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RESEARCH ARTICLE

A simulation study of techno-economics and resilience of the solar PV irrigation system against grid outages

Hemal Chowdhury[1] · Tamal Chowdhury[2] · Md Salman Rahman[3] · Hasan Masrur[4] · Tomonobu Senjyu[4]

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Abstract
Water is the most fundamental need for better yield in agriculture. Worldwide, diesel and electricity are typically used to pump water which contributes to atmospheric pollution. Besides, a power outage affects the irrigation process badly. Without water, the crop may wither away, causing a substantial economic loss. This paper discusses the resilience of a solar PV system during a power outage. HOMER Pro software was used to perform the techno-economic analysis of solar-based irrigation for four major divisions of Bangladesh, while 1-hour power outage was assigned in REopt lite to model the survivability of the system against the grid outage. The simulation outcomes showed that the energy cost is \$0.1496/kWh, \$0.1502/kWh, \$0.1557/kWh, and \$0.1576/kWh for Rajshahi, Sylhet, Dhaka, and Chattogram, respectively. About 45% of excess electricity can be stored after fulfilling all requirements. The system is more economical than a microgrid-based water pumping system and a diesel-based system, and the photovoltaic system is technically and economically suitable to pump water if the nearest grid connection is impossible. When connected to the main utility grid, the system can survive without grid power for several hours, subject to daytime outages.

Keywords Grid extension · Solar photovoltaic · Bangladesh · HOMER Pro · Water pumping

Nomenclature

BADC	Bangladesh Agriculture Development Corporation
BMDA	Barind Multipurpose Development Authority
COE	cost of energy
CRF	capital recovery factor
IDCOL	Infrastructure Development Company Limited
NPC	net present cost
NREL	National Renewable Energy Laboratory
NOCT	nominal operating cell temperature (°C)
PDB	Power Development Board
RF	renewable fraction
REB	Rural Electrification Board
SIP	solar irrigation pump
SREDA	Sustainable and Renewable Energy Development Authority
C_a (\$/ year)	sum of every year capital, replacement and operational and maintenance cost of each component
E_{demand}	total load demand
E_{excess}	excess electricity (kWh.yr^{-1}) generation from the renewable energy sources
$E_{production}$	total electrical energy (kWh.yr^{-1}) production from all the sources.
E_{ren}	energy generated from renewable sources per year
f	annual inflation rate (%)
f_{PV} (%)	derating factor of PV
H	no. of hours during a year (8760)

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Tamal Chowdhury
tamalshanto@gmail.com

1 Department of Mechanical Engineering, Chittagong University of Engineering & Technology (CUET), Chattogram 4349, Bangladesh

2 Department of Electrical and Electronic Engineering, Chittagong University of Engineering & Technology (CUET), Chattogram 4349, Bangladesh

3 School of Mathematical and Statistical Sciences, The University of Texas Rio Grande Valley, Edinburg, TX 78539, USA

4 Department of Electrical and Electronic Engineering, Faculty of Engineering, University of the Ryukyus, 1 Senbaru, Okinawa 903-0213, Japan

I_T (kW/m^2)	solar irradiation incident on the PV array
I_S (kW/m^2)	incident solar irradiation at standard test conditions
i	annual real interest rate (%)
i'	nominal interest rate (%)
$L_{0,\,dg}$	fuel curve intercept coefficient
$L_{1,\,dg}$	fuel curve slope
P_{dg}	electrical output of the generator
PV	photovoltaic
N	project lifetime
T_C (°C)	PV cell temperature
T_a (°C)	ambient temperature
T_S (°C)	PV cell temperature under standard test conditions (25°C)
Y_{dg}	rated capacity of the generator
Y_{PV} (kW)	rated capacity of PV array
η_{PV}	PV panel efficiency
γ	ground surface friction coefficient
a,b	constant
α_P	temperature coefficient of power

Introduction

Despite frequent disasters, extreme population pressure, and limited land resources, agriculture in Bangladesh has experienced major growth in recent years (Ismail 2016). The increase in rice production boomed up to 217 kg per capita in 2010 from 151 kg per capita in 1995 (Ismail 2016). The increase in irrigation water availability is the main factor behind this growth (Rana et al. 2020). The energy requirement of irrigation schemes generally defends the agricultural land, irrigation systems, and cropping calendars. The number of pumps operated via diesel in Bangladesh is 1.34 million (low lift pump – 0.14 million; shallow tube well (STW) – 1.2 million; and deep tube well pump – 3000). In Bangladesh, mechanized irrigation is responsible for 43% of total cultivation costs (SREDA 2020). Lands such as char lands, hilly and coastal areas requiring irrigation are not connected to the grid (World Bank 2015). In Bangladesh, it is reported that over 25% of electricity is used for irrigation purposes (Rana et al. 2020). Solar PV has found its way into the irrigation scheme because of its reliability and sustainability. Pumps powered up by solar PV help in reducing costs and protecting the environment (Sarkar and Ghosh 2017).

