A Sustainable Energy Approach for Pumping and Irrigation in the Barind Region of Bangladesh

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Abstract

The continuous use of fossil fuels has prompted scientists and researchers to convert to renewable sources for powering water pumps. By converting sunlight into electrical energy, the photovoltaic (PV) panels are able to drive the water pump or produce electricity through an inverter. Over the past few years, scientists have been working on developing more efficient solar-powered water pumps. A summary of existing research and development activities for developing a dependable and cost-effective solar irrigation system is described in this study. The paper outlines Bangladesh's present irrigation scenario, the problems associated with solar irrigation systems, and government policies and actions promoting solar irrigation. The main objectives and aims of the proposed project are to develop an efficient standalone hybrid solar PV-pyro-oil generator-based water pumping system for the Barind tract and off-grid remote areas. Moreover, the techno-econo-environmental feasibility of the proposed project has also been evaluated. The total life cycle cost and investment payback period of the 20-year project were found to be 14,377.32 dollars and 7.04 years, respectively. Moreover, the project's internal rate of return and CO_2 reduction potential were found to be 21% and 197.1 tons, respectively. Therefore, the project is sustainable and feasible, which provides a guideline for researchers and investors.

1. Introduction

Bangladesh is the most compactly populated country in the world, and around 165 million of its people are facing unyielding challenges and problems due to energy insufficiency, which is clogging socio-economic development and industrial growth [1]. Agriculture is the predominant industry in Bangladesh, and about 60–70% [2] of its population directly depends on agriculture for their livelihood. It has been found that Bangladesh's population reached 167.33 million in 2021, which is about 2.11% of the world population in 1,48,460 square kilometers of land, giving it an average density of nearly 1,265 people per square kilometer [3]. The prediction of the country's total population by 2050 is about 195 million, but only 130 million by the year 2000. As a result, the country's population grows by a million people every 50 years. New businesses and residences are acquiring land for agriculture to fulfill the urgent demand of the expanding population [4]. Approximately 14.76 million hectares of the country's total land area are net cultivable, and 51% are irrigated [5]. Currently, agriculture accounts for 15.96% of the nation's GDP and provides a living for between 60 and 70 percent of the people [6]. Since the population of the country is gradually increasing, the effective cultivation land of the country is decreasing day by day for establishing new industries, residences, etc. A few years ago, most of the land in this country was irrigated by using river water, but in recent years, most of the rivers have faced scarcity of water, especially in the summer season. WHO estimates there are 1.1 billion people worldwide without access to pure water for drinking and that this number will increase to 3 billion by 2025 [7].

The country's need for energy is growing significantly as a result of the nation's rapid industrialization, financial system transformation, and population growth [8]. Growing demand for power is not only reducing the supply of fossil fuels, such as coal and natural gas, but also having an impact on the environment [9]. Therefore, to satisfy strength in addition to mitigating environmental troubles, many countries are seeking out green electricity sources, e.g., solar and wind energy [10]. In Bangladesh, which is largely an agricultural nation, more than 70% of the land is used for growing crops, and close to 50% of the population is engaged in the irrigation sector [11]. Judicious use of energy and water is essential to the agricultural sector's growth. Besides, the amount of average rainfall has also decreased in recent years. Therefore, the only source of water for irrigation is groundwater, but the level of groundwater varies throughout the year, and the value of the water for the fiscal year 2020-21 is depicted as a maximum of 15.55 m and a minimum of 7.32 m [12]. Agricultural sustainability in Bangladesh is highly dependent on water because its timely existence and prime use determine both the quality and volume of food produced [13]. Energy is critical to pumping and conveying water for irrigation [14]. Global food production faces serious threats from the diminishing and dwindling supplies of water and energy in the environment and from climate change, which poses a particular challenge to low-income countries [15]. In Bangladesh, the area under cultivation is approximately 59.8% of the total 14,757 thousand hectares. About 52% of Bangladesh's total land area is arable, and 60–70% of the population depends on agriculture for a living [16]. In spite of using river water for the purposes of irrigation, in recent times most of the rivers have been bothered by a shortage of water, mainly in dry seasons. Consequently, for irrigation purposes, a prime source of water comes from underground. Farmers irrigated their fields using diesel and water pumps connected to the grid. In Bangladesh, there are more than 1.75 million irrigation pumps in service, 82% of which are powered by diesel engines and 18,000 by electricity [17]. Nearly 45% of the population of the nation lives in remote places that may be distant from the current grid line and isolated from the mainland. The availability of grid power will be insufficient in most of the far-off and remote regions for the subsequent 10 to 30 years [18]. Moreover, the underground water stage in a few areas of the country and in the northern region is simply too deep and it is not possible to elevate water using diesel pumps [19]. In the Barind region, the ground water level is deeper than 30 feet, making it difficult to lift water for agriculture and drinking purposes using a diesel pump or a surface pump [20]. However, people in the Barind zone depend only on submersible pumps to lift groundwater [21].

Alternative energy sources mitigate the dependency on fossil fuels and/ or the national grid. Therefore, 94% of the people have been brought under electricity facility, among which 55 lakh families enjoy power from solar panels [22]. Solar is one of the renewable sources of energy that can be used to power water pumps [23], as it is available in most places, even in remote spots, lowering the reliance on grid power and diesel for pump driving [24]. Moreover, Bangladesh is a suitable place for solar power production since it is located between 88.04° and 92.44° east longitudes and 20.30° to 26.38° north latitude [25], [26]. In Bangladesh, average solar insolation varies between 4 and 6.5 kW/m^2/day, whereas that in the Barind tract varies between 3.96 and 6.24 kW/m^2/day [25]. Significant solar power capacity has been added to the electrical networks of many nations and territories as a complement to or replacement for traditional energy sources. The rate of global photovoltaic growth varies greatly per nation and is quite dynamic. A total of around 629 GW of solar energy had been deployed globally by the end of 2019. China is the country of maximum solar power generation by the year 2019, while in Bangladesh, the solar energy generation till 2019 was 0.4 terawatt hours, or 400 gigawatt hours, which is quite sufficient for the employment of solar irrigation establishments in Bangladesh [25]. On the other hand, by introducing proper alternative sources like solar energy, the cost of irrigation and safe drinking water in off-grid remote areas can be minimized, the socio-economic conditions of the people in the remote areas can be improved, and the vital sustainable development goals of Bangladesh can be easily met. Due to the poor solar input at night and during the rainy season, it is often not possible to completely replace diesel generation with solar electrical power [27]. Therefore, the incorporation of a battery bank is necessary for the proposed project to achieve maximum system efficiency as well as account for variations in solar radiation. In Bangladesh, the peak radiation occurs between 12:00 AM and 14:00 PM, while the PV power supply is available from 8:00 AM to 17:00 PM [28]. Therefore, a hybrid solar energy-based system could be a possible solution in this regard.

According to research by Sitharthan et al. [29], China, the nation with the biggest solar energy harvesting capacity, has irrigation pumps and photovoltaic systems installed on 99% of its land. For agricultural areas in India, the government intends to construct 181000-volt photovoltaic water pumps. Fossil fuels will be gradually phased out by the government by 2050. For long-term sustainable development, solar energy technologies are beneficial, and the Indian government's energy regulations and aim to minimize CO_2 emissions favor their use and installation [30]. The adoption of this technology has been gradual despite the fact that there are around 3000 bright hours per year and 5 to 7 kWh/m^2 of solar irradiation that can be completely exploited in solar-powered irrigation systems with a total installed capacity of 1083 MW [31]. Under, a government of Pakistan subsidy program, the agricultural industry has benefited from this technology for deploying drip and sprinkler irrigation systems driven by solar energy [32].

According to Wazed et al.'s investigation, the traditional solar water pumping technology has a number of drawbacks that will prevent its widespread use for irrigation purposes [33]. As a result, a novel solar water pumping system needs to be developed that will minimize the investment cost, maintenance cost, lower carbon emissions, etc. Solar irrigation is unquestionably a new technology, but Mertens stated that further research is needed to expand it and address its other drawbacks, including its dependence on the nature [34]. According to Terang and Baruah's examination of the techno-economics of solar, diesel, and electricity-operated submersible pumps, solar submersible pumps have more favorable results in terms of values than diesel and electricity-operated pumps [35]. The techno-econo-environmental analysis of the solar-powered water pumping system conducted by Kumar et al. [36] revealed that it is environmentally friendly and energy-efficient, but more study is needed to lessen its reliance on the environment. According to Mohan et al., [30] solar energy-based irrigation has encountered a number of issues, including a high initial cost, accessibility issues, capacity issues, and technological inefficiencies. According to Hussain et al.'s [32] assessment, location and weather have an impact on the production of solar irrigation technology systems.

The aforementioned literature review reveals that significant research has been carried out on solar irrigation problem and in most of literature, it reports that the conventional solar irrigation system contained various problems like nature dependency, intermittency of power supply, sitting idle in off season time etc. Therefore, a sustainable model is required to overcome these limitations. In this research work, we have proposed a sustainable energy model which will address this type of obstacle. In addition, the techno-economic evaluation of the proposed model has also been investigated. The results show that the project is economically feasible. As far as the author's knowledge, no extensive studies have been conducted regarding the proposed model and its techno-econo-environmental feasibility analysis. There have been no studies earlier of such hybridization for irrigation purposes, and that's the novelty of this research work. This work critically reviewed sustainable energy for irrigation in Bangladesh and proposed a sustainable hybridization system for irrigation purposes. Moreover, the techno-econo-environmental feasibility of the proposed project has also been analyzed. It has been found that the proposed model is sustainable as well as feasible for the irrigation sector of this country.

2. Irrigation scenario in Bangladesh

2.1 Rice production scenario in Bangladesh

Sun energy is adequately available in Bangladesh, with an average sun insolation of between 5 and 7 kW/m^2/day. Rice is the main crop of Bangladesh, and Boro production is greater than Aus and Aman. The growing period of Boro is in the dry season. Consequently, during dry seasons, significant areas of the nation continue to be unirrigated and uncultivable. Moreover, rice is Bangladesh's principal food crop, accounting for over 70% of the total calorie supply and half of the total protein intake. Bangladesh is the world's fourth-largest rice producer, with rice accounting for over 75% of all agricultural acreage [26]. Moreover, three main rice ecosystems—Aus, Aman, and Boro—are cultivated during the pre-monsoon, monsoon (rain-fed), and dry seasons, respectively [37]. According to analysis, 661 liters of water were utilized to produce one kilogram of Boro paddy in 2016–17 [38].

Aman's output was roughly 98 lac metric tons (LMTs) in 2004–2005, but Boro's production was about 130 LMTs. Aman's output is gradually growing. However, since 2014-15 Boro output has risen quickly, surpassing Aman production in 2006–2014 [39]. From 2004 to 2021, **Fig. 1** depicts the production of Aus, Aman, and Boro. In 2021, Aman and Boro output totaled about 295 and 305 LMTs, respectively. During the period 2004–2021, however, annual output of Aus remained nearly constant at 12–15 LMTs. Following that, it steadily fell to 10.7 LMTs in 2012-13. Despite occasional changes in rice output throughout the years, the average total rice production steadily rises. The overall rice production in 2021 was more than a million tons. Aside from Aus, Aman, and Boro, the country grows about 3.5 million metric tons of hybrids each year [40]. To meet its rice demand and avoid food shortages caused by droughts, floods, or storms, the nation imports rice from neighboring countries [41]. In 1990, the amount of rice imported was 0.2 MT, but it has increased by 1.6 MT in the year 2020, as a result of rapid population growth, industrialization, etc. Because of changes in rice ecosystems, the average farmed area for both Aman and Aus are shrinking every year. Aus has been impacted more than Aman typical farmed regions [42]. Aus and Aman had cultivable areas of roughly 3.7 and 10.8 million hectares, respectively, in 1990. In 2021, it was cut to 1.2 million hectares for Aus and 6.3 million hectares for Aman, respectively. Moreover, the average Boro area increases year after year. Boro was farmed on roughly 5.4 million hectares in 2021, compared to only 3.1 million hectares in 1990 [43]. Despite the fact that total rice farmed lands stayed constant at 12 million hectares from 1990 to 2005, they gradually declined from 11.32 million hectares in 2010 to 11.9 million hectares in 2021, as shown in **Fig. 1 (b)** [44]. It has been found that the number of electricity- and diesel-operated pumps in Bangladesh is 0.33 and 1.28 million, respectively, for irrigation purposes. Therefore, a huge amount of energy is consumed by the irrigation sector in Bangladesh. Thus, researchers and scientists come forward to reduce the dependency on fossil fuels, as their reserves will vanish one day. In this regard, the solar irrigation pumping system could play a great role in minimizing the use of conventional energy sources. Table 1 shows the research study based on the performance analysis and study approach of solar powered water pumping systems all over the world. The research findings have also been included in the table. In most of the research, it has been found that natural dependency of the solar irrigation system should be reduced to get the maximum benefit from it.

