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A Short Assessment of Renewable Energy for Optimal Sizing of 100% Renewable Energy Based Microgrids in Remote Islands of Developing Countries: A Case Study in Bangladesh

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Abstract: This study explores Bangladesh's present energy condition, renewable energy (RE) possibilities and designs an optimal 100% RE-based off-grid power system for St. Martin's Island, Bangladesh. The optimal size of a hybrid renewable microgrid based on photovoltaic (PV) cells, a battery energy storage system (BESS), fuel cells (FC), and an electrolysis plant (EP) is proposed. Advanced direct load control (ADLC) and rooftop PV meet the energy demand at the lowest cost, and profits are maximized by selling chemical products produced by seawater electrolysis. Four cases are explored with the mixed-integer linear programming (MILP) optimization technique using MATLAB® software to demonstrate the efficacy of the suggested power system. The system cost in case 1 is lower than in the other cases, but there is no chance of profiting. Cases 2, 3, and 4 have greater installation costs, which may be repaid in 8.17, 7.72, and 8.01 years, respectively, by the profits. Though the revenue in case 3 is 6.23% higher than in case 2 and and 3.85% higher than in case 4, case 4 is considered the most reliable power system, as it can meet the energy demand at the lowest cost while increasing profits and not putting a burden on customers.

Keywords: renewable energy; sustainability; advanced direct load control; sea water electrolysis; MILP optimization technique; rooftop PV

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1. Introduction

Energy is a critical issue for every country's long-term growth, and worldwide energy consumption is growing day by day as the world's population grows. Bangladesh, which has a population of 156 million people and a power capacity of slightly over 11,000 MW (as of December 2015), is predominantly (approximately 70–75%) powered by indigenous natural gas collected from onshore sources [1]. Agriculture is the primary source of revenue for the people of this country. However, Bangladesh's Gross Domestic Product (GDP) grew by 7.05% in 2016 [2]. A minor portion of Bangladesh had electricity in 2012, accounting for around 18% of the total population. People in the electrified region had to deal with a lot of load shedding [3]. However, only 83% of the country's population has access to grid energy. About 76% of Bangladeshi people had no grid-connected electric power in 2014, and about 70% of people lacked access to electricity, most of whom lived in villages. Approximately 40% of them were living below the poverty line [4]. According to estimates, power demand is rising at a pace of 10% per year and will continue to rise in the next few years. Energy demand was supposed to increase by 185% by 2021 [5], and by 2030, power consumption is predicted to reach 34,000 megawatts (MW) [6].

To ensure access to electricity to rural people, both the public and private sectors in Bangladesh should focus on working with sustainable energy sources [7]. The Bangladesh Power Development Board (BPDB) recently announced a major capacity expansion plan for power production in Bangladesh. In light of this, the installed capacity was boosted to 22,031 MW in November 2021, but the derated capacity was reduced to 20,934 MW [8]. Bangladesh's total installed capacity, which includes captive power and off-grid renewable energy (RE), topped 25,235 MW in September 2021, with more than 97% of the population now having access to electricity [9]. In Bangladesh, not all demand-side power generation is efficient, which is a barrier to the country's progress and advancement.

Bangladesh's principal energy sources are natural gas and oil. Everyday, a large volume of natural gas is used by power plants, posing a grave danger to future natural gas reserves and electricity supply. According to a survey conducted in June 2015, total gas storage in Bangladesh then was 14.16 TCF, and that would be depleted by 2031 if gas usage remained constant [10]. The combustion of fuel oils, such as HFO and HSD, produces the second-largest share of power. Bangladesh's power industry imports nearly all of its fuel oil and roughly 1160 MW of energy from foreign nations. As a result, local money is exported to foreign nations, with severe negative economic consequences. Due to the generation of bulk energy from fossil fuels, greenhouse gas emissions, particularly carbon dioxide, are quickly increasing. In Bangladesh, 0.64 kg CO_2 is created for every kWh of electricity generated. In the years 2024–2025, 83,000 M ton CO_2 will be emitted as a result of energy generation [11]. The government of Bangladesh plans to produce 5% of the total energy from RE resources by 2015 and 20% by 2020 [12]. RE systems that are used in Bangladesh are solar energy, wind power, biomass energy, and hydroelectric power, which aim to satisfy the energy demand while emitting less CO_2 [13]. A major goal for Bangladesh is to achieve 100% energy access by 2022. Due to local geography, however, one of the challenges to achieving this goal is electrifying remote areas. In these remote places, there is no electricity supply from the main grid, and it would not be economically viable to provide electricity from the main grid. The total electricity demand was approximately 20,000 MW in 2021, which is lower than the total generation capacity. The Business Standard collected data from rural and semi-urban regions in 21 districts, finding that many of these locations were without power for an average of 6 h. The biggest power outage lasted 12 h because of weak transmission networks. The government needs to pay a penalty of Tk9000 crore a year for leaving the capacity of power companies unused [14–16]. These challenges might be solved with hybrid renewable energy (HRE) based on an off-grid power system to serve electricity to remote areas where surplus power can be stored and utilized.