Many researchers carried out their research to explore the suitability of solar-powered irrigation systems. Niajalili et al. (2017) determined the technical and economic suitability of solar-powered irrigation for a rice paddy field in Iran. This study found that the initial cost of solar-based irrigation is nine times higher than a diesel-fueled system, but the PV-based system's lifecycle cost is 65.6% of the conventional system (Niajalili et al. 2017). Similarly, Sarkar and Ghosh (2017) evaluated the feasibility of solar power irrigation for Bangladesh and determined the cost of energy (COE). The study found that the cost of energy from a PV-based irrigation system is \$0.182/kWh (Sarkar and Ghosh 2017). Rana et al. (2020) identified the economic benefit of the solar power irrigation system (SPIS) in Boro rice production (Rana et al. 2020). They found a higher benefit to cost ratio and higher gross return of SPIS than diesel-fueled irrigation system (DGIS). Islam et al. (2017) determined the challenges and barriers against the development of SPIS in Bangladesh. This study suggested that proper financing is a must to accelerate SPIS progress in Bangladesh (Islam et al. 2017). Hossain et al. (2015a) explored the feasibility of SPIS for different crops of Bangladesh and found that cultivations of tomato, brinjal, and wheat are profitable when solar power is used to irrigate the field. Parvaresh Rizi et al. (2019) made a comparative study between regular and solar irrigation pumps for southern and eastern Iran and found that the length of the transmission line and the required power of pumps play critical roles in the feasibility of SPIS (Parvaresh Rizi et al. 2019). Yu et al. (2018) determined the potential of solar power irrigation for cassava production. This study found out that solar power can be used to irrigate a total land of 623,000 ha to cultivate cassava (Yu et al. 2018). Nikzad et al. (2019) reported that a solar-powered pumping system is more environmentally benign than a conventional diesel system as it emits 190–201 times lower CO_2 emissions. Also, a considerable portion of diesel fuel (1700–1800 liters) could be saved in the irrigation period (Nikzad et al. 2019). Chilundo et al. (2019) explored the feasibility of integrating a PV water pumping system (PVWPS) in fulfilling the water demand for horticulture crops irrigation. The study found that implementing PVWPS will save a considerable portion of electrical energy and be both economical and environmentally sustainable (Chilundo et al. 2019). Powell et al. (2019) implemented a PV-based irrigation system to irrigate sugarcane lands and found that implementing a small-scale PV-based system can reduce net present cost by up to 25% (Powell et al. 2019). Yavuz (2020) designed a solar thermoelectric generator to assist water pumps for irrigation purposes. This author reported that if the advancement can be made in the module materials, this system can easily compete with PV panels (Yavuz 2020). Rathore et al. (2018) analyzed the prospects of a solar-powered water pumping system for India and proposed a robust framework to enable the implementation of solar-powered water pumping systems at a large scale (Rathore et al. 2018). Chahartaghi and Nikzad (2020) performed an exergy analysis of a PVWPS and found its exergy efficiency of 3.56% (Chahartaghi and Nikzad 2020). From the above literature review, it is clear that the resiliency of a solar PV system is yet to be explored by the researchers.

Access to reliable electricity is a must for the growth of irrigated agriculture. While many high-income countries benefit from the use of electricity in agriculture, middle income and developing countries are suffering the most due to the poor coverage of electricity (Patil et al. 2021). Besides, extreme weather conditions take the reliability test of power infrastructure (Maliszewski et al. 2012). The resilience of a system can be defined as the system's capability to hold out against and restore from any remarkable devastating event such as natural hazards. From the power grid perspective, the resilience emphasis is always to preserve the supply of energy before, during, and after these destructive events. To our knowledge, previous studies did not take into consideration the resilience of a solar PV irrigation system against grid outage. Resilience in power systems is a complicated and broad issue, but our study focuses only on enhancing operational resilience instead of infrastructure resilience. Therefore, in this present research, solar PV has been proposed as a backup to a grid-connected irrigation system and the backup system's survivability against power outage has been modeled. The system is modeled for four major divisions of Bangladesh. A detailed techno-economic analysis has been presented in this analysis. In the next section, the current status of solar irrigation pumps in Bangladesh is provided. The third and fourth section outlines the method and findings of this analysis.

Present status of solar irrigation pumps

Bangladesh, a tropical country in South Asia, is blessed with abundant solar energy resources. Approximate ranges of solar insolation received by the land are 4–6.5 kWh/m^2/day, and a typical sunshine hour ranges from 6 to 9 h/day (Hossain et al. 2015b). Figure 1 shows monthly solar insolation in different regions of Bangladesh.

The long duration of sunshine hours and solar insolation in different regions provide a realistic indication of solar irrigation in Bangladesh (Fig. 1) (Chowdhury 2020). Approximately 1.28 million (M) irrigation pumps are fueled by diesel. For this reason, the government has to import 1.06 million tons of diesel for irrigation and has to provide annual subsidies of 280 million USD to make it more affordable (Haque 2018). On the other hand, 0.33 M electric pumps consume 1500 MW of electricity (Haque 2018). Thus, solar irrigation has enormous potential in Bangladesh as it can reduce emissions and develop the rural economy. Realizing this potential, the government has a future plan to install solar pumps of capacity 500 MW within 2040 (SREDA 2020). The number of pumps operated via electricity can

Table 1 Present status of irrigation pumps in Bangladesh (BADC, 2020)

Type of equipment	Name of agency	Operated by electricity (unit)		
		PDB	REB	Total
DTW	BADC	882	10115	10997
	BMDA	963	14590	15553
	Others	1020	7860	8880
	Total	2865	32565	35430
STW	BADC	8	131	139
	BMDA	0	0	0
	Others	35562	253733	289295
	Total	35570	253864	289434
LLP	BADC	110	2416	2526
	BMDA	28	491	519
	Others	880	10058	10938
	Total	1018	12965	13983