Table 1 Overview of performance analysis research work

Source	Year	Location	Applications	Types	Study Approach	Research findings	Ref.
A. Al-Badi and H. Yousef	2016	Oman	Irrigation and domestic	Solar PV water pumping system	Experimental	• A grid connected centrifugal type induction motor pump is replaced by a solar pump having 17 m well depth and 1000 l/min discharge. The present value cost of the solar pump is $21.101×10^3$ ($) and energy cost is 0.17 ($/kWh) with present worth factor 0.17.	[46]
Hadole et al.	2020	India	Irrigation	PV water pumping system	Simulation	• There is a proportional relationship between flow rate and pump power for each head. • There are about 25-27% reduction of PV system capacity as well as 3% (can be neglected) due various month and temperature rise (climate change) respectively. • The flow rates and energy generation capacity of the solar pump reduced due to degradation of the system equipment as well as climate change.	[47]
Mokeddem et al.	2011	Algeria	Irrigation and domestic	Directly coupled PV water pumping system	Experimental	• Directly connected solar water pumping systems have cheap starting costs as well as minimal maintenance, replacement, and repair costs due to the lack of a battery and complicated electronic management. The directly coupled system	[48]

						is able to attain steady state soon during any abrupt changes. • Only low head irrigation systems in remote places may use the technology, and motor-pump efficiency was never 30%.	
S. Rehman and A. Z. Sahin	2016	Saudi Arabia	water pumping in remote localities	wind-solar PV hybrid power system with battery backup	Simulation (HOMER)	• When employing a PV-Wind water pumping system, the monthly total water pumping capacity is nearly consistent. • In the spring and summer, there is a larger pumping capacity. • The system is capable to produce 25865 kWh energy annually with cost of energy 0.212 $/kWh including 3 wind turbine of 2.5 Kw each, 1.5 Kw PV panels, 5 kW inverter and 44 batteries of 1900 Ah each.	[49]
P. Santra	2020	India	Irrigation	solar PV pumping system	Experimental	• The CO_2 emissions from diesel operating pump is 0.382 kg-ha-mm^{-1} and electricity operated pump is 1.214 kg-ha-mm^{-1}but solar pump of 1 hp is quite low i.e 0.009 kg-ha-mm^{-1}. • The DC pump has a longer operating window each day than the AC pump, while the AC pump has a far higher pressure head than the DC pump. A solar DC pump's life cycle cost is also	[50]

						considerably cheaper than an AC solar pump's. • The discharge rate is decreasing with increasing in pumping head. Besides, pump discharge shows proportional relationship with solar irradiation.	
N. I. Sarkar and H. R. Ghosh	2017	Bangladesh	Irrigation	Solar PV pumping system as well as PV-Generator-Battery	Experimental	• Internal Rate of Return (IRR) of 12.95%, simple payback duration of 9.33 years, equity payback period of 8.26 years, and benefit to cost ratio of 1.08 are all guaranteed when a 1 kW diesel pump is replaced with a solar PV pump. • The total decrease in greenhouse gases (GHG) is roughly 0.9 tons. The COE is modest with PV operating alone, around $0.182 or such. • Single PV systems are appropriate for irrigation loads under 4 kWh/day, whereas hybrid PV-Generator-Battery systems are useful for loads between 4 and 20 kWh/day.	[37]
Powell et al.	2019	Australia	Irrigation	Hybrid solar PV-diesel generator system	Experimental	• When considering discounted cash flow over a 25-year period for investment analysis, the internal rate of return is 23%, with a payback period of almost 5 years. • The addition of diesel generator will increase pumping	[51]

						capacity during summer season when crop water demand is high. Besides, the addition of solar PV system will lower the emissions as well as running cost. • By addition of battery back-up system will help to operate pump during cloudy days as well as during night.	
M. Chahartaghi and A. Nikzad	2020	Iran	Irrigation	PV water pumping system (PVWPS)		• The higher and lower exergy efficiency of the PVWPS are obtained 3.56 and 0.2% respectively. The system is capable of reduce 4.8 tones CO_2 emissions in each year.	[52]
B. Ali	2019	Sudan	Irrigation	Parabolic trough pump (PTP), concentrating dish pump (CDP), and PV pump (PVP).	Survey/Case study	• The levelized cost of energy of Photovoltaic pump is only 0.033 $/kWh which are less than thermal-based parabolic trough pump (0.075 $/kWh) and Concentration dish pump (0.062 $/kWh). • The solar pump's initial cost per KW of hydraulic power is just 1351 $, which is less expensive than the thermal-based parabolic trough pump's initial cost per kW of 4884 $ and the Concentration dish pump's initial cost per kW of 4072 $.	[53]
M. Niajalili et al.	2017	Iran		PV water pumping system	Survey/investigate/survey	• Although the life cycle cost of the PV	[54]

							system is just 65.6% of the cost of the regular pumping system, its starting cost is nearly nine times that of the conventional system. Following the aforementioned watering period, the conventional pumping system's final cost will be 1.56 times that of the PV system. • The initial cost of a PV system is equal to a conventional one after 9 years. After that point, the cost of a PV panel system will be higher than a normal pumping system.	
A. H. Yavuz	2020	Turkey	Irrigation	Solar Thermoelectric Generator Assisted Water Pump (STEGWP)	Simulation		• The energy cost of the PV panel is lower (0.72 $/W) than the Solar Thermoelectric Generator Assisted Water Pump (STEGWP) cost (2.87 $/W). Besides, STEGWP system will provide same efficiency as diesel system. Moreover, PV system provides better advantages than STEGWP.	[55]

2.2. Water pumping techniques for irrigation in Bangladesh

Water is a very crucial thing for irrigation. In Bangladesh, irrigation is mainly performed in the Barind area. In these regions, there are two different kinds of submersible pumps that are used for irrigation purposes. One is connected to the grid, and the other is powered by solar energy. In the next subsections, a brief description of these two types of pumps is provided.

2.2.1 Grid-connected submersible pump

In Bangladesh, farmers often obtain irrigation water from a variety of sources, including Deep Tube Wells (DTW), Shallow Tube Wells (STW), and Low Lift Pumps (LLP) owned by governmental and private entities. In the case of a private irrigation pump, the owner develops a system in accordance with his wishes, taking advantage of the area's poor socioeconomic conditions. The pump owner charges the farmer a substantial irrigation fee. Farmers may have to pay seasonal rent for pumps run on a private level. Due to the complexity of this system's irrigation exploitation, farmers must pay much higher irrigation fees. Regarding the level of irrigation water to be used, the equipment owner and the farmer continue to hold opposing views. Less water is often provided for irrigation by equipment owners. On the other hand, landowners want to get more water for the same amount of property. due to the landowner's belief that less weeding and tending entails more water. But he is unaware that, despite substantial water savings on weeding, it hinders crop tillering and lowers crop output. In the majority of traditional public irrigation management systems, irrigation fees or taxes are collected annually. A significant portion of the irrigation bill is typically lost each year. In these situations, BMDA has attempted to come up with an irrigation charge solution that is farmer-friendly. The BMDA started its mission while being propelled by DTW's diesel engine. In this arrangement, irrigation costs were quite high. Problems with diesel engines used to routinely limit crop production. The BMDA faced a significant problem in maintaining the irrigation management system, reducing irrigation water loss, and realizing irrigation charges. To address this issue, the authority started electrifying the DTW in areas where submersible pumps are used and where problems are significantly less frequent than in diesel-powered DTWs. Figure 2 displays a schematic diagram of an electrically powered submersible pump. The authority devised coupons for the irrigation management system and subsequently introduced a prepaid meter system for electrified DTWs. The prepaid meter system may be called the improved version of the coupon System. Now all the DTWs are electrified and running on a prepaid meter system. Under BMDA, there are 15796 grid-connected submersible pumps commissioned, of which 15496 are operational. Table 2 shows the distribution of zone-wise grid-connected submersible pumps used by BMDA [56].

Table 2
Number of zone wise grid connected submersible pumps running in Barind zone up to 2022

Serial No.	**Name of the water supply authority**	**Division**	**Name of zone**	**Number of commissioned submersible pumps**	**Number of running submersible pumps**
01	BMDA	Rajshahi	Rajshahi	2870	2829
02			Chapai Nawabgonj	1615	1575
03			Naogaon	4103	4085
04			Joypurhat	359	355
05			Bogura	284	283
06			Sirajgonj	160	152
07			Natore	301	297
08			Pabna	330	286
09		Rangpur	Thakurgaon	1431	1418
10			Dinajpur	1651	1630
11			Panchagarh	438	436
12			Gaibandha	460	460
13			Rangpur	699	681
14			Nilphamari	282	277
15			Kurigram	521	495
16			Lalmonirhat	292	237
Total				**15,796**	**15,496**

2.2.2 Solar-driven submersible pump

Solar water pumps are driven by either the electricity produced by photovoltaic (PV) panels or the radiant heat produced by solar energy that has been gathered. Operating a solar-powered water pump is more effective. Compared to pumps driven by IC engines or grid electricity, solar pumps have a less detrimental effect on the environment. A wonderful technological advancement that provides isolated communities with water access while also being socially and environmentally friendly is the solar-powered pump. For water supply in remote places, diesel engines and human resources are typically needed. Existing diesel and grid-powered water pumps are being replaced by solar ones since they have several advantages in terms of the environment, society, and economy. For reservoirs and irrigation systems, these pumps work well.

The photovoltaic principle is the foundation of how a solar pump operates. PV systems absorb radiant solar energy and convert it to electricity while a solar pump is operating. The entire system received an electricity supply as a result of this. The PV system's output of direct current is changed into alternating current by the pump's inverter, which powers the pump. To achieve the highest power point tracking, these inverters also modify the output frequency and voltage in real time in accordance with variations in sunlight intensity. When the sun's rays are weak, a mechanism called the solar pump controller is used to regulate the solar pump and prevent it from stalling. When the water tank is full, some sophisticated controllers incorporate a terminal for the float switch that allows the pump to be turned off. Additionally, they could have overvoltage protection. Bangladesh uses three different types of solar pumps, including:

- Solar deep tube well pump (SDTP)
- Solar low lift pump (SLLP)
- Solar dug well pump (SDWP)

The following subsections offer a brief explanation of each type of solar submersible pump:

Solar deep tube well pumps (SDTP)

Deep tube well pumps can be installed in huge wells and can lift up to 198 m of water. These pumps work as long as the well water is higher than 6 meters above the ground. When the sun is out, a pump raises the water all day long, and it is then stored in tanks for later use. The highest recommended pump depth is 50 m. A deep tube well pump powered by solar energy is shown schematically in Fig. 3. Essentially, Solar-powered water pumps function by converting photons from the sun into electricity to power the pump. It makes direct current (DC), which powers the motor that pumps water away from its source, using solar panels to harvest photons (units of light) from the sun. In addition to providing residential water, solar submersible pumps can automatically water and irrigate plants, flowers, and fields.

Solar low lift pumps (SLLP)

These pumps are used to draw water from ponds, canals that have been excavated, and streams. These pumps are typically not able to pump deep well water to very high elevations. The majority of the time, surface water irrigation uses low-lift pumps. The electricity needed to operate the centrifugal low lift pump is provided by solar panels. The header tank serves as a storage area for water, which is then used to supply water as needed for irrigation. Figure 4 displays a schematic of a low-lift pump powered by solar energy.

Solar dug well pump (SDWP)

Dug wells have been constructed in order to irrigate low-water use crops, including cauliflower, potatoes, chilies, and other vegetables. A towering overhead water tank and a solar-powered rainfall collection structure have both been constructed over the dug well. When it rains, the solar panel rainwater collection structure collects the rainfall and stores it in the well. A solar-powered pump then transfers the stored water to an above-ground tank, where it is used for irrigation. There is also room to use the additional water for groundwater replenishment in the water-stressed Barind tract. A schematic of a solar-powered drill well pump is shown in Fig. 5. Dug wells have been constructed in order to irrigate low water-use crops including cauliflower, potatoes, chilies, and other vegetables. A towered overhead water tank and a solar-powered rainfall collection structure have both been constructed over the dug well. When it rains, the solar panel cum rainwater collecting structure collects the rainfall and stores it in the well. A solar-powered pump then transfers the stored water to an above-ground tank where it is used for irrigation. There is also room to use the additional water for groundwater replenishment in the water-stressed Barind tract.