This study's overarching purpose was to analyze Bangladesh's current energy generation, RE scenarios, and future prospects; and to propose a hybrid microgrid system based on the analysis to electrify remote areas while minimizing the difference between energy generation costs and revenue of surplus power utilization. The following tasks were done in order to attain this goal:

- The issues related to Bangladesh's existing energy condition, current RE scenarios, and efficient renewable energy sources for future use were investigated in order to select the most appropriate renewable sources for the proposed microgrid architecture.
- An optimal sizing strategy for a hybrid renewable microgrid based on photovoltaic (PV) cells, a battery energy storage system (BESS), fuel cells (FC), and an electrolysis plant (EP) is proposed. The microgrid is intended for a remote island of Bangladesh named St. Martin's Island.
- We determined that a seawater electrolysis facility should be used to gain revenue by utilizing surplus electricity to produce chemical products for the market.
- The use of demand–response methodology was examined as a way to boost revenue.

The rest of the paper is organized as follows: The literature review is described in Section 2. Overview of current energy sector of Bangladesh is described in Section 3. Proposed microgrid for remote island is discussed in Section 4 which includes present condition of St. Martin's Island and proposed power system description with all parameters. The objective function, the techniques of solving the objective function and constraints are explained in Section 5. The results of 4 different case studies are compared to show the effectiveness of the proposed method Section 6. In Section 7, the discussion of the simulation result are analyzed. Finally, the conclusion and future modification of this paper are presented in Section 8.

2. Literature Review

Some other existing works on the power systems of remote islands are reviewed for better understanding. In addition, a comprehensive literature review is presented in order to assess the performances of various methodologies, models, and energy systems in remote areas. After combing through this literature, our conclusion was that indigenous renewable energy sources (RESs), particularly solar and wind resources with batteries, have significant potential for supplying energy to remote areas [17].

Renewable energy integration into the smart grid has the potential to enhance the percentage of renewable electricity in Bangladesh's overall electricity output while also providing off-grid electrification choices that can help close the power gap between urban and rural regions [18]. In [19], numerous RESs in Bangladesh and their potential to help with the country's energy issues, along with a summary of the current situation and actions taken by various governmental and private groups to encourage RE generation and consumption, are reviewed. In these papers, only analyses of the energy system in Bangladesh are presented.

For Bangladesh, energy transition paths were analyzed in [20] using the LUT Energy System Transition model; specifically, they studied the energy system transition from 2015 to 2050. The findings suggest that increasing emission prices accelerate the transition to a 100% RE system; however, eliminating these costs will have no substantial impact, since renewables will still account for 94% of power generation by 2050.

In [21], a decentralized mini hydroelectric power plant was proposed to fulfill the electricity demand of the tourist resorts of St. Martin's Island during peak demand hours, which could be a cost-effective and environmentally friendly alternative to the existing stand-alone diesel generators (DG). Searaser's hydrodynamic calculations were primarily based on forecasted wave data rather than real field measurements.

For the remote areas of Ashuganj, Bangladesh, RETScreen simulation software has been used to assess the cost and pollutant emission characteristics of a PV, biomass, and extra storage based off-grid hybrid system, which is more efficient than a traditional kerosene-based system [22]. HOMER software was used to develop three optimal hybrid renewable energy system configurations to fulfill the residential and agricultural power consumption requirements of particular energy-deprived rural areas in India in [23], where wind power, PV, and battery based HRES are the most cost-effective solutions. For fulfilling the load requirement, the performance of a stand-alone PV, diesel, and battery based hybrid application in a remote village in Bangladesh was explored in [24]. Using two prominent battery technologies (lead acid (LA) and lithium-ion), the impacts of alternative dispatch techniques on the COE and the net present cost (NPC) were investigated. In comparison to the load following (LF) and cyclic charging (CC) techniques, the combined dispatch approach has a somewhat lower COE. The cost of the battery storage system is still high.

The technical and economic feasibility of a solar-powered central receiver system was analyzed in [25] using SolarPILOT and system advisor model software. They wished to provide a reliable and affordable source of energy to the St. Martin's island where the cost of energy (COE) is significantly less than the current rate. However, only solar power is not very cost-effective.

