3. Amortized cost of different parameters of the PV system

Parameter	Value ($/annum)	Source/comment
Solar panel	505.78	Calculated based on capital cost and lifetime of solar PV
Battery (lead-acid)	2155.10	Calculated based on capital cost and lifetime of lead-acid battery
Charge controller	361.40	Calculated based on capital cost and lifetime of charge controller
Inverter	168.10	Calculated based on capital cost and lifetime of inverter
Supporting structure (steel)	39.56	Calculated based on capital cost and lifetime of steel material
Copper cable	20.06	Calculated based on capital cost and lifetime of copper cable
Testing and installation	51.06	Testing and installation cost was assumed to be 3.75% of the total capital cost [30]
Maintenance	231.86	Maintenance cost was assumed to be 2.00% of the total capital cost [30]
Civil works	74.75	Calculated based on capital cost and lifetime of civil

works

The cost of electricity was calculated from the annualized cost of the system and the yearly electricity production. The system can generate 5.008 MWh electricity per year. If the total annual cost is divided by the annual average electricity generation, the unit cost of electricity would be \$0.72/kWh or 55.47 BDT/kWh. The percentage contribution of the components of the PV system to the total annualized cost is shown in Fig. 7. As the system components were designed based on the peak energy requirement to avoid shortage of electricity in summer, the system will produce excess electricity during winter season. The system generates an excess electricity of 1080 kWh/year which can be used to satisfy if there is any unexpected additional load. The excess electricity can also be supplied for water pumping for irrigation [8].

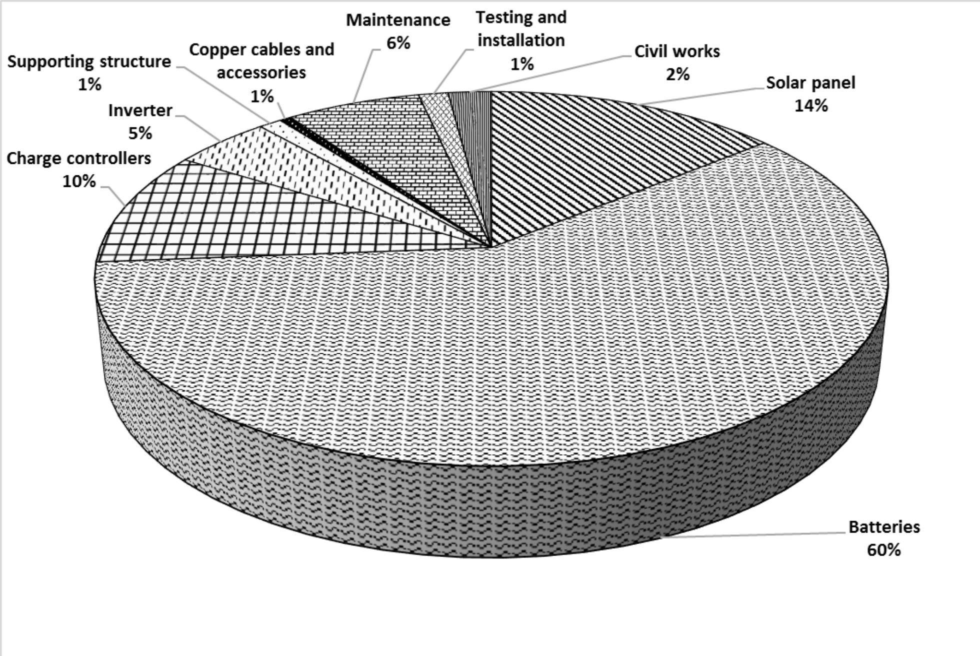


Fig. 7. Percentage contribution of the components to the total annualized cost of the system.

3.2. Sensitivity Analysis

A sensitivity analysis was conducted to check the impact of various input parameters on the cost of electricity of the system. Seven independent parameters – interest rate of the project, lifetime of solar panel, battery and charge controller, and cost of solar panel, battery and charge controller were varied by ±20%. Fig. 8 represents the sensitivity analysis conducted in this study. An increase in the interest rate and cost of components increases the unit cost of electricity (\$/kWh), because the increased interest rate and capital costs lead to an increased total cost of the system. Lifetime and cost of battery have the largest impact on the price of electricity as battery has the largest contribution to the total system cost (see Fig. 7). The COE changes from \$0.63/kWh to \$0.81/kWh for a variation in cost of battery (\$/battery) from -20% to 20%. On the other hand, if the lifetime of components increases, COE decreases. When the lifetime of battery increases by 20%, cost of electricity decreases by 9%. When the interest rate is increased from 10% to 12%, COE increases from \$0.72/kWh to \$0.76/kWh. The other parameters have minor impact on the cost of electricity (COE).