Recent research indicates that Bangladesh presently has 1.34 million diesel-powered irrigation pumps spanning 3.4 million hectares of land. The government intends to switch out these diesel-powered pumps for solar-powered ones in order to ensure 150 MW of electricity generation from the irrigation sector. In Bangladesh, a variety of governmental and non-governmental organizations support, run, and maintain solar irrigation pumps. Among them, Infrastructure Development Company Limited (IDCOL) installs the majority of solar-powered pumps. In the Rangpur division, the majority of solar-powered pumps are installed. A total of 2,899 solar-powered pumps have been placed around the nation, 2,145 of which are operating in the Barind zone. The BMDA, IDCOL, BADC, BREB, RDA, and BARI all operate solar pumps in the Barind zone. Table 3 lists the many organizations' running solar pumps in the Barind zone [56].

The fact that most of these solar pumps currently sit idle for a significant amount of time due to the restricted irrigation season in Bangladesh (110–150 days per year) is a crucial aspect of solar irrigation. Some organizations have begun putting that enthusiasm to use by offering more agricultural services. The energy generated cannot be fully absorbed despite the development of alternative solar power sources. Another alternative for selling surplus energy is to connect solar panels to the national electrical grid. The grid connection strategy and the SDC-SOLAR project in collaboration with IDCOL have already received approval from the Bangladeshi government. This project includes the experimental operation of a few grid-connected solar irrigation pumps.

Table 3
Number of zone-wise solar pumps running in Barind zone up to 2022

Division	**Name of zone**	**Number of solar pumps**					
		BMDA	**IDCOL**	**BADC**	**BREB**	**RDA**	**BARI**
Rajshahi	Rajshahi	86	0	0	3	1	4
	Chapai Nawabgonj	90	0	0	0	0	0
	Naogaon	441	1	0	5	1	0
	Joypurhat	4	0	0	0	0	0
	Bogura	7	88	0	12	5	4
	Sirajgonj	0	69	0	12	0	0
	Natore	64	0	2	15	0	0
	Pabna	0	0	0	0	0	0
Rangpur	Thakurgaon	13	222	9	2	0	0
	Dinajpur	3	396	8	7	0	4
	Panchagarh	2	94	4	3	1	0
	Gaibandha	16	48	0	0	1	0
	Rangpur	39	207	40	21	1	0
	Nilphamari	8	0	8	0	0	0
	Kurigram	10	0	0	0	1	0
	Lalmonirhat	9	2	54	0	1	0
Total		789	1127	125	80	12	12
Grand Total		2,145					

The aforementioned information has revealed that a solar deep tube well is capable of pumping water to any irrigation head and position. Additionally, a solar low lift pump can be used to pump water out of ponds, canals, rivers, etc. Therefore, this form of solar irrigation pump is only appropriate for irrigation from a low head and where the presence of rivers, canals, ponds, etc. is present. In addition, a solar-powered well pump is utilized to draw water from a well that is actually filled with rainwater. This kind of solar pump is used to supply water at low levels. This is the main distinction between the solar water pumping systems that are available in Bangladesh. The comparative analysis of diesel- and electricity-operated pumps with solar PV pumping is presented in Fig. 6.

3. Effect of various parameters on irrigation system

The effect of sunshine hours and temperature on solar irrigation is presented in **Fig. 7**. It has been found that the variation of daylight and sunshine hours is increases from January to July, then decreases in of December. The temperature of the atmosphere has a significant impact on the vegetative development and reproduction of any crop. Rice, for example, requires temperatures between 25 and 30 degrees Celsius for optimal photosynthesis [57]. Rice production will be reduced if the ambient temperature exceeds the recommended range. The average Boro rice yield was observed to be reduced by 7.5 percent and 20 percent, respectively, when the temperature was raised by 3°C and 5°C to cover the maximum range [58]. But, while decreasing the temperature by 3°C and 5°C less than the minimum value, the decrease in the average Boro rice yield was by 5.2% and 17.7%, respectively. Figure 8 indicates monthly sun insolation and rainfall at six different vital regions of Bangladesh [59]. The average brilliant sunshine hours vary from 6 to 9 hours per day which is one of the most vital top-notch warning signs to the viability of sun irrigation obligations. Underground water has become a major source of water for irrigation due to the unavailability of river water in dry seasons [60]. Moreover, the variations in average rainfall from the month of January to December throughout the year are due to the change in temperature. The temperature from January to July is gradually increasing, and then it is decreasing towards December. On the other hand, the average rainfall has the same trend as nature, like temperature. Thus, during the Boro rice (major crop in Bangladesh) cultivation, the amount of rainfall is very low (November to May); therefore, irrigation water is required for Boro cultivation as well. Crops require a sufficient amount of water to grow. Boro is often reliant on irrigation, whereas Aman is mostly dependent on rainfall during the monsoon season. Rainfall is being recorded by the Bangladesh Metrological Department in various parts of the country [61]. The average rainfall ranges from 110 to 580 mm, with May to October accounting for almost 90% of total rainfall. As illustrated in **Fig. 8**, the nation has had almost no rain for nearly half a year. In most parts of the nation, the yearly average rainfall has been declining [62]. In 2021, the annual average rainfall in Rangpur was 597 mm, compared to 730 mm in 2005 [63]. A similar trend was obtained for other locations as well. Floods significantly impact crops in the impacted areas; for example, the 1988 flood resulted in a 45 percent drop in agricultural production [64]. Since 1971, the nation has been hit by seven major floods [65]. A protracted flood may cause Aman planting to be delayed and harmed. Every year, flash floods in the Haor districts damage numerous Boro agricultural farms. However, it has a beneficial consequence in that flood water transports sediments that enrich agricultural areas during floods.

4. Problems associated with solar irrigation systems and challenges regarding implementation

Solar-powered water pumping systems (SPWPS) have gained popularity as power shortages increase in rural and remote areas due to their ability to run independently without dependencies on other energy sources like diesel and power from grid electricity. The effectiveness of the SPWPS has been the major focus of recent studies. It has been found from various literature that the solar irrigation system has various shortcomings which are listed below:

- The discontinuity of supply i.e., nature dependency is the main obstacles towards its operation.
- The solar panel remains idle most of the time of the year rather than irrigation season.
- The farmers are comparatively less interested to use solar irrigation pumping system because of high energy bill and nature's control water supply.
- The larger space is required for installation of the solar panel. Moreover, impossible to operate at foggy and cloudy weather as well as at night hour.
- The installation and initial cost is higher than that of diesel or electrical energy operated pump. In addition, maintenance cost is higher and regular maintenance is necessary.

Despite the clear benefits of solar technology, stakeholders, communities, and local governments sometimes feel a lack of knowledge of the installation's technical capabilities. Installing a solar irrigation system requires consideration of several factors, including cost, material accessibility, and maintenance assistance. The installation of such systems in rural locations is constrained by a lack of awareness about these elements. Local groups are interested, but they lack management, financial, and technical skills. To play a significant part in the spread of technology, cooperatives and microfinance institutions must take it forward [66]. The solar irrigation systems in Bangladesh do not connect to the grid. This results in a 50–60% loss of solar energy installed. The nation has a net metering policy that permits renewable projects to sell power to distribution companies, but the current regulation stipulates that the system must have a capacity of more than 10 kWp, which is a prerequisite for systems that are privately funded. Officials stated in a previous article that the government had no interest in adding small-scale solar PV systems to the grid to prevent instability issues [67].

Moreover, because qualified individuals go to cities in pursuit of employment, solar specialists are not accessible in rural areas. This indicates that repairs take time and money. More technicians need to be trained. Costs are considerably higher than they should be until then because of higher wages and related travel expenses to repair systems in remote areas. To remove these obstacles, it is necessary to educate all parties involved on the best ways to encourage the use of the technology as well as increase awareness among local governments, agencies, and communities about the advantages of this technology and government-provided subsidies. Farmers, government agencies, and private companies must all be involved in all phases of the process, from needs analysis through building and monitoring to designing water management strategies. There are various negative effects of using a solar SWP system, like the inability to operate in foggy and cloudy weather. Moreover, the initial cost of a solar pump is higher than that of a diesel or electrically operated pump. On the other hand, a larger space and regular maintenance are necessary for solar panels. The discontinuity of supply, i.e., nature's dependency, is the main obstacle to its operation. The farmers are comparatively less interested in using solar irrigation pumping systems because of the natural control of the water supply. Moreover, the solar panel remains idle most of the year, of the year other than during irrigation season. Thus, there are many challenges associated with the implementation of the solar irrigation program in Bangladesh, which are summarized in Fig. 9.

5. Materials and Methods

5.1 Proposed model with its component's details

The hybrid solar PV and pyro-oil generator with battery storage backup system comprises a solar PV array, a diesel generator, a charge controller, a battery bank, a inverter and a submersible pump, as presented in Fig. 10. The tire and/or plastic waste-derived oil for running the pyro-oil generator will be obtained from a mini pyrolysis unit. The diesel generator converts pyro-crude oil fuel energy into mechanical energy. The mechanical energy was then converted into electrical energy by means of an electrical generator. The pyro-oil generator will supply electricity to meet the load and charge the battery at the same time through the rectifier when the solar panels and the battery can no longer meet the load to run a submersible water pump. The pyro-oil generator is mainly used to meet the load when there is no output power from the solar PV array.

The output power of a generator is always termed in kVA, and its value to drive a 2 HP pump is 4 kVA, which has been calculated as follows:
2 HP = $(2 \times 0.746) = 1.492$ kW;

Actual power (kW) / power factor (pf) = apparent power (kVA);

The apparent power of the generator = $1.492/0.6 = 2.486 \times 1.5 = 3.73 \approx 4$ kVA;

Considering diesel generators have a power factor of 0.6 and AC motors have a startup factor of 1.5.

The solar array is the main source of electricity for the submersible water pump in the proposed research project. The experiments under the project will be conducted by installing a 2400 Wp (watt-peak) solar panel to drive a 2 HP capacity single phase AC submersible pump. In this proposed system, 8 nos. battery banks with a capacity of 100 Ah each may be used. The battery bank may be used as energy storage, which will be charged by solar energy during the daytime and discharged at night. Inverters are used to supply AC control from DC sources on sunlight-based boards or batteries for the proposed system. Moreover, the controller protects the system by turning it off when the tank is full. A charge controller also keeps batteries from overcharging and regulates the voltage and current coming from the solar panels transfer to the battery. A 96 volt, 6-kVA charge controller (AC supply) may be used in the proposed system. In the proposed investigations, a 2 HP single-phase AC motor submersible pump will be used to lift water. During sunny day, the pump is operated through the solar PV panel, but, at night, the pump is operated by means of batteries first and then by a pyro-oil generator. Thus, a continuous supply of water is possible in the proposed hybrid solar and renewable energy systems. Moreover, the idle time of operation can be minimized by providing electrical energy to the nearby village. On the other hand, a pyro-oil generator can be used, which will be utilized at night and on foggy and cloudy days in order to provide a continuous supply of water. The proposed system is capable of minimizing the natural dependency of the solar irrigation system. The system is suitable for off-grid as well as on-grid applications. Moreover, pyrolytic oil is renewable and is used to run the pyro-oil generator, which can help to utilize the off-sunshine periods. Therefore, the proposed model could reduce the dependency on fossil fuels and/ or the national power grid. Moreover, it is capable of helping the United Nations achieve one of its vital sustainable development goals. The attracting feathers of the proposed water pumping system are summarized in Fig. 11.

Finally, without hesitation it can be concluded that the proposed solar irrigation system could plays a great role for maintaining sustainable environment.

5.2 Techno-economic evaluation of the proposed project

The cost structure of the required components and expected outcomes of the proposed project are presented in Table 4. It has been found that the total initial cost of the proposed project is 10,334.87 dollars. The major components of the proposed project are PV panel cost, battery cost, pyrolytic oil generator cost, and pyrolytic oil plant cost. Moreover, it has been found that the working period of the project is 20 hours per day and capable of providing 360 m^3/day of discharge. The average time for rice cultivation is 5 months, and the average water requirement for the cultivation of one-hectare of rice is 4,000 m^3 per season (5 months). Thus, the proposed project is capable of cultivating 13.5 hectares (53 bigha's) of land for rice cultivation. The watering cost of rice cultivation on 53 bigha of land is 978.38 dollars through electricity or a diesel-operated pump. Therefore, the proposed project could save this amount of money during the irrigation season. Moreover, this project is capable of generating 80 kWh/day of electricity during the off-season period. The revenue of 3,052.8 dollars per year could be earned by selling electricity to the nearby localities, which are far away from grid electricity. The techno-economic feasibility of the proposed hybrid solar irrigation project is presented in Table 5. It has been found that the total life cycle cost (TLCC) of the 20-year project is 14,377.32 dollars. The revenue earned from the project from irrigation and electricity sales is 19,567.6 and 28,492.8 dollars respectively. The calculation formula with explanation is provided in Table A1.