All possible configurations of the proposed microgrid system have been simulated [26], and it was found that the optimal PV, wind, battery, and diesel based system for the St. Martin's Island (found using hybrid optimization of multiple energy resources (HOMER) and the proposed system) is more cost-effective and eco-friendly than the conventional system. Using HOMER software, several combinations of off-grid hybrid energy systems were optimized in [27] for a rural hilly area of Bangladesh, with the goal of minimizing energy costs, net present costs, and CO_2 emissions. PV–diesel–PHS systems were found to be the most cost-effective. HOMER software was used in [28] to optimize hybrid PV–DG–battery systems for Benin's rural areas. The proposed strategy, according to the findings, is superior to the present approach in terms of reducing energy expenses and carbon emissions. In these papers, DG was used, which is responsible for carbon emissions.

In [29], an appropriate improved genetic algorithm (GA) program was built using the MATLAB toolbox to minimize the total/net current cost of hybrid energy systems encompassing solar PV, wind power, DG, and battery storage for powering rural regions in stand-alone applications. GA was used in [30] to optimize a PV, wind, battery, and diesel based hybrid system to meet the energy needs of a rural region in northern Nigeria at the least cost and with the least carbon emissions. GA has a high computational cost, since it takes a long time to reach convergence.

A solar module, wind turbine, biogas generator, and vanadium redox flow battery based hybrid energy system was introduced in [31], its intent being to supply reliable electricity to St. Martin's Island. The hybrid system components were sized based on the COE and life cycle emissions under a certain level of reliability using two multi-objective optimization techniques: non-dominated sorting GA II and infeasibility-driven evolutionary algorithms. Using GA and HOMER, the optimal sizing and analysis of techno-economic aspects of PV, battery, and DG based systems was performed in [32] to meet the peak load on an island in Bhola, Bangladesh. The GA solution is more cost-effective. A GA was employed in [33] to optimize an off-grid hybrid system for a remote island consisting of solar power, wind power, and a storage system, and the results were compared to those of the HOMER program. GA provided a more trustworthy result than HOMAR.

In [34], a local-level study of a rural off-grid system in Bangladesh is presented, in which three energy sources, solar power, wind power, and diesel fuel, are considered. The results show that there is a lack of consistent electricity supply from the national grid to the countryside.

In [35], an intelligent flower pollination algorithm was used to find optimal decision variables at the lowest cost, producing better reliability values in various reliability indices. This provided optimally designed hybrid systems to reduce the total net energy cost in the northwest region of Iran. The demand–response topic was not addressed in these articles, which might raise energy costs.

In [36], a firefly algorithm was used to calculate the optimal scale of a hybrid energy system based on solar power, wind power, and battery storage for remote villages in India, with the priority being minimizing the cost of electricity. Simulations were performed for one summer day and one winter day in this work, which is not sufficient to represent an entire year.

In [37], the mixed-integer linear programming (MILP) optimization algorithm was used to design a tool capable of determining the optimal sizing of an HRES that can assist engineers in identifying the best trade-off between costs and energy deficiency. This was performed during the planning stage of a case study of a mountain hut in South Tyrol (Italy) with solar, wind, DG, and battery storage based HRES. Carbon emissions were not taken into account.

The goal of [38] was to figure out the optimal size of a hybrid energy storage system with a hydrogen fuel cell, and a supercapacitor was used for a commercial load supplied by solar panels. A sensitivity analysis on the anticipated prices of hydrogen storage was performed using HOMER Pro under Cape Town weather conditions to assess the impacts of hydrogen cost on the cost of the system and the levelized cost of energy. Despite the fact that the cost of such a hybrid storage system is expected to drop in the future, it is too expensive to implement for a commercial load.

St. Martin's Island is surrounded by seawater. The electrolysis of seawater using the surplus power of renewable generation would effectively turn a profit, which was not discussed in the above literature. The contributions of this study are as follows:

- Using surplus electricity in the EP for seawater electrolysis at St. Martin's Island to cover for the installation costs and make a profit from the sale of chemical products is analyzed.

- To flatten the load curve and enhance the profits from selling chemicals, advanced direct load control (ADLC) is utilized in our model. Only the consumers who have rooftop PV will be considered for the ADLC, which can improve the profits from chemical sales while also minimizing the amount of IL on the system, making it more stable by reducing the impact of power interruptions.

3. Overview of Current Energy Sector of Bangladesh

3.1. Current Power Generation

The rapid growth of the population, urbanization, and industrialization have led to costly use of electricity in Bangladesh. The power generation sector of the country is improving day by day. Per capita, the electricity consumption of Bangladesh was 329.85 kWh in 2020, which is low compared with other developing countries such as India and Pakistan, whose per capita energy consumption values are 857.41 and 395.42 kWh, respectively [39].