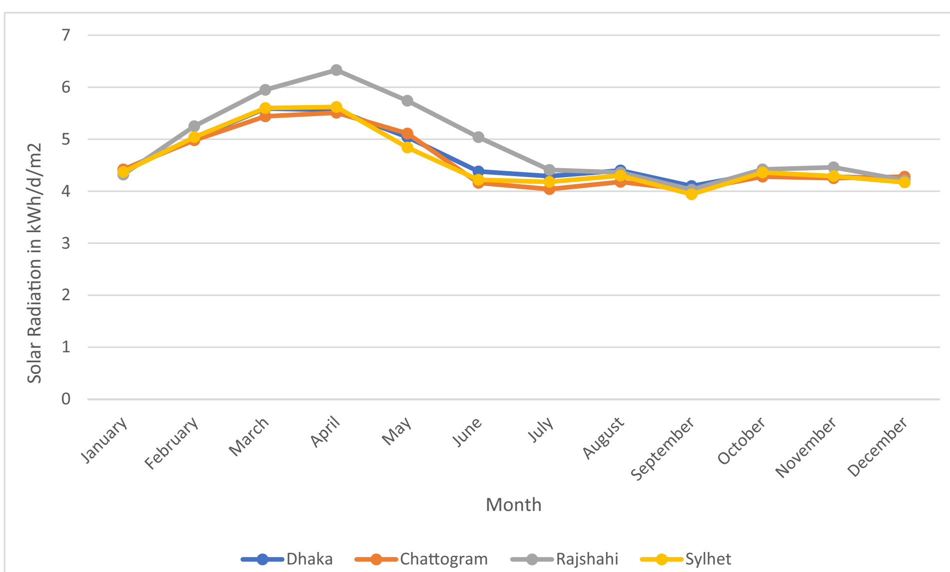


Fig. 1 Daily solar radiation in four cities of Bangladesh (Chowdhury 2020)

be found in Table 1. From Table 1, it is clear that the share of STW among irrigation pumps is very high. Among these pumps, only 2787 pumps are operated via solar. Despite its enormous scope, this technology has not been widely used in Bangladesh since its introduction in 1980. The high initial investment, subsidy on fuels, high grid penetration, lack of interest from investors, lack of technical knowledge and awareness for farmers, and absence of collateral for investors have narrowed the success of solar irrigation pumps in Bangladesh (Ali et al. 2020).

Methodology

To simulate the system, HOMER Pro software is employed in this study. Data regarding solar resources have been collected from the website (www.nasa.gov.sse). Different optimization concerns such as economic and environmental have been analyzed in this study. The resiliency of the system is done in REopt Lite (REopt Lite API 2020).

Software and load data

HOMER Pro software version 3.7 is utilized to design the whole system (www.HomerPro.com). National Renewable Energy Laboratory (NREL) developed this software. This software can carry out many types of research, for example, feasibility, techno-economic, and optimization problems. In Bangladesh, generally, three types of pumps, such as low lift pump, shallow tube well (STW), and deep tube well pump, are utilized for irrigation purposes. Among these pumps, STW is popular among farmers of Bangladesh since the static head of surface water is generally low (20–30 m) for most of the places (Bangladesh Agriculture Development). So, in this study, the irrigation pump is modeled for STWs only. A deferrable load is considered here since water requirements for irrigation do not need to be met up immediately. Water can be preserved in storage and can be used during irrigation. Without causing any disturbance in the production process, irrigation can be delayed for 1 to 3 days (Sarkar and Ghosh 2017; Bangladesh Agriculture Development). The water requirements of different crops can be found in Table 2.

To model the load, irrigation is considered maximum during the winter season (November to February). In the rainy season, irrigation is less required due to the water availability (May to September). However, since solar energy is intermittent, an additional load of 0.5 kWh/day is added for these months. One hectare of land is considered for irrigation in this study. The monthly average daily deferrable load profile can be found in Fig. 2.

Table 2 Water requirements and the irrigation period of different crops in Bangladesh (Khan et al. 2014)

Crop types	Irrigation period	Water volume (m^3/ha)
Rice-Boro	February–March	750
Rice-Aman	September–October	700
Rice Aush	July–August	650
Wheat	February–March	700
Mustard	December–January	300
Maize	October–January	152
Potato	January–February	283
Lentil	January–February	700

Solar resources

National Aeronautics and Space Administration's (NASA) website has been accessed to determine monthly average solar radiation data (www.nasa.gov.sse). This data was given as input to the software for designing a PV system. From Fig. 1, it can be seen that the highest solar radiation occurs in March and April in Bangladesh. Rajshahi district has the highest daily solar radiation of 4.88 kWh/m^2/day among these districts.

Optimization problem

Economic and environmental indicators are incorporated to highlight hybrid systems' optimization problems (Lu et al. 2017). Economic indicators showed the financial performance of these technologies to generate energy, while the environmental indicators are used to show the impact of these technologies to produce power on the environment. Cycle charging is considered as an energy management strategy in this study.

Economic investigation

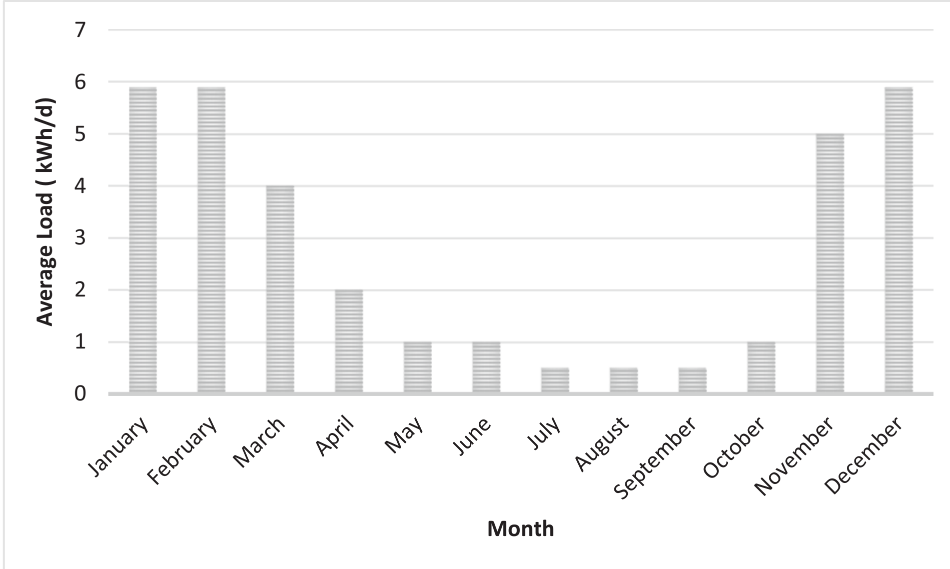
HOMER simulation cannot operate without the economic parameters. This research consists of the net present cost (NPC), annual real interest rate, cost of energy (COE), initial capital cost, and replacement cost for the various energy system arrangements.