Table 4
Required components cost structure and expected outcomes of the proposed project

Sl. No.	Required components cost structure of the proposed project	Unit	Values
1.	4 kVA to 6 kVA Diesel generator (1 No.) including installation	$	922
2.	2400 to 4800 Wp (watt-peak) solar PV array including installation cost	$	2,307
3.	2HP single phase AC submersible pump (1 No.) including charge controller, inverter, electrical wire etc.	$	920
4.	Battery of capacity 100 to 200Ah each (8 Nos.)	$	1,569
5.	Mini pyrolytic plant (1 No.) including installation	$	3,692
6.	Miscellaneous accessories	$	923
		Subtotal	10,334.87
Expected outcomes of the proposed project			
7.	Project life time	year	20
8.	Discharge capacity	m^3/day	360
9.	Working period	hour/day	20
10.	Water requirement for one-hectare rice cultivation	m^3/season	4,000
11.	Average time for rice cultivation	month	5
12.	Cultivable land (rice)	hectare (53 bigha)	13.5
13.	Cost of diesel or electricity operated pump	$/bigha/season	19
14.	Total cost for diesel or electricity operated pump (for 53 bigha land)	$/season	979
15.	Off-season time utilization of the proposed project (7 months)	kWh/day	80
16.	Revenue from selling electricity to the nearby village of remote area during off season period (considering transmission loss)	$/year	1,781

*1 USD = 108.35 BDT (as on February 5, 2023)

Table 5
Economic feasibility analysis of the proposed solar irrigation project for Bangladesh

Components	Unit	Value
Cost		
Initial investment cost	$	10,334.87
Maintenance and operating cost (feed material collection, transportation and preparation cost for pyrolysis plant)	$	4,042.45
Project life time	year	20
Total life cycle cost (TLCC)	$	14,377.32
Tax paid on profit	$	7,209.06
Benefits		
Profit	$	40,851.34
Revenue	$	48,060.4
Net cash flow	$	8,362.66
Investment Payback Period (IPBP)	year	7.04
Internal Rate of Return (IRR)	%	21
CO_2 reduction potential	ton	197.1

Our findings demonstrate that, in comparison to conventional irrigation techniques, the suggested system may successfully meet the water requirements of crops while consuming less energy and emitting fewer greenhouse gases. Additionally, we conducted a cost-benefit analysis of the system, accounting for the initial capital cost, the maintenance cost, and the energy return. Our analysis demonstrates that the system can deliver a positive return on investment over the long term, making it a workable and sustainable solution for small-scale farmers and rural communities. The investment payback period of the 20-year project is only 7.04 years, whereas the internal rate of return (IRR) is 21%. The CO_2 reduction potential of the project is 197.1 tons throughout its lifetime. That's the result of the economic feasibility of the project, proof that the project is economically as well as environmentally feasible, which will be a smart guideline for the researchers as well as for the investor. It has been found from relevant literature that the main disadvantages of the conventional solar irrigation system are its power instability and dependence on nature [68]–[70]. In this regard, the proposed hybrid model could play a great role in irrigation and electricity supply to the nearby village. Therefore, it can be said without any doubt that the proposed solar-powered irrigation system has the potential to promote sustainable agricultural methods, reduce energy consumption and carbon emissions, and benefit farmers and rural communities economically. As a result, more research and development are needed to enhance, scale up, and lower the cost of the system. The key findings of the review work are presented in Fig. 12.

6. Government policy and initiatives for successful implementation of solar irrigation pump

Bangladesh's government has been giving priority to renewable energy to secure the country's energy from both sustainable (solar, wind, hydro, biomass, etc.) and conventional (oil, gas, coal, etc.) sources. As a result, various renewable energy-based schemes have been initiated that could be beneficial as well as secure, reliable, and affordable for its people [71]. In this regard, BPDB and IDCOL (two major renewable energy implementing institutions) have taken various steps to implement renewable energy-related projects to promote the energy efficiency of the country [71], [72]. Moreover, the installation of solar irrigation pumps could be an effective way to reduce the dependency on fossil fuels and grid electricity. Diesel fuel is currently the most widely used fuel in the country. About 1.12 million tons of diesel fuel are imported by the country each year for irrigation. In order to make diesel cheap for irrigation, the government of Bangladesh typically offers subsidies, which adds to the burden on the nation. It would be beneficial to use solar irrigation in this case. Not only will it reduce pressure on the economy, but farmers will also be encouraged to cultivate more land through irrigation [73]. Therefore, it increases crop production and helps rural and national economies alike. The Bangladeshi government established the Infrastructure Development Company Limited (IDCOL) in 1997 to fill the financial vacuum for medium- to large-scale infrastructure and renewable energy projects in Bangladesh. It has found that until October 2019, IDCOL had installed 1,630 solar irrigation pumps and had targeted installing 50,000 solar irrigation pumps by 2025. Again, the company readjusted the target to install 10,000 pumps by 2027 and has managed to install only 1,515 pumps so far [72]. It has been found that the largest organization for solar irrigation pump installation is IDCOL (1,007 nos.) and smallest organization for solar irrigation installation is RDA (10 no.). On the other hand, BMDA is the second-largest organization for solar irrigation pump installation, having implemented 267 submersible pumps [37].

The target of the government is to replace diesel-operated pumps with solarow korana ones and ensure 150 MW of energy for the irrigation sector [22]. On the other hand, the Bangladesh Rural Electrification Board (BREB) plans to sell 2,000 environment-friendly solar irrigation pumps to marginal farmers, which is now at implementation stages. Some other organizations are also working to install solar irrigation systems [74]. BREB will be selling the pumps at 70 percent of the project cost under a 10-year installment facility. Power Division and IDCOL sources said, 43 percent of the cost of agriculture is spent on irrigation [74]. The government has started several initiatives to reduce agricultural costs. A solar pump can provide continuous irrigation water for 20–25 years [75]. The government is giving subsidies of Taka 75 to 80 crore on diesel for irrigation [75]. Still, during the agricultural season, a diesel deficit is artificially created, which leads to the soaring price of diesel locally. On the other hand, 310 lakh tons of carbon dioxide are emitted annually due to diesel-powered pumps [75]. Therefore, solar irrigation pumps will save electricity and diesel costs in addition to protecting the environment.

The renewable energy target of Bangladesh government till 2030 and the number of solar irrigation pumps (SIP) with their installed capacity of various organizations are presented in **Fig. 13**. It has been found that the main focus of the government is on solar, wind, and biomass, among various renewable energy sources. Moreover, by the year 2030, the target of renewable energy generation will be 4,189.98 MW, whereas it was only 1,315.98 MW by the year 2022. Moreover, the primary focus of the government to attain this goal is solar energy, whose target value by the year 2030 is 2,124 MW. The maximum SIP installed by IDCOL is about 1,600 with a capacity of 45 MWp. The second and third largest organizations for SIP installation are BMDA and BADC, respectively.

The initiatives and policy framework of the Bangladesh government for successful implementation of the solar irrigation program are presented in **Fig. 14**. It has been found that various roles should be performed by the government for its successful implementation, like financial support, collaboration with industry and non-government organizations (NGO), training, policy, ethics, etc., for attaining the 4th revolution goal. Moreover, various policies should be adopted for effective implementation of the SIP program, such as incentives and subsidies, collaboration with industry, universities and NGO’s, funding from international agencies, scientific support, environmental audits, etc. Therefore, the adoption of this framework could play an important role in the effective implementation of solar energy-based program in Bangladesh. It has been observed that most people don’t have enough knowledge regarding solar energy-based irrigation. Thus, a sufficient amount of seminars, conferences, training programs should be arranged to motivate village people regarding this.

Through numerous channels and sponsored programs, the government must encourage Bangladeshi farmers to install and utilize solar energy-based irrigation technologies at affordable prices. Solar energy technologies are used and installed with the assistance of the Bangladesh government's energy policies and desire to minimize CO_2 emissions, which is beneficial for long-term sustainable development. A strategy will be needed to achieve Bangladesh’s sustainable energy objectives. Fossil fuels will be gradually phased out by the government. More infrastructure integration, capacity creation, and investment will be needed for the generation and use of solar energy in the future. In order to consume only the appropriate quantity of solar energy, adjust agricultural subsidies. In the last ten years, China rose to prominence as a producer of solar energy-based irrigation. Bangladesh's geography calls for worldwide encouragement of renewable energy loans and financial help for the advancement of solar energy-based irrigation technologies. Although solar energy benefits society, the economy, and the environment, its development is hampered by its high installation costs. Therefore, in Bangladesh, significant R&D work should be done in order to enhance solar energy-based irrigation and lower production costs.

7. Conclusions and future recommendations

The water crisis is turning acute in many areas of the Barind tract and remote areas of Bangladesh to maintain a smooth supply for irrigation and drinking purposes. The main objectives and aims of the research work are to find out sustainable pumping for irrigation and drinking purposes. Moreover, the present situation of solar PV water pumping systems has been critically reviewed. It has been determined that conventional pumping and solar PV water pumping systems have various disadvantages. It has been found that various parameters are associated with solar PV for sustainable pumping, such as temperature, solar radiation, rainfall, etc. The contribution of different organizations in this sector has also been investigated. Meanwhile, government policy and initiatives regarding sustainable solar PV water pumping systems have been explained briefly. The main disadvantages of the conventional solar irrigation system are nature/s dependency, intermittency of power supply, high initial cost, etc. Moreover, during the summer season, smooth supply of water for irrigation as well as drinking is quite much more impossible because of huge demand on the national grid or fossil fuels. Besides, most of the energy comes from fossil fuels, which will vanish in the near future (expected by 2040). Thus, we have to think about available alternative energy sources such as solar energy, wind energy, bio-crude oil, etc. In this regard, the hybrid solar energy-based water pumping system could be an emerging solution. The standalone hybrid solar PV and pyro-oil generator with battery backup system will maintain continuous water supply for irrigation and household purposes throughout the year. However, the implementation of hybrid solar PV and pyro-oil generators with battery backup systems will help us reduce our dependency on fossil fuel-based energy or national grid power. The proposed project comprises only renewable sources, has the potential to save fossil fuel combustion, and helps to ensure a pollution-free, healthy environment, which is one of the vital sustainable development goals of the United Nations. It is expected that if the proposed technology is implemented on a larger scale over different areas of Bangladesh, the power crisis would be relieved by 50% for irrigation and pure drinking water supplies, and hence the oil import bill will be reduced as well, which eventually helps to improve the socio-economic development of Bangladesh. Moreover, the techno-econo-environmental analysis of the project proves that the proposed project is sustainable as well as feasible. The total life cycle cost and internal rate of return of the project were found to be 14,377.32 dollars and 21%, respectively. Moreover, the investment payback period of the 20-year project was found to be only 7.04 years. Besides, the CO_2 reduction potential of the proposed project is reported as 197.1 tons. Therefore, finally, without any hesitation, it can be said that such a project could be an attractive and emerging way not only for sustainable irrigation but also provide a scientific guideline for the investor and researchers as well. The practical implementation of this project is not so much smooth, and that's the scope of future research. The authors are working on evaluating the experimental performance of this project, and that is our future research work. Future studies may be necessary to examine how operating parameters affect performance of solar water pumping system. The sustainability analysis of the proposed water pumping systems can be investigated in future studies.