There are both public and private power generation sectors in Bangladesh. According to BPDB, the install capacity has increased in the last ten years, and the total power generation capacity was 25,235 MW in 2021, including public and private sectors, captive power, and RE [9].

In the Bangladesh, electricity demand is increasing rapidly with the increasing population and their economic activities. According to the master plan of BPDB, the peak demand was 15,527 MW in 2019, yet only 5271 MW in 2009, and it will increase more in the next ten years.

The electricity demand from 2010 to 2030 is shown in Figure 1. In Bangladesh, the demand for electricity varies during the day. From 5 pm to 11 pm are peak hours, as the maximum electricity demand occurs in this period. Therefore, from 5 pm to 11 pm, the electricity price is high to influence the consumer to reduce their use. Most of the energy is consumed by the industrial and residential sectors in Bangladesh, and the rest of the energy is consumed by the commercial and agricultural sectors. According to the sustainable and renewable energy development authority (SREDA), 30% of total energy is consumed by industry; the residential sector consumes 36%. The other 30–40% is use by the commercial sector.

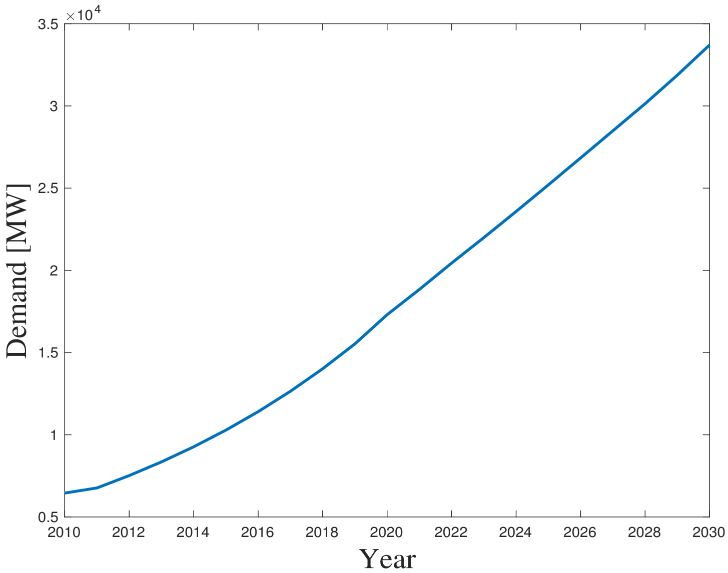


Figure 1. Electricity demand over time.

Energy generation in Bangladesh mainly depends on fossil fuels, such as natural gas and oil. RE sources such as biomass, solar power, hydropower, and wind power make up a minor contribution. Table 1 shows the installed and derated capacities of BPDB power plants.

Table 1. Installed (I) and derated (D) capacities of BPDB power plants [8].

Fuel Type	I Capacity (MW)	I Total (%)	D Capacity (MW)	D Total (%)
Coal	1768.00	8.03%	1688.00	8.06%
Gas	11,450.00	51.97%	11,100.00	53.02%
HFO	5953.00	27.02%	5341.00	25.51%
HSD	1341.00	6.09%	1286.00	6.14%
Hydro	230.00	1.04%	230.00	1.1%
Imported	1160.00	5.27%	1160.00	5.54%
Solar	129.00	0.59%	129.00	0.62%
Total	22,031	100%	20,934	99.99 %

Natural gas is the major source of power generation among all fossil fuels. There are 37 natural gas-dependent power centers in Bangladesh, including six integrated centers. These six power centers have been integrated with diesel and heavy fuel oil (HFO). According to the report on BPDB in November 2021, 53.02% of electricity is generated by natural gas-based power centers. The remaining 46.97% is dependent on HFO, high-speed diesel (HSD), imported power, hydropower, coal and solar power—25.51%, 6.14%, 5.54%, 1.1%, 8.06%, and 0.62%, correspondingly.

At present, Bangladesh is facing a natural gas crisis because of extreme use and a shortage of gas reserves. The average annual demand for natural gas is increasing by 10%, but gas reserves are limited. Bangladesh is also importing liquefied natural gas (LNG). The Petrobangla is currently re-gasifying around 600 million cubic feet per day (mmcfd) of LNG from two LNG import terminals, out of their capacity to re-gasify around 1000 mmcfd. This gas is being supplied to the national gas transmission line mixed with natural gas to supply power plants and other industries [40]. The second-largest portion of electricity is generated by burning fuel oils, i.e., HFO and HSD. By using fuel oils, i.e., HFO and HSD, the power sector generates about 31.65% of its electricity. The power sector of Bangladesh needs to import fuel oil from other countries, because oil mines in Bangladesh are very few, producing negligible amounts of oil. There is no significant place for oil drilling other than Haripur [41]. That is why, without a doubt, the power industry must import nearly all of its oil from other nations. These imported fuels are increasing in price (affecting the electricity price) and polluting the environment.