The cost of energy is a crucial financial measure to determine the optimal size of a hybrid energy system. "COE is the ratio of the system components annualized cost (Ca) to the total energy generation (Es) that supports the demand." COE has been calculated using Eq. (1) (Das et al. 2021).

$$\mathrm{COE} = \frac{\mathrm{c_a}}{\mathrm{E_s}} \tag{1}$$

"NPC is the ratio of Ca to the capital recovery factor (CRF)" and can be evaluated from Eq. (2) (Das et al.

Fig. 2 Monthly average daily deferrable load profile



2021). NPC can also be defined as the summation of all costs such as replacement cost, fuel cost, initial capital cost, operation, and maintenance cost over a project's lifetime. HOMER software used Eqs. (1)–(4) to calculate NPC and COE of the hybridized system. Capital recovery factor (CRF) and annual real interest rate (i%) are manifested through Eqs. (3) and 4.

$$\mathrm{NPC} = \frac{Ca}{\mathrm{CRF}(i, N)} \tag{2}$$

$$\mathrm{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

$$i = \frac{i' - f}{1 + f} \tag{4}$$

Here, i' (%) is the nominal interest rate, N is the project lifetime (in the year), f (%) is the annual inflation rate, and Ca is the total annualized cost ($/year). A discount rate of 10% and an inflation rate of 2% are considered in this investigation by the authors.

Renewable fraction

In this subsection, renewable energy's contribution to meet up energy demand has been outlined through an indicator named renewable fraction (RF). The share of load met up by energy produced from renewable energy technologies is called the renewable fraction. The ideal value for RF is 100% since renewable energy resources have covered all the load. Equation (5) is used by HOMER to calculate RF:

$$RF = \frac{E_{\mathrm{ren}}}{E_{\mathrm{demand}}} \tag{5}$$

Here, E_{ren} depicts energy generated from renewable sources per year and E_{demand} delineates total load demand.

Excess electricity

In this subsection, excess electricity has been determined. This electricity can be stored in the battery and can be used for other purposes such as lighting the house. Excess electricity is the electricity available after the fulfillment of the load. In this study, excess electricity is determined using Eq. (6) (Das et al. 2021). HOMER utilized Eq. (6) to measure excess electricity at the end of each simulation. Minimum storage capacity is considered 6 kWh as input in this study.

$$F_{\mathrm{excess}} = \frac{E_{\mathrm{excess}}}{E_{\mathrm{production}}} \tag{6}$$

where E_{excess} denotes the excess electricity (kWh.yr^{-1}) generation from the renewable energy sources and $E_{\mathrm{production}}$ denotes the total electrical energy (kWh.yr^{-1}) production from all the sources.

Mathematical modeling of the water pumping system

In this section, modeling of the water pumping system is done. Solar PV utilizes solar radiation to pump water from the ground. A water tank can store the excess water. Therefore, solar PV is modeled in this section. Besides, the cost of extending the grid to pump water is also designed in this section.

Modeling of photovoltaic (PV) system

The availability of solar resources is an essential criterion in designing a PV system (Halabi et al. 2017). PV module manufactured by Generic is considered in this study. Several sizes have been inputted in the Homer Pro software to determine the PV system's optimum size. The life span of PV is considered 25 years. The derating factor of the PV is inputted 80% in the software. Many researchers have found that a slight increase (0.1%) in the temperature coefficient can raise the PV power output (Das et al. 2021). Hence, in this regard, Eq. (7) is applied to measure the hourly PV power output (Halabi et al. 2017).

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{I_T}{I_S} \right) \left[1 + \alpha_P \left(T_C - T_S \right) \right] \quad (7)$$

Here, Y_{PV} (kW) is the rated capacity of the PV array, I_T (kW/m^2) is the solar irradiation incident on the PV array, f_{PV} (%) is the derating factor, I_S (kW/m^2) is the incident solar irradiation at standard test conditions, T_c (°C) is the PV cell temperature, T_s (°C) is the PV cell temperature under standard test conditions (25 °C), and α_P is the temperature coefficient of power.

The cell temperature of PV (T_c) is calculated by applying Eq. (8). The effective transmittance-absorptance is the ratio of the heat conveyed to the fluid to the heat generated on the absorber surface by absorbed solar radiation, and it is considered 0.95 in this investigation (Das et al. 2021). Table 3 signifies the various parameters of solar PV.

$$T_C = T_a + I_T \frac{T_{c,\mathrm{NOCT}} - T_{a,\mathrm{NOCT}}}{I_{T,\mathrm{NOCT}}} \left(1 - \frac{\eta_{PV}}{0.9} \right) \quad (8)$$

Here, T_a (°C)is the ambient temperature, and η_{PV} (%) is the PV panel efficiency.

Grid extension

For modeling grid extension, HOMER Pro software is utilized. In Bangladesh, the required initial capital cost for the grid extension is 1182.08$/km, and the yearly required maintenance cost of the grid extension is 236.5$/year/km. The grid power price of 0.035$/kWh is considered to estimate the break-even grid extension distance (Hoque and Nandi 2012). The break-even grid distance is the distance from the grid, making the NPC of extending the grid equal to the NPC of the stand-alone system (Hafez and Bhattacharya 2012). The model of this system can be found in Fig. 3.