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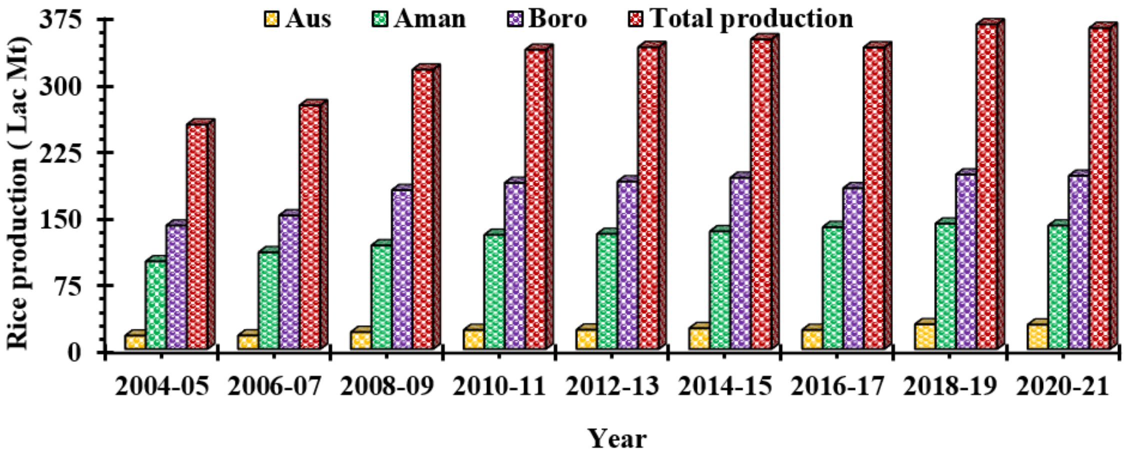
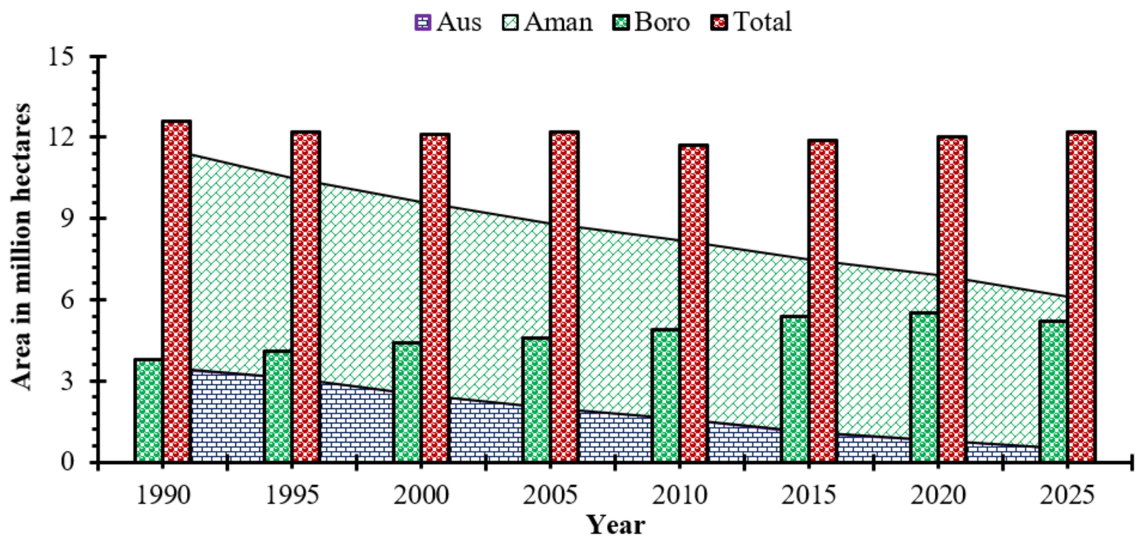
Figures



(a)



(b)

Figure 1

(a) Rice production (Aus, Aman and Boro) scenario and (b) Average area used for rice production in million hectares [45].