In Bangladesh, there is not enough coal either; and electricity generation from coal only constitutes 8.06% of the whole. The production of power from coal is inexpensive, but it has particularly negative impact on the environment. Although there is only one coal power plant in Bangladesh, it creates a lot of smoke, fly ash, bottom ash, sludge, and so on, all of which is harmful to our environment. In addition, there is the release of carbon dioxide (the greenhouse effect and global warming).

The power sector of Bangladesh cannot meet the demand for electricity; that is why electricity is imported from other countries. Imported electricity in Bangladesh totaled 1160 MW, or 5.54% of the total demand, in 2019. However, imported power is a lot cheaper than electricity from liquid fuel (HFO and HSD) based power plants, which provide more than 30% of the country's electricity. Imported electricity has a long-term disadvantage because it still increases the per unit electricity price on average. Moreover, lots of local money going to other countries harms the economy.

Using fossil fuels to generate energy has a long-term detrimental influence on the environment. According to data from the International Energy Agency (IEA), global CO_2 emissions from fossil fuel combustion were 321.3 billion tons in the year 2013, with the power sector emitting 136.6 billion tons of CO_2, accounting for 42.5% of total emissions[42]. Using quarterly data from 1975 to 2010, a study on the link between industrialization, power consumption, and CO_2 emissions in Bangladesh was conducted, and the results show that electricity consumption Granger causes energy sector pollution, industrial growth, and financial development [43].

Solar power, wind power, geothermal power, hydropower, and other RE produce very little in the way of emissions. The CO_2 output can be reduced by generating electricity from these sources rather than fossil fuels.

3.2. Renewable Energy Scenarios

RE is produced from renewable sources that are naturally restocked, such as sunlight, wind, rain, tides, waves, and geothermal heat. RE contributed 19.3% and 24.5% to the generation of energy in 2015 and 2016, respectively, according to REN21's 2017 report [44]. Bangladesh is blessed with RESs such as biomass, wind, sunlight, some areas suitable for hydroelectric generation, and geothermal energy. Total off-grid and on-grid renewable energy generation capacities according to SREDA are listed in Table 2.

Table 2. Off-grid and on-grid RE capacities of Bangladesh [45].

Technology	Off-Grid (MW)	On-Grid (MW)	Total (MW)	(%) of Total
Solar	347.43	194.98	542.42	69.8%
Wind	2.00	0.90	2.90	0.4%
Hydro	0.00	230	230	29.6%
Biomass to Electricity	0.40	0.00	0.40	0.1%
Biogas to Electricity	0.63	0.00	0.63	0.1%
Total	350.52	425.88	776.41	100%

3.2.1. Solar Power

Bangladesh has long sunshine periods with solar intensity of 4–6.5 KWh/m^2/day, which falls on the ground for about 300 days per year, but most of the solar radiation is not used. The most solar radiation is received between March and April, and the least from December to January [46,47]. There are several types of solar energy technology, such as solar PV, solar home systems (SHSs), and concentrated solar power. Many benefits of using SHSs were evaluated in comparison to other solar energy technologies for pastoral life in emerging nations such as Bangladesh. Around fifteen million rural people use kerosene lamps in their homes, since they do not have access to electricity. In this case, the SHS might be an ideal alternative for supplying electricity to those remote communities. Houses with SHSs consume less kerosene and are less reliant on rechargeable batteries, saving 20–30% on monthly costs [48]. The SHS is beneficial for electrification in off-grid areas of Bangladesh, and more than 4.5 million SHSs with 150 MW of total capacity have been acquired in rural and isolated areas of Bangladesh [49].

Infrastructure development company limited (IDCOL), Grameen Shakti, etc., are involved in several projects of SHSs. SHSs are saving around USD 220 million annually as they replace the 180,000 tonnes of kerosene used in Bangladesh every year. In order to attract a group of poor people, cheap SHSs should be introduced with low down-payments, combined with more flexible micro-loan facilities [50,51]. Another important use of solar energy in Bangladesh is the rooftop solar system [52]. This method has just provided new potential for industrial customers by allowing them to generate electricity from their unused roof space [53]. It is feasible to lessen reliance on grid power by installing a rooftop solar system.

PV-based smart houses can contribute by injecting power into the national grid, besides fulfilling their own electricity demands. Additionally, PV-based irrigation systems and electric vehicles can reduce the electricity load, and decrease production costs and carbon emission [54,55].