Diesel generator

In Bangladesh, diesel engines are mainly used for irrigation purposes. In this study, HOMER Pro software is used to model this system. The fuel cost is taken as $0.91 per liter (Mandal et al. 2018). The expected life duration is taken as 1500 hours, and the operation and maintenance cost is inputted at 0.05 per hour. The life cycle emission is inputted as 0.88 kg CO_2-eq/kWh (Mandal et al. 2018). The fuel consumption can be evaluated from the following Eq. (9) (Mandal et al. 2018):

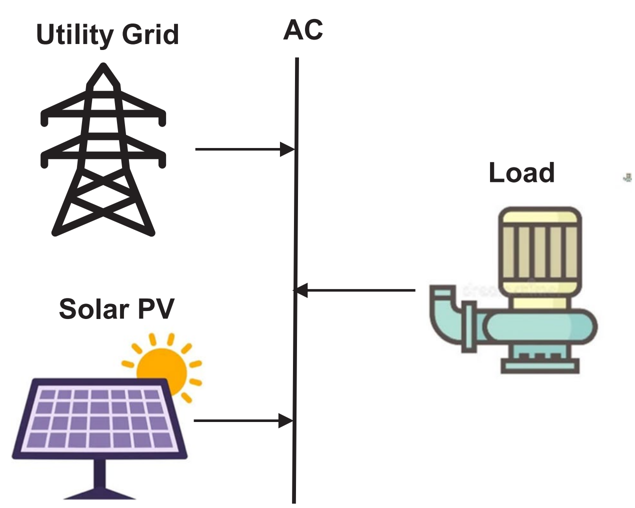


Fig. 3 Schematic diagram of the research

Table 3 Technical parameters used in the present study (Das et al. 2021; Hoque and Nandi 2012)

Component	Technical description	Capital cost ($)	Replacement cost ($)	O and M cost ($)	Lifetime	LCE (kg CO_2-eq/kWh)
PV module	327 W	1300 $/kW	0	20$/year	25 years	0.045
Grid extension		1182.08 $/km		236.5$/year/km		
Diesel generator		370 $/kW	296 $/kW	0.05$/h	15000 h	0.88
Discount rate	8–12%					
Inflation rate	3–7%					
Fuel cost ($/l)	0.91					

$$L = L_{0,dg} Y_{dg} + L_{1,dg} P_{dg} \quad (9)$$

Results and discussion

Case I (PV vs grid extension)

In this section, both financial and technical results were presented. The optimization system is found after the simulation in the software. From Fig. 4**,** it is clear that the lowest COE is observed for the Rajshahi district. The energy costs are \$0.1496, \$0.1502, \$0.1557, and \$0.1576 for Rajshahi, Sylhet, Dhaka, and Chattogram, respectively. The net present cost of the system is found to be higher for Chittagong. It is found that the NPC of Dhaka is 4.24% and 4.46% higher than Sylhet and Rajshahi, respectively. The cost of energy for Dhaka city is found to be 14.83% less than reported by Sarkar and Ghosh (2017). A comparison has also been made with a microgrid-based irrigation system (Shoeb and Shafiullah 2018). Obtained COE is 34.09% less than microgrid-based irrigation systems. Another study found that irrigation through diesel pumps costs 0.195 \$/kWh (Rezk et al. 2019). This study also showed that irrigation through a PV-battery system costs \$0.059, 39% less than found in our study. Babkir Ali has compared PV and solar thermal technologies to find their feasibility in the irrigation system (Ali 2018). The obtained COE to pump water by PV is 0.033 \$/kWh which is also less than the cost found in this study. The cost of electricity for irrigation in China is reported to be 0.056 US\$/kWh (Zou et al. 2013). Powell et al. reported that PV-based irrigation would cost Australia 0.128 per kWh (Powell et al. 2019). The COE found by both of these authors is less than found in our study. The main reason behind this high initial cost of solar PV technologies in Bangladesh is the higher initial cost, poor technical design such as poor-quality materials or manufacturing issues, design flaws, and fill factor that affect the energy performance of the PV module and thus affecting the cost of energy severely (Aziz and Chowdhury 2021).

The renewable fraction is observed at 100% for all these cities since there are fossil fuels involved. The PV system has met up the all the load. The optimum size of the PV system is found to be 1.09 kW. The electricity produced by the PV system is 1696 kWh/year. After meeting up the load, the excess electricity found is 45%. The capacity factor (CF) is simply the ratio of energy generated over a while (typically a year) divided by the installed capacity. The CF of PV is found to be 16.9%. The output of the PV system can be found in Fig. 5. From Fig. 5, it is clear that the energy production from PV is lower at 6 AM due to the lower availability of solar radiation, and the power production is higher during noon since there is the possibility of having high solar radiation**.**

In this analysis, the distance of the grid for the irrigation purpose is also taken into consideration. The NPC of the PV system with grid extension is very less when the PV system is very close to the external grid point of connection. NPC showed a significant increment when the grid extension distance increased. Beyond the interception of grid extension and stand-alone (PV system), it becomes expensive for the PV system to connect to the external grid. If the grid extension is done, it would need to be within 0.32 km for Sylhet, 0.33 km for Dhaka, 0.34 km for Chittagong, and 0.31 km for Rajshahi. If the nearest grid connection is further away, then serving the pumping load by a PV system is a viable option.