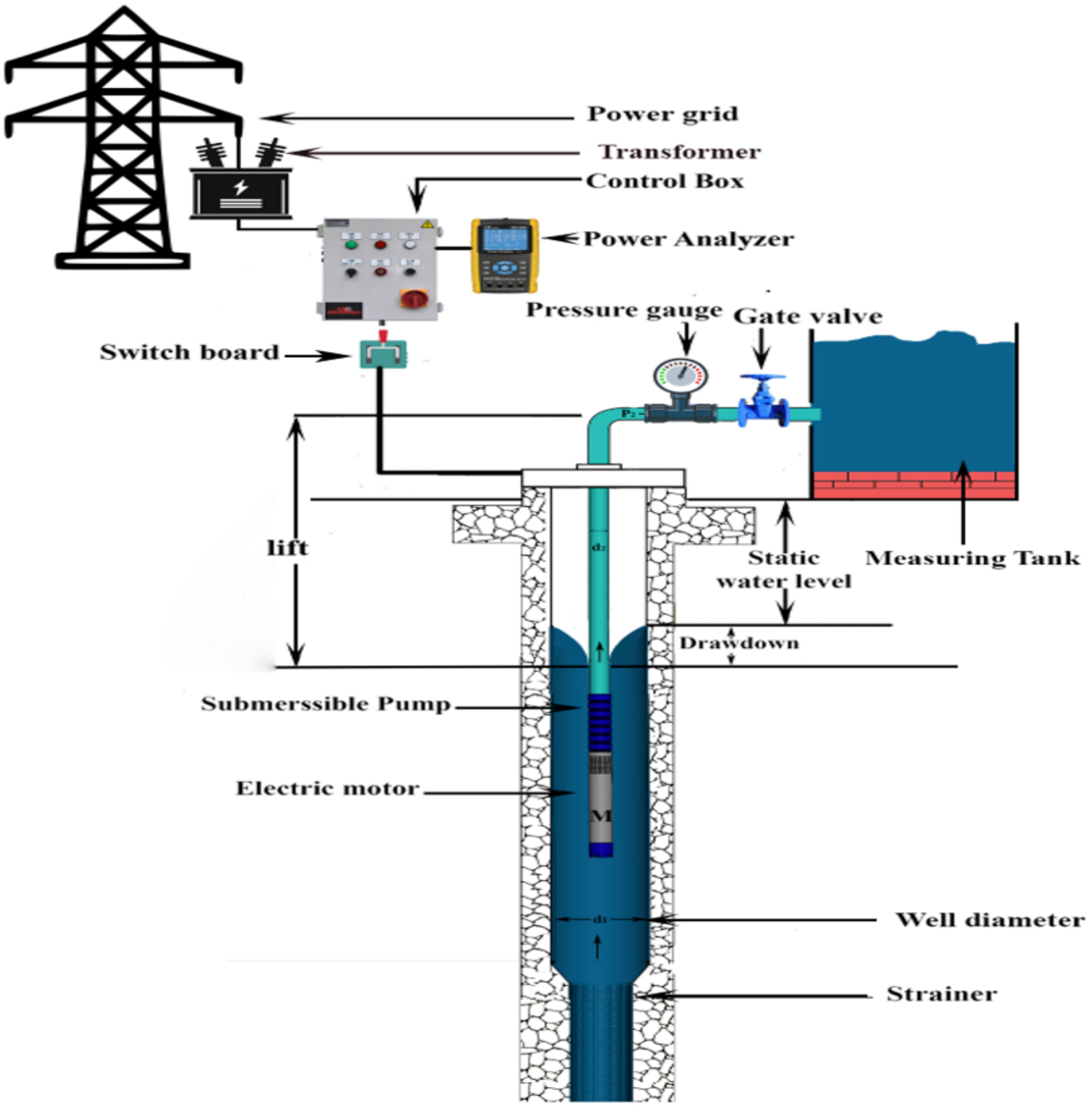


Figure 2

Schematic diagram of grid electricity driven submersible pump

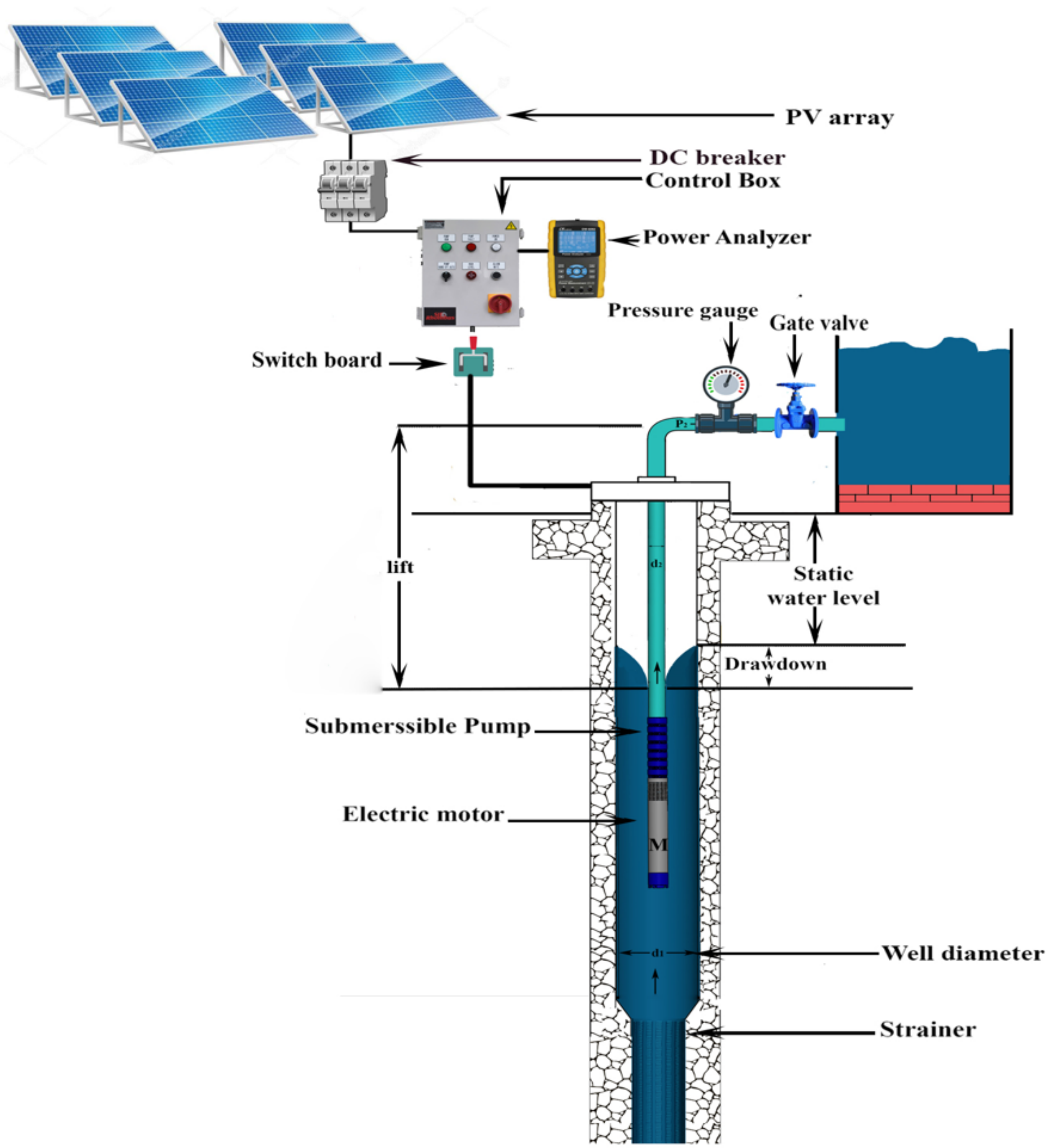


Figure 3

Schematic diagram of solar power-driven deep tube well pump

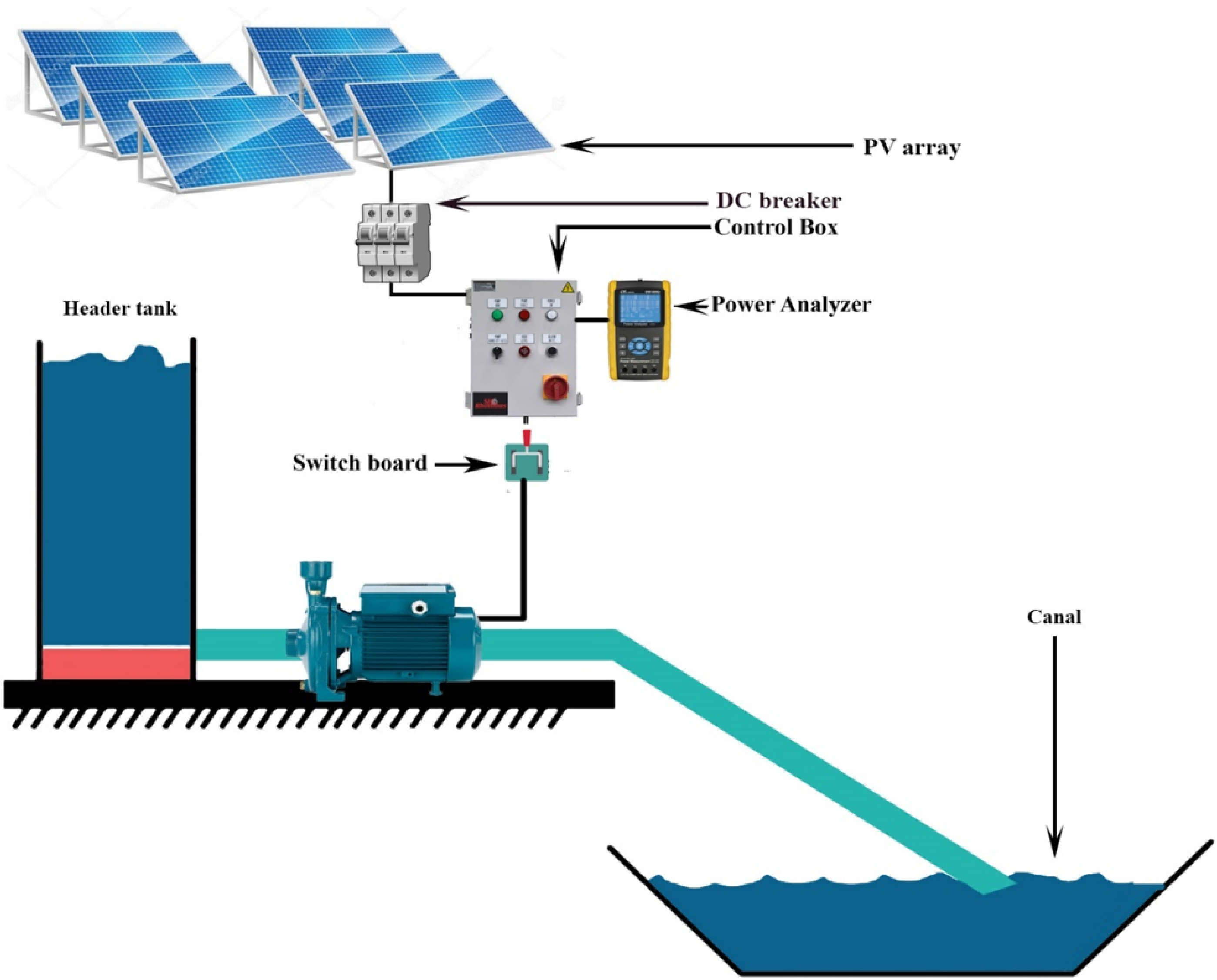


Figure 4

Schematic diagram of solar power-driven low lift pump

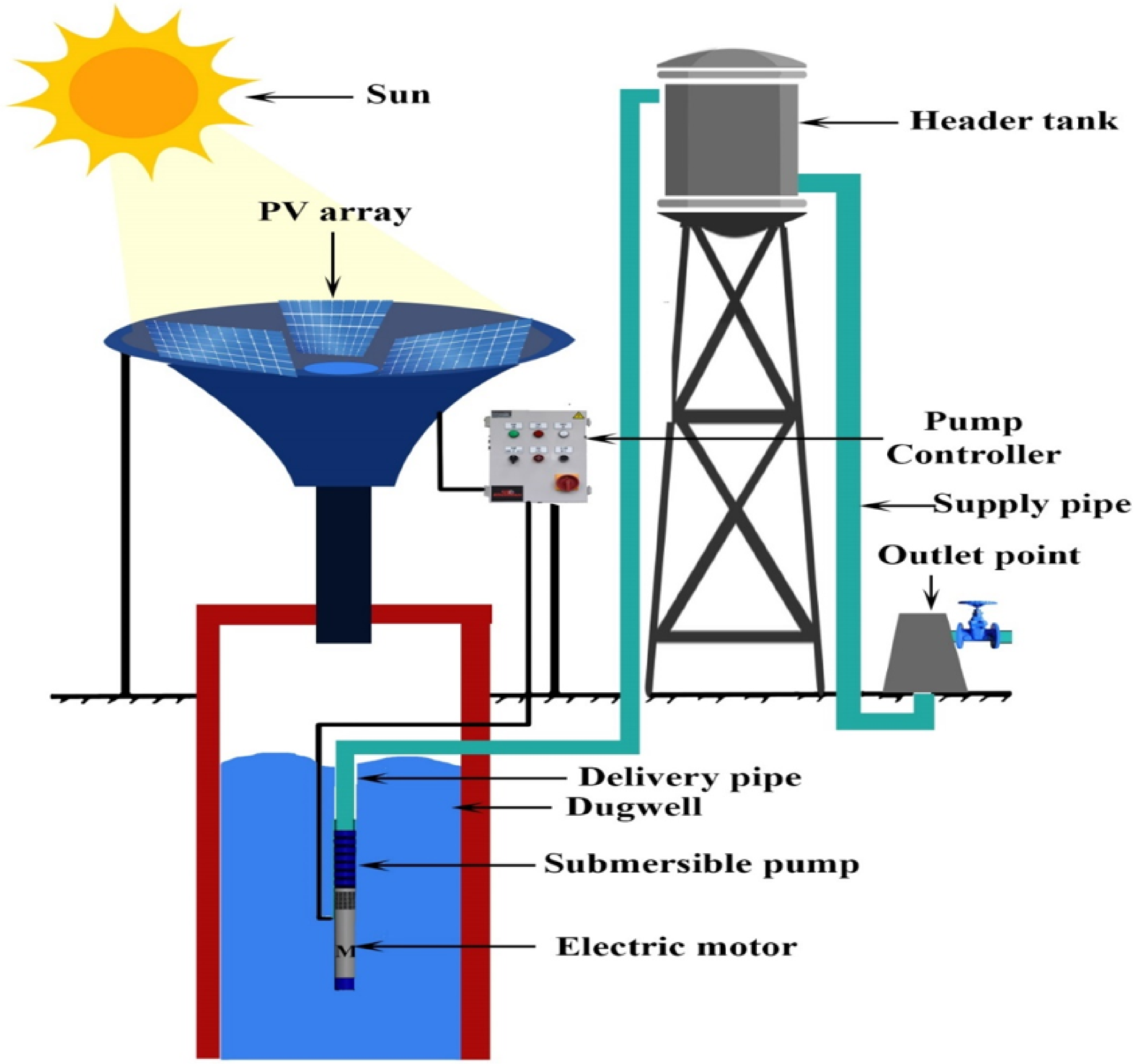


Figure 5

Schematic diagram of solar power-driven dug well pump

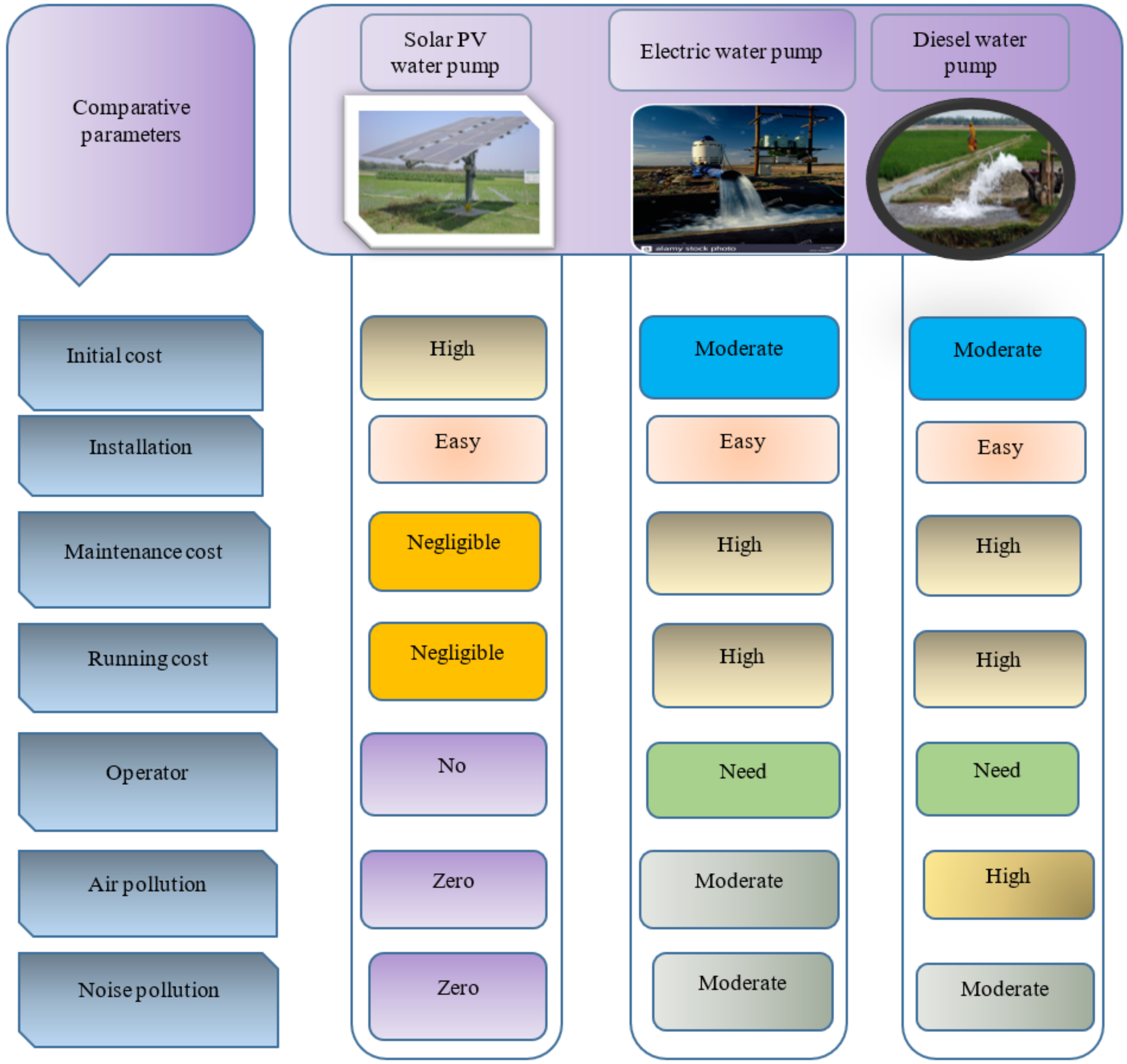


Figure 6

Comparison among solar PV water pump, electric water pump and diesel water pump

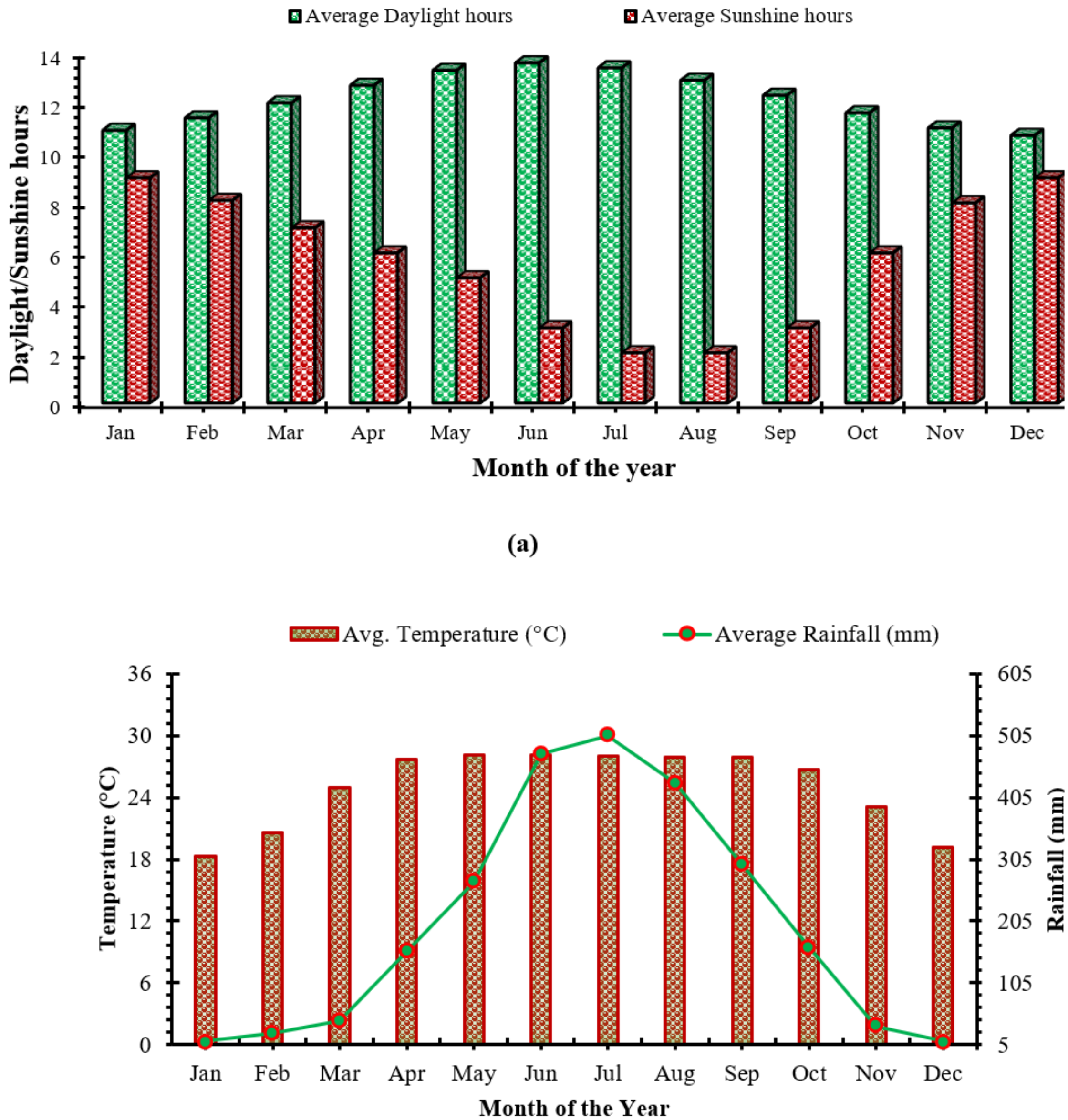
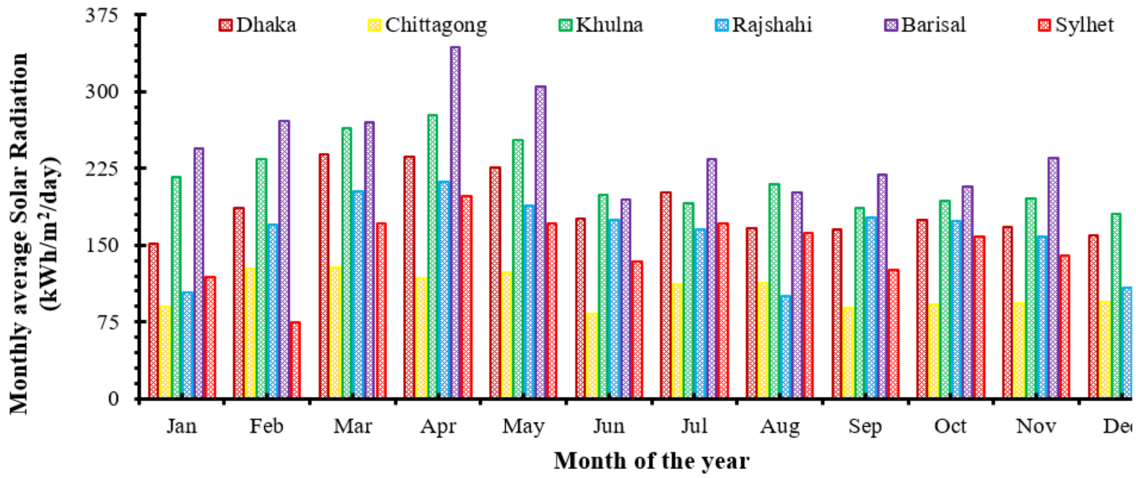