In many areas and sectors in Bangladesh, PV electrification could contribute significantly, e.g., remote rail stations, remote villages that are off the grid, street lights, remote and rural health centers, and religious institutions.

The total number of completed and running solar power systems is 4112, and their capacity is 2360.672 MW. Some major projects are listed in Table 3.

Table 3. Solar projects of Bangladesh [56].

Technology Type	Project Name	Capacity (MW)	Location
Net Metering Rooftop Solar	NEM rooftop solar by Paragon Feed Ltd. of Gazipur PBS-2	0.575	Gazipur Sadar-Joydebpur Gazipur
	NEM Rooftop Solar by Simftex Apearls Ltd. of Gazipur PBS-2	0.700	Gazipur Sadar-Joydebpur Gazipur
	NEM rooftop solar by Far East Spinning Industries Ltd. of Hobiganj PBS	1.1	Ajmiriganj Habiganj
Rooftop Solar Except Net Metering	Far East Spinning Industries Ltd. 1100 kWp Roof-top Solar Project	1.1	Madhabpur, Habiganj
	Roof Top Solar System on DESCO Consumer Roof Top in 2015	4.22	Dhamrai Upazila, Dhaka
	Roof Top Solar System on DESCO Consumer Roof Top in 2015	3.45	Savar Upazila, Dhaka
	Roof Top Solar System on BPDB Consumer Roof Top in 2015	2.54	Whole Bangladesh
	Roof Top Solar System on BREB Offices in 2016	2	Whole Bangladesh
Solar Mini-Grid	650 kWp Solar Minigrid Pilot Project at remote haor areas of Sullah, Sunamganj	0.65	Sullah Sunamganj
Solar Park	20MW (AC) Solar Park by Joules Power Limited (JPL)	20.0	Teknaf Upazila Cox's Bazar
	3 MW Grid-connected PV Power Plant at Sharishabari, Jamalpur	3.0	Sarishabari Upazila Jamalpur
	8 MW Solar Park by by Parasol Energy Ltd.	8.0	Panchagarh Sadar Panchagarh
	Kaptai 7.4 MWp Grid-connected Solar PV Power Plant	7.40	Kaptai Upazila Rangamati

There are some under-plan and ongoing solar projects also. The completed and ongoing solar power capacity of net metering rooftop solar, solar park, rooftop solar except net metering, solar irrigation, solar mini-grid, the solar charging station is 34.043 MW, 2230.6 MW, 41.092 MW, 48.872 MW, 5.656 MW, 0.282 MW [54].

3.2.2. Biomass Energy

Biomass is considered as an alternative source of energy globally because of its energy potentiality. It can be produced in crops on surplus agricultural land and marginal land, or from agricultural residues, forest residues, dung, organic wastes, etc. In 2050, the technical potential of these sources will be 0–700, <60–110, 15–70, 30–150, 5–55, and 5–50 exajoule per year (EJ/year), respectively [57].

As Bangladesh has some of the most fertile soils in the world, over 70% of the land is used for farming crops. Bangladesh is trying to increase biomass resources, and the government is taking some proper steps for producing large scale power from biopower plants [58].

There are common biomass resources that are obtained from the agricultural sector. These resources are rice husks, jute sticks, sugarcane, corn residue, wheat residue, animal waste, other crop residues, and so on. Besides, wood and municipal waste are also great sources for producing biomass-based electricity. In Bangladesh, biomass accounts for around 70% of total energy consumption [59]. Potential energy generation capacities from biomass residues are listed in Table 4.

Table 4. Potential energy generation capacities from biomass residues [60–62].