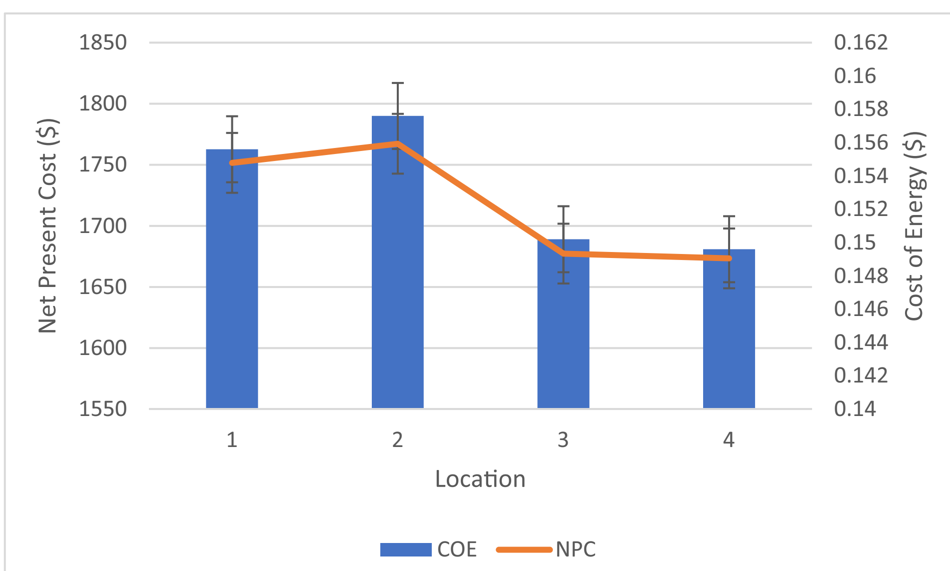


Fig. 4 COE and NPC of the solar irrigation system

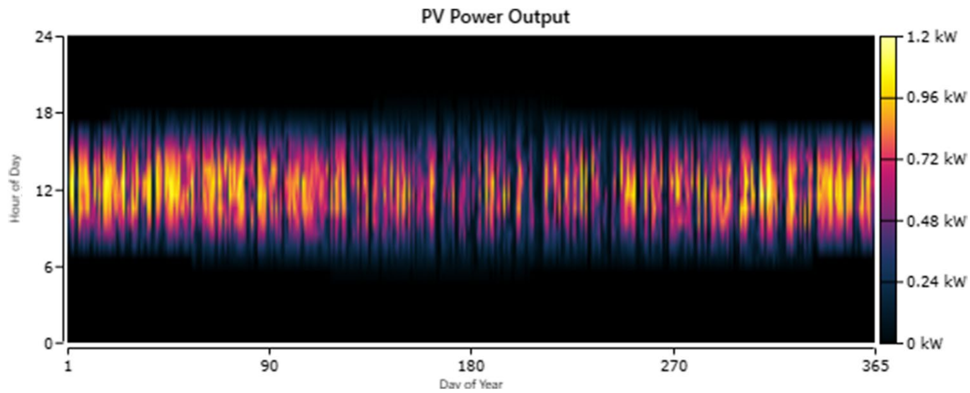


Fig. 5 Output of the PV system

Case II (only diesel-based system)

Diesel fuel is used in the diesel-based system to fulfill the irrigation load. From the simulation, COE and NPC of the diesel-based system are \$0.336/kWh and \$4003.68. The size of the diesel generator is 0.25 kW. Fuel cost comprises 78% of the total cost. Both COE and NPC of this system are found to be higher than the case 1 system. To satisfy the demand, the total fuel consumed was 289 liters. The total electricity produced by the generator was 991 kWh/year, and the capacity factor of the generator was measured to be 45.3%. The mean electrical efficiency was calculated to be 34.8%. RF of this system is zero since diesel is used in this system. The excess electricity is also observed to be zero. This means that all the generated electricity is employed to meet the demand. The environmental performance of this case is also simulated. It was observed that this system emits 757 kg CO_2 per year, while case 1 does not emit any CO_2. So, the case 2 system is both environmentally and economically less viable than the case 1 system.

Sensitivity analysis

The inflation and discount rate have been changed to observe their impact on NPC and COE for sensitivity analysis. Different capacities of storage have been inputted in the HOMER Pro software. The capacity of storage has varied from 6 to 36 kWh. The inflation rate has been varied from 3 to 7%, while the discount rate has been varied from 8 to 12%. From the simulation, it has been found that the optimum capacity size of the storage is 12 kWh. The effect of changing discount rate and inflation rate on NPC and COE can be found in Fig. 6. When the discount rate (DR) is 10% and the inflation rate (IR) is 3%, the value of COE and NPC is found to be \$0.1544 and \$1693.56. When DR and IR increased to 12% and 7% from the base case of 10% DR and 3% IR, respectively, COE showed a 15.65% decrease while NPC exhibited a 3.51% increment. Additionally, a 20% decrease in DR would result in a 39.35% decrease in COE and a 13.44% increase in NPC from the base case scenario.

Resilience analysis of solar water pumping system

Figures 7 and 8 show the optimal energy management scheme of the modeled irrigation system when connected with the grid. Since the maximum and lowest average loads are in January and August, respectively, the energy dispatch strategy in these months almost reflects for the entire year. The weather data of Dhaka city has been used to realize the hourly energy dispatch scheme. The solar pump is considered to run from 9 AM to 5 PM in the presence of daylight, and it has a flat load demand.

The PV system mainly supplies the power to the irrigation load demand during normal operating conditions, followed by the utility grid, as seen in Figs. 7a and 8a. This is because the renewable source appears cheaper than the fossil fuel-based generation, i.e., the main grid. Compared to January, the PV output is curtailed more in August because of the higher solar radiation. In addition, due to higher solar radiation and thus higher PV production, PV power is curtailed more during the daytime in both months. It is noted that there is a provision for battery in this model as the surplus PV power would be used to charge this energy storage, resulting in the reduction of the PV curtailment. Net energy metering was not considered in this study; otherwise, the reduced PV power could have been exported to the grid, resulting in system economic savings.