Figure 7

Effect of monthly sunshine hours, and (b) temperature on irrigation



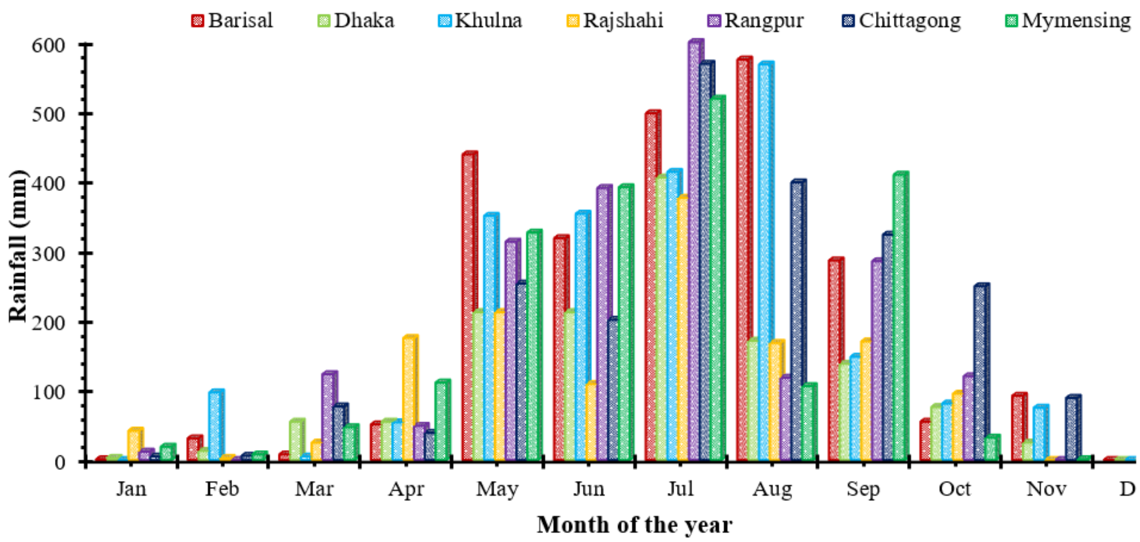


Figure 8

The division-wise (a) solar radiation, and (b) rainfall at different location and times of a year in Bangladesh.

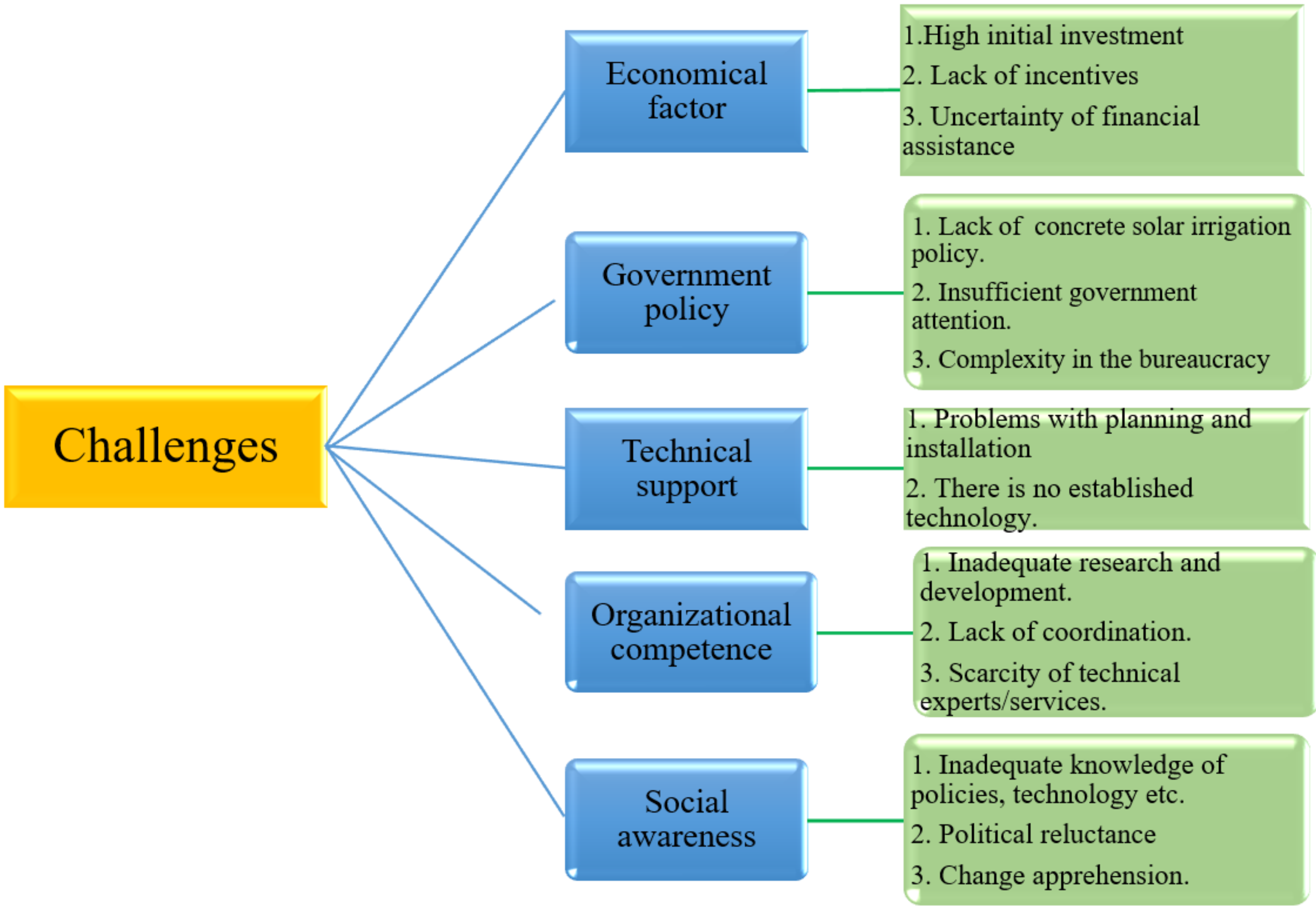


Figure 9

The challenges associated with successful implementation of solar irrigation program in Bangladesh