Sources	Residues	Moisture Content (%)	Dry residues Recovery (10^3 t)	Calorific Values (GJ/ton)	Energy Content (PJ)	Application
Field Residues	Rice's straw	12.7	17,831.55	16.60	283.15	Fuel, animal feed housing material
	Field's Weeds	13.6	-	15.97	267.70	Fuel, animal feed
	Jute's residues	9.5	1574.56	16.91	134.75	Fuel, housing material
	Maize's stalks	12	1257.87	14.70	9.22	Fuel, animal feed
	Wheat's straw	7.5	586.96	15.76	8.68	Fuel, housing material
	Pulses' residue	20	408.05	12.80	4.52	Fuel, animal feed
	Vegetables' residue	20	1480.75	13	4.46	Fuel,animal feed
	Sugarcane's tops	50	383.25	15.81	3.56	Fuel, animal feed
	Groundnut straw	12.1	89.16	17.58	0.67	Fuel, animal feed
	Cotton stalks	12	23.76	16.40	0.58	Fuel
	Millet	15	12.51	12.38	0.16	Fuel
	Tobacco Stalks	8.9	50.38	17.70	0.89	Fuel
	Barley straws	15	0.37	12.38	0.005	Fuel
	Subtotal	-	23,699.17	-	**735.155**	
Residue while processing crops	Rice bran	9	2600.50	13.97	353.91	Fuel
	Rice husk	12.4	8052.90	16.30	153.73	Fuel, animal feed
	Sugarcane bagasse	49	1079.67	18.10	12.51	Fuel
	Maize cob	15	473.85	14.00	3.31	Fuel, animal feed
	Maize husks	11.1	363.07	17.27	3.13	Fuel, animal feed
	Coconut husks	11	118.96	18.53	2.20	Fuel
	Coconut shells	8	35.99	18.53	0.67	Fuel
	Groundnut husks	8.2	55.17	15.66	0.37	Fuel, animal feed
	Subtotal	-	**12,780.11**	-	**529.83**	
Others	Animals waste	-	-	13.86	249.62	Fuel, manure
	MSW	45	-	18.56	84.34	
	Wood	20	-	15.00	83.18	Fuel, furniture
	Tree residues	-	-	12.52	22.80	Fuel, fencing
	Poultry droppings	-	-	13.50	12.94	
	Sawdust	20	-	18.00	1.77	Fuel
	Total	-	-	-	**1707.77**	

According to Table 4, in Bangladesh, every year the estimated residues of agriculture reach 717.29 Petajoule (PJ) for fields and 529.83 PJ for crop processing. In addition, animal waste, MSW, wood, tree residues, poultry droppings, and sawdust are excellent biomass sources: 249.62, 84.34, 83.18 PJ 22.80, 12.94, and 1.77 PJ, respectively. Thus, potential biomass residues total about 1707.77 PJ, which is equivalent to 474.38 TWh.

Usually, some barriers occur to developing biopower plants in Bangladesh, such as limited availability of loans, poor availability of the fuel type to be used, byproduct utilization problems, poor technical knowledge of rural people, etc. [63].

3.2.3. Hydropower

Hydro energy is one of the most productive renewable sources in the world. Hydroelectricity is very simple and inexpensive, which is very suitable for developing countries, such as Bangladesh. There are lots of rivers with currents and few waterfalls in Bangladesh. The flowing water of these rivers can be a great source of kinetic energy, which can be utilized for producing hydroelectricity [64,65]. However, there is only one complete hydropower plant in Bangladesh named Kaptai Hydropower Plant, which has 230 MW derated capacity per day that can produce 37.8% of the total renewable energy in Bangladesh.

Bangladesh abuts by the Bay of Bengal, resulting in the river and river connected canal in the southern regions experiencing a tidal head/height rise and fall of about 2–5 m. Adequate energy can be produced from a tidal water source if a micro-hydropower plant can be installed on the canal [66]. However, Bangladesh has many potential places to install more small and micro-hydropower plants because of its geographical location, which are identified in Table 5.

Table 5. Potential places for hydroenergy generation [67–69].

	District	Potential Place	Potential Energy [kW]
Small hydro sites	Chittagong	Foy's Lake	4
		Choto Kumira	15
		Hinguli Chara	12
		Lungi Chara	10
		Budia Chara	10
	Chittagong Hill Tracts	Sealock	81
	Sylhet	Nikharichara	26
		Madhabchara	78
		Rangapani Gung	616
	Jamalpur	Bhugani-Kongsa	65.5
		Marisi at Dukabad	32.5
	Dinajpur	Dahuk at Burabari	24
		Chawai	32
		Talam	24
		Pathraj at Fulbaria	32
		Tangon	48
		Punarbhanba at Singraban	11
	Rangpur	Buri khora chikli at Nizbari	32
		Fulkumar at Raiganj Bazar	48
Micro hydro sites	Chittagong	Nunchari Tholi Khal in khagrachari	5
		Sealock Khal in Banddarban	30
		Taracha Khal in Bandarban	20
		Rowangchari khal in Bandarban	10
		Hnara Khal in Kamal chari Rangamati	10
		Hnara Khal in Hang Khrue, Rangamati	30
		Monjaipara microhydropower Unit	10
		Bamer Chara Irrigation Project	10
	Hilly Districts	Sailopropat, Bandarban	5
		Madhobkundu, Moulvibazar	15

A hybrid power system based on hydro, PV, wind, etc., is more efficient for the remote area because of the low electricity rates in those areas [70]. The conversion efficiency of micro-hydroelectric plants can be increased by 90% by using solar hybrid technology [71].

3.2.4. Wind Power

The current global installed wind capacity is 430 GW, and it was extended by 17% in 2015. Production costs for onshore wind were expected to decrease by 15% by 2021 [72].