Generally, solar PV-based energy systems are expected to survive short-term power outages subject to robust energy management schemes and high-to-moderate solar radiation of the site (Masrur et al. 2020, Masrur et al. 2021). Since the solar irrigation pumps typically are installed in rural areas, there is a good chance of power outages. Also, the solar irrigation system may be considered a critical infrastructure as it directly affects agricultural production. Therefore, a 1-h

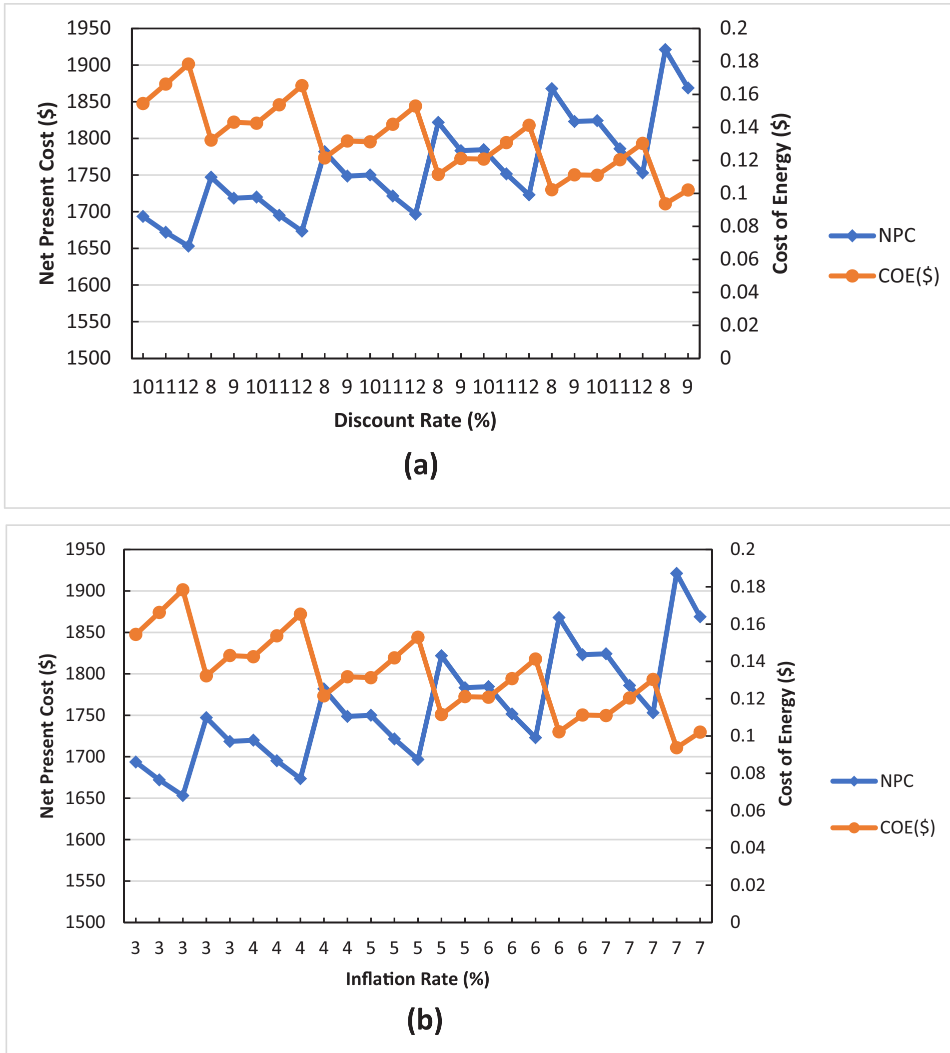


Fig. 6 (**a**) Effect of changing discount rate on NPC and COE. (**b**) Aftermath of varying inflation rates on NPC and COE

outage is assigned to realize its impact on the grid-tied system via REopt Lite tool. Simulation results showed that the model successfully endures the outage in January (Fig. 7b) and August (Fig. 8b) and serves the load via PV generation. Figure 9 shows the survivability of this system against the grid outages. It showed that the model could easily withstand at least nine hours of a power cut with 100% survival probability, making the system robust and reliable.

Conclusion

Despite having good potential for solar irrigation systems, this technology has not seen widespread use in Bangladesh. This article explores the feasibility of installing solar PV for irrigation purposes for four major divisions of Bangladesh. A new concept of extending the grid for water pumping application against designing a PV system is also presented. The energy costs are \$0.1496/kWh, \$0.1502/kWh, \$0.1557/kWh, and \$0.1576/kWh for Rajshahi, Sylhet, Dhaka, and Chattogram, respectively. The system provides better economic performance than a microgrid-based water pumping system. After fulfilling the pumping load, 45% of excess electricity can be utilized for other agricultural purposes. The system is also more environmentally sustainable than diesel and electricity as all the load is met up by solar resources. The use of PV will result in the avoidance of 757 kg of CO_2. Moreover, given the energy management scheme, the system is reliable as it can adequately endure grid interruptions. The outage probability of the PV system is 100%, and the system can withstand a nine-hour outage. The limitation of this study is that this study did not consider cyber vulnerabilities and weaknesses associated with the system. Only power outages caused by natural disasters are considered in this study. Besides, the solar radiation data and load data have been collected from published literature and the NASA website. Therefore, it is suggested that actual weather and load data should be collected to determine the