4. Conclusion

This paper provides an estimation of cost of electricity for an off-grid community through the development of a data-intensive spread-sheet-based model. There have been many studies on hybrid renewable energy systems, but assessment of stand-alone PV system is limited. The model developed in this research estimates the cost of electricity for an off-grid community of Char Godagari. To satisfy the load demand of the community, a 3.40 kW_p solar PV system is required. The net present cost and unit cost of electricity were found to be \$12,027.83 and \$0.72/kWh, respectively. The accuracy of the model was checked by the numbers published in literature [39] and sharing the results with renewable energy experts. The small variation of results between the studies is due to variation in input parameters and assumptions. Sensitivity analysis shows that lifetime and cost of battery have the biggest impact on the cost of charging. The results of this paper will help the industry to consider solar energy as an attractive alternative to the conventional energy systems in Bangladesh to generate clean electricity not only for remote locations but also for urban regions. It is important to quantify the cost of electricity for other renewable energy technologies (e.g. wind, hydro, biomass, etc.) for policy making purposes. So there is a scope of future work. Future work includes conducting techno-economic assessment of other renewable energy systems which will facilitate the comparison of cost of electricity for solar electricity and the other renewable energy technologies (e.g. wind, hydro, biomass, etc.) widely used for electricity production.

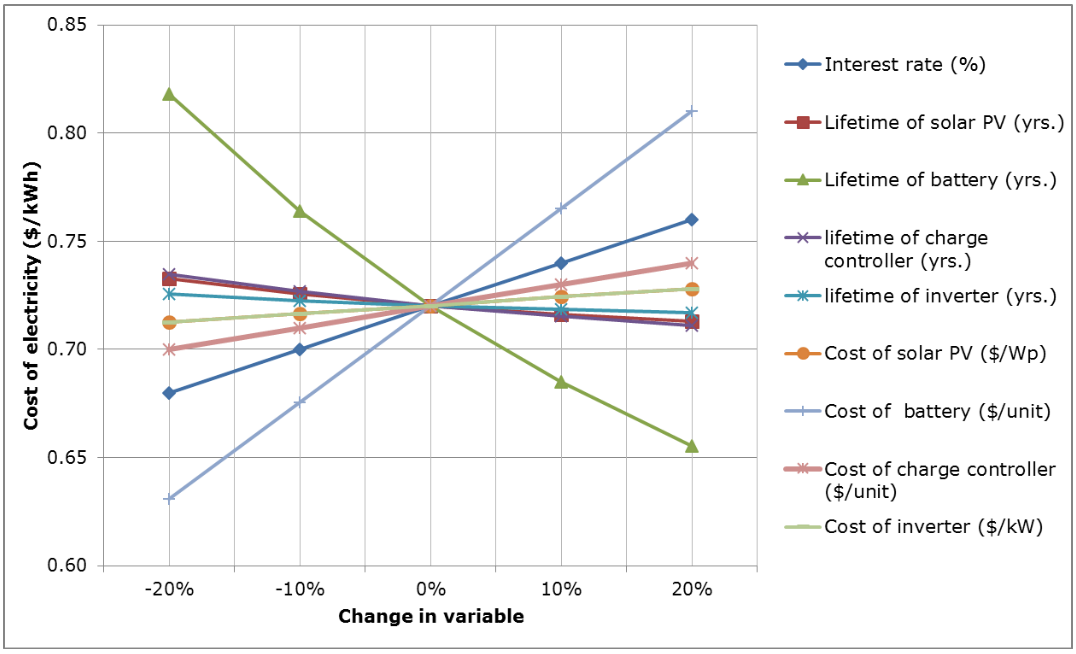


Fig. 8. Sensitivity analysis for the cost of electricity (COE).

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