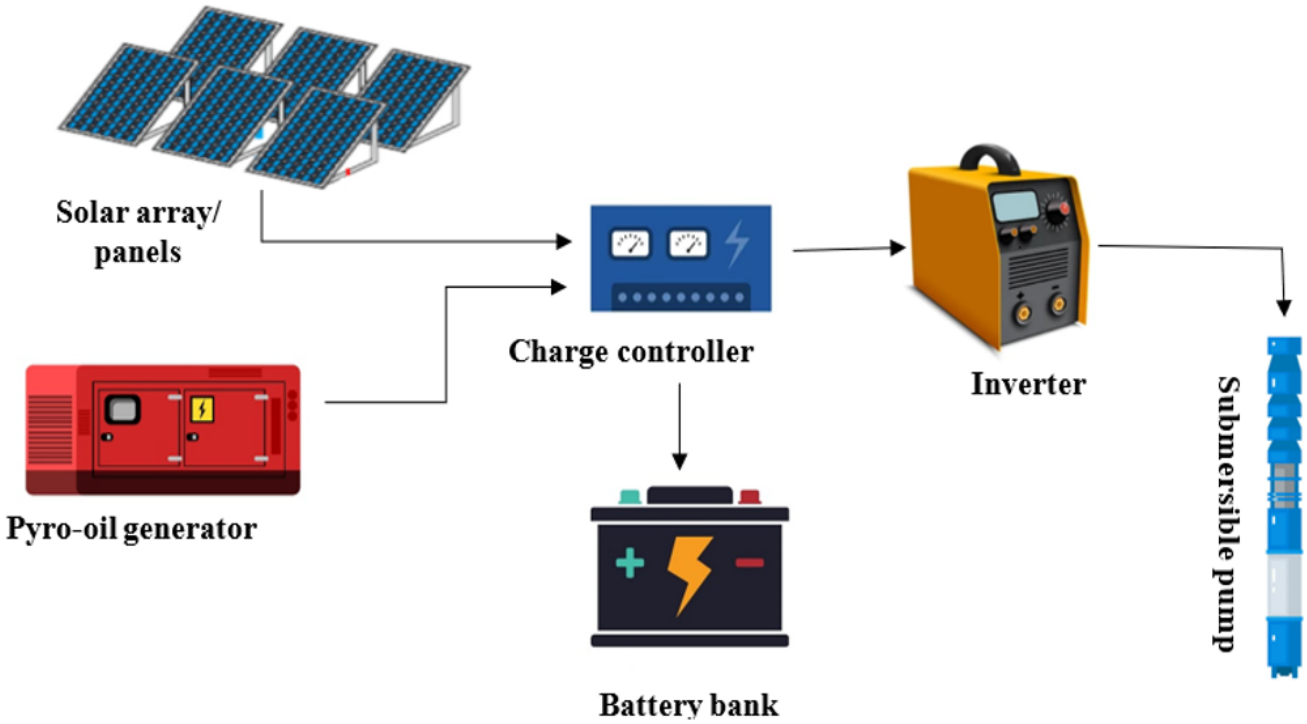


Figure 10

Proposed model of hybrid solar water pumping technology

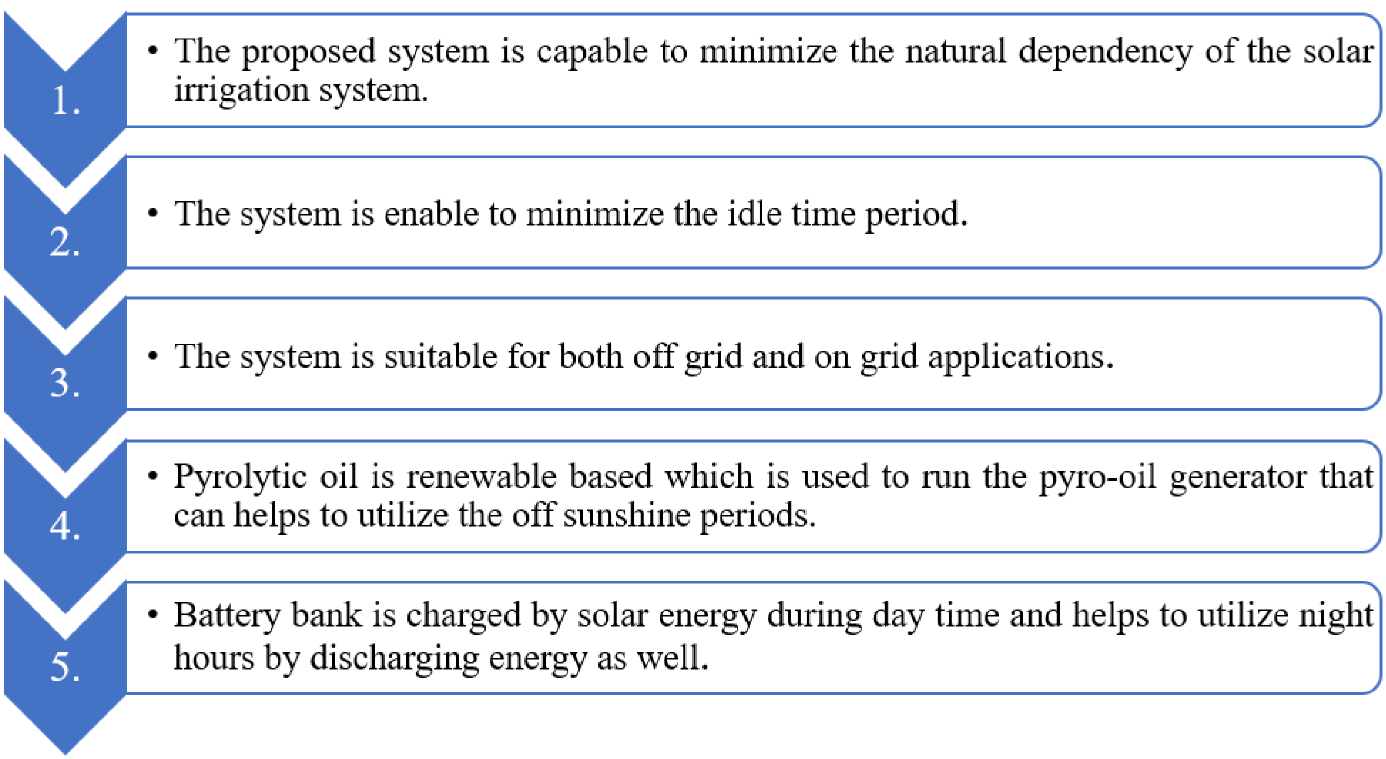


Figure 11

Expected outcomes of the proposed project

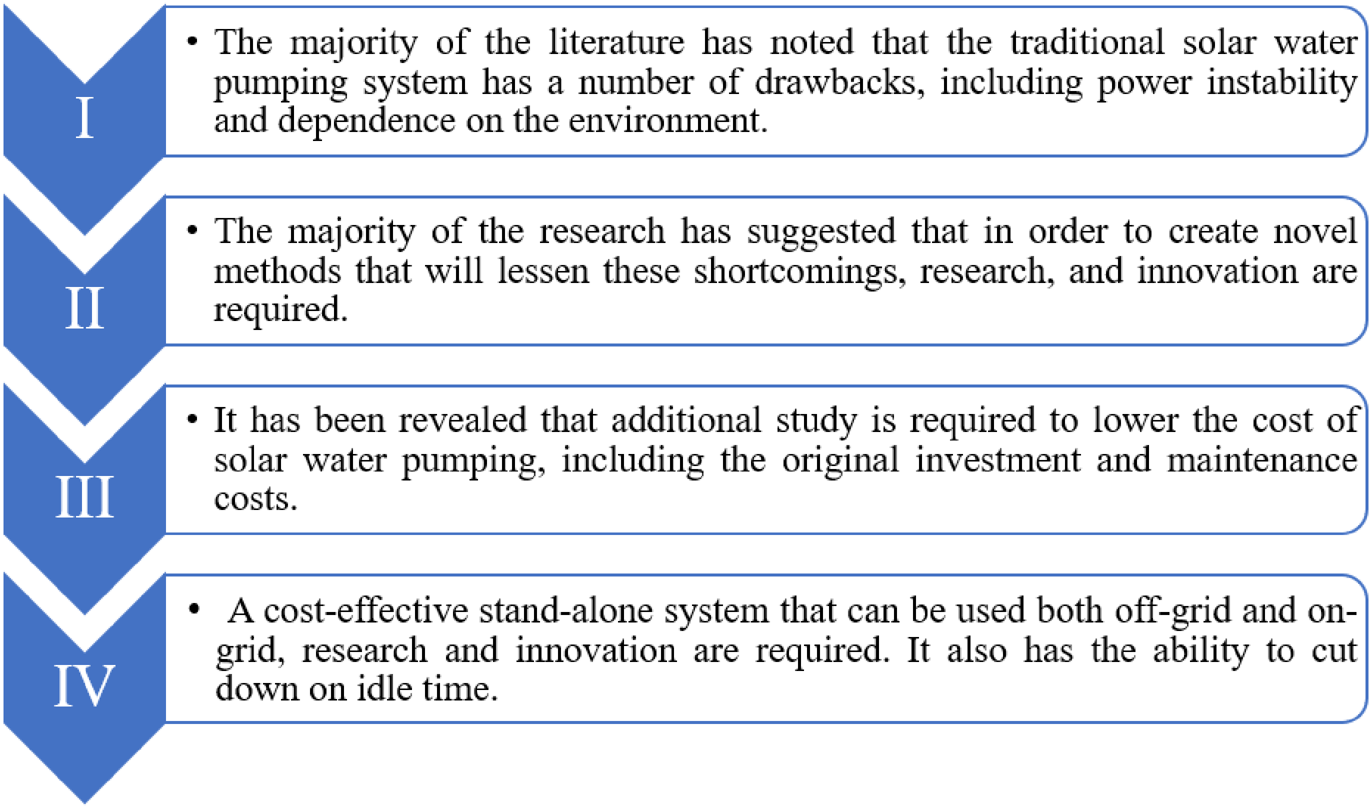
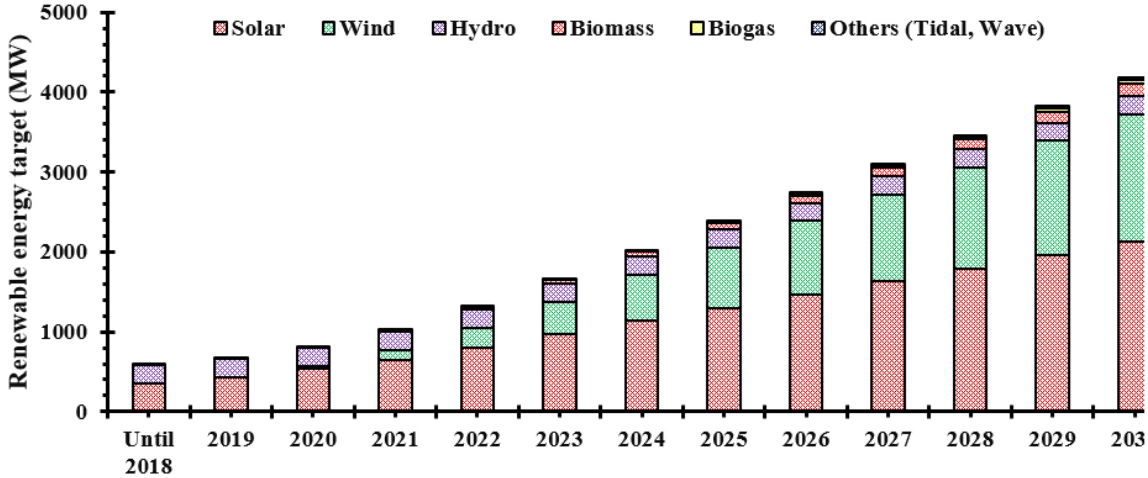
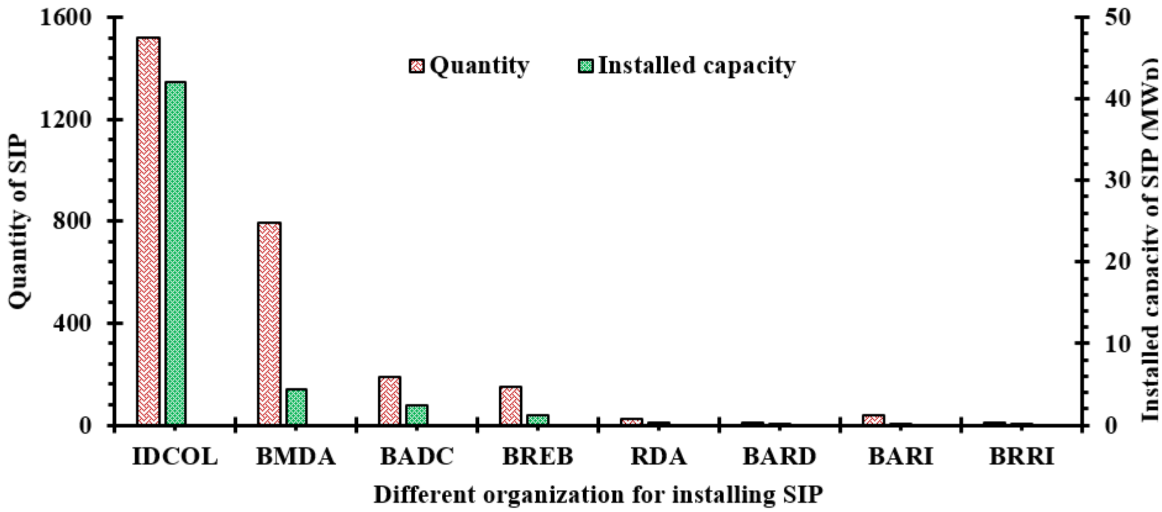


Figure 12

The key findings of the review work



(a)



(b)

Figure 13

(a) Year wise renewable energy target of Bangladesh government and (b) Number of SIP installed by various organization with their capacity [22]

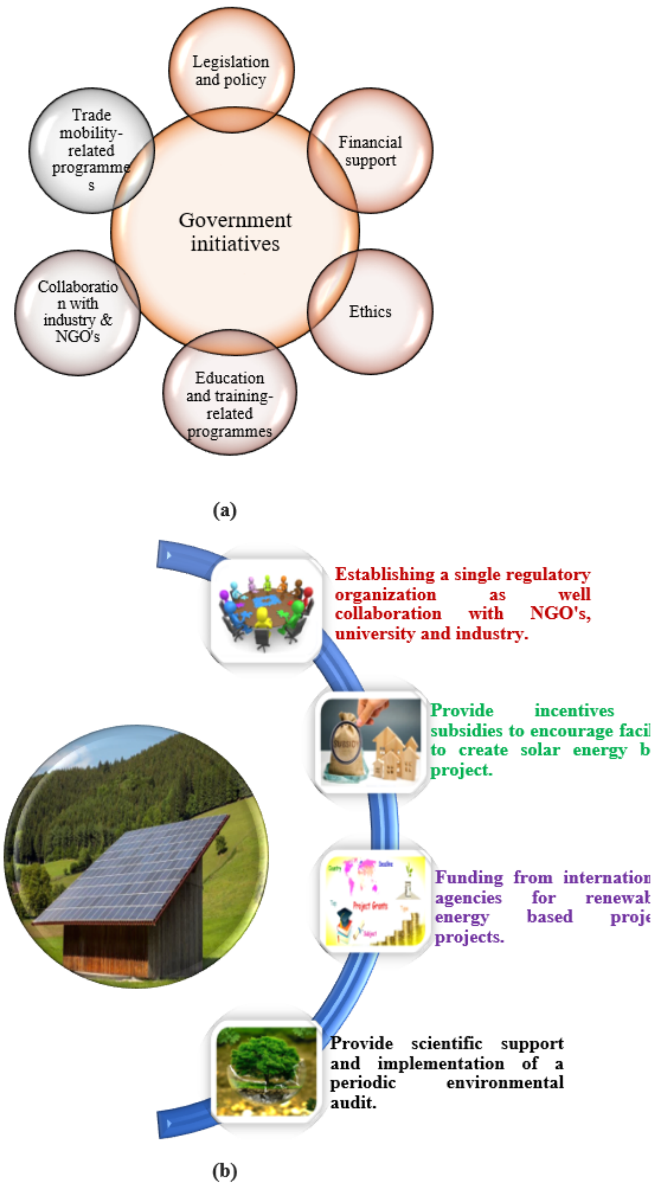


Figure 14

The government (a) initiatives, and (b) policy framework for successful implementation of solar irrigation programmed in Bangladesh

Supplementary Files

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