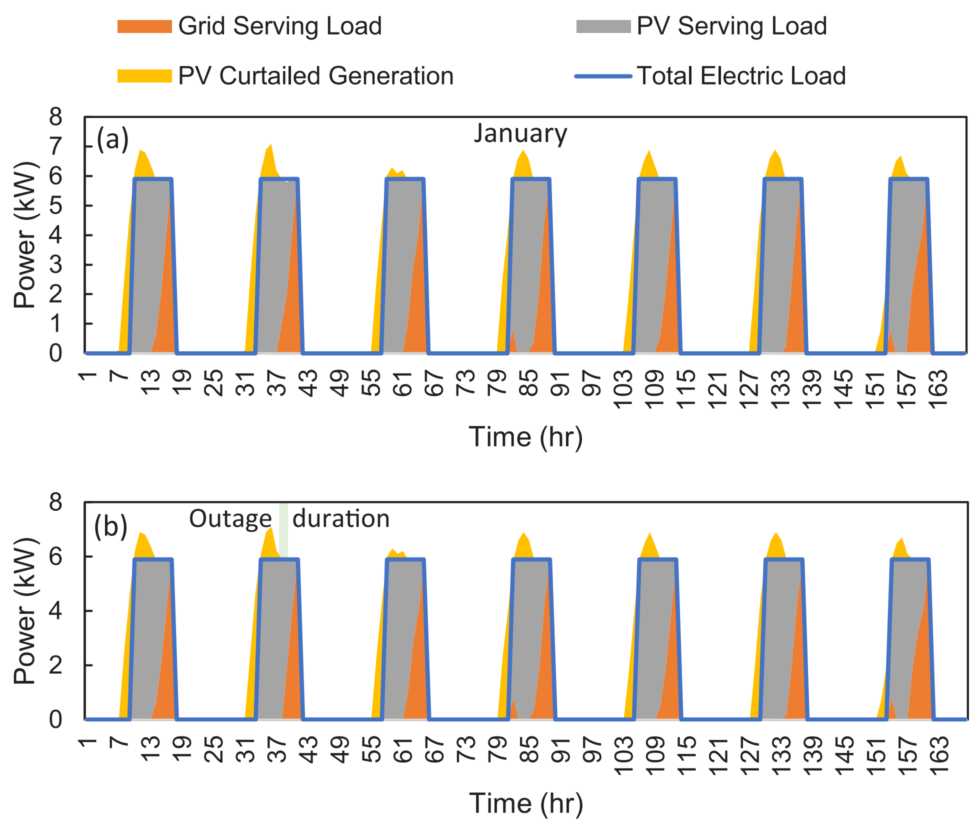


Fig. 7 Dispatch strategy of the system in a typical week of January under (**a**) normal operation and (**b**) 1-h blackout

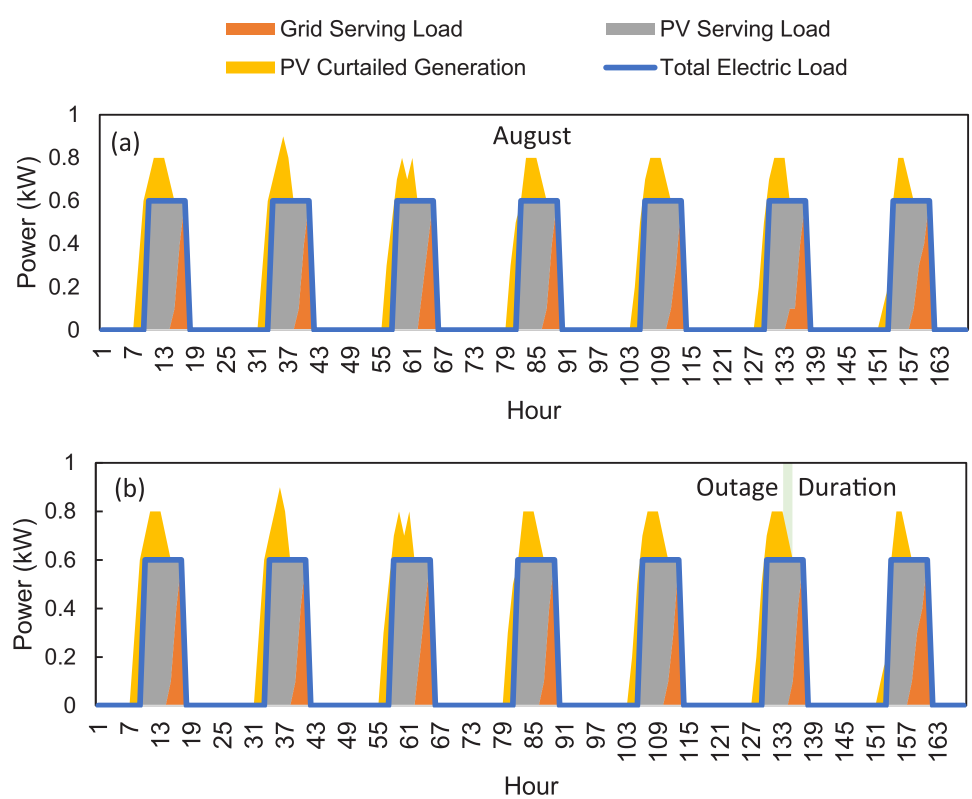


Fig. 8 Dispatch strategy of the system in a typical week of August during (**a**) normal operation and (**b**) 1-h blackout

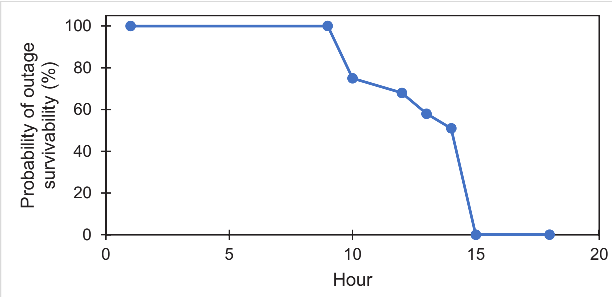


Fig. 9 Outage survival probability of the system

resiliency benefits of the solar PV system. Preference should also be given to the thermal loads for future study. For future study, the feasibility of applying fuel cell and wind solar-based hybrid systems for irrigation purposes should also be studied. Detailed techno-economic and environmental analysis should be carried out to find out the suitable system for rural areas.

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Data availability The data that support the findings of this study are available from the corresponding author, Tamal Chowdhury, upon reasonable request.

Declarations

Ethics approval and consent to participate The facts and views in the manuscript are solely ours, and we are responsible for authenticity, validity, and originality. We also declare that this manuscript is our original work, and we have not copied it from anywhere else. No plagiarism is detected in this manuscript.

Consent for publication We undertake and agree that the manuscript submitted to your journal has not been published elsewhere and has not been simultaneously submitted to other journals.

Competing interests The authors declare no competing interests.

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