However, wind power generation in Bangladesh is inferior compared to other developing countries. Only 3 MW of electricity comes from wind generators in Bangladesh, from the Kutubdia Hybrid Power Plant and Feni Wind Power Plant, where the wind power potentiality is more than 20,000 MW. We hope that Bangladesh is going to increase its wind power, and BPDB has established several initiatives in order to generate 1.3 GW energy from wind [73]. There are 724 km long coastal belts around Bangladesh and numerous undeveloped small islands in the Bay of Bengal. In coastal areas, at 30 m high, the average annual wind speed is above 5 m/s. The wind speed is more than 4.5 m/s in the north-eastern part of Bangladesh, whereas it is only around 3.5 m/s in other parts [74,75]. Small wind turbine installations may help to study the real-time generation of wind power in the coastal areas. In [76], it has been shown that the yearly scale factor is 2.2 m/s, and the shape factor is 1.8 for the Chittagong export processing zone. The maximum scale and shape factors are 3.95 m/s and 3, respectively, obtained in June. The wind power density of different regions has been calculated at 50 and 120 m height, and wind power classes and generation scales are listed in Table 6.

Table 6. Wind energy potential in Bangladesh [77].

Places	Wind Density		Wind Power Class		Generation Scale	
	At 50 m	At 120 m	At 50 m	At 120 m	At 50 m	At 120 m
Chittagong	187	532	1	5	Micro	Large
Jessore	180	511	1	5	Micro	Large
Khepupara	130	368	1	3	Micro	Medium
Hatiya	94	268	1	2	Micro	Small
Cox's Bazar	72	204	1	2	Micro	Small
Syedpur	64	180	1	1	Micro	Micro
Sylhet	51	145	1	1	Micro	Micro
Barishal	49	141	1	1	Micro	Micro
Comilla	47	132	1	1	Micro	Micro
Sitakunda	41	117	1	1	Micro	Micro
Sandwip	41	116	1	1	Micro	Micro
Kutubdia	37	106	1	1	Micro	Micro
Monga	37	106	1	1	Micro	Micro
Srimangul	36	102	1	1	Micro	Micro
Maijdee	35	98	1	1	Micro	Micro
Ambagan_CTG	32	90	1	1	Micro	Micro
Dhaka	31	89	1	1	Micro	Micro
Rangpur	26	73	1	1	Micro	Micro
Khulna	26	72	1	1	Micro	Micro
Rangamati	25	72	1	1	Micro	Micro
Faridpur	24	70	1	1	Micro	Micro
Teknaf	24	69	1	1	Micro	Micro
Gogra	24	68	1	1	Micro	Micro
Ishwardi	24	68	1	1	Micro	Micro
Mymensingh	21	59	1	1	Micro	Micro
Rajshahi	18	52	1	1	Micro	Micro
Patuakhali	18	50	1	1	Micro	Micro

Table 6. *Cont.*

Places	Wind Density		Wind Power Class		Generation Scale	
	At 50 m	At 120 m	At 50 m	At 120 m	At 50 m	At 120 m
Feni	15	42	1	1	Micro	Micro
Chuadanga	13	37	1	1	Micro	Micro
Madaripur	12	35	1	1	Micro	Micro
Chandpur	10	30	1	1	Micro	Micro
Satkhira	10	30	1	1	Micro	Micro
Tangail	9	27	1	1	Micro	Micro
Bhola	7	18	1	1	Micro	Micro
Dinajpur	5	15	1	1	Micro	Micro

Table 6 shows that Chittagong, Jessore, Khepupara, Hatiya, and Cox's Bazar have high potential for generating electricity from wind.

3.2.5. Geothermal Potentiality

Geothermal energy is typically ecologically favorable, since it releases a small quantity of toxic gas compared to the pollution caused by traditional fuels, such as coal and other fossil fuels. The output power of a geothermal power plant can be predicted with exceptional accuracy, which is not achievable with solar or wind energy. For the steam/hot water system, the cost of producing power from it is still cheap [78]. The worldwide installed capacity of geothermal energy plants is set to reach 14.3 GB in 2017 [79]. On the other hand, in Bangladesh, there is only a little information about this resource. A company called Anglo MGH has planned to set up Bangladesh's first geothermal power plant in Thakurgaon with a capacity of 200 MW [80,81]. Geothermal energy is the most efficient method of heating and cooling for homes. The efficiency is around 50% for heating and 70% for cooling, which is 20% and 40% more efficient than conventional heating and cooling systems, respectively, at a relatively cheap cost [82]. Potential places for geothermal energy are listed in Table 7.

Table 7. The geothermal gradients of deep wells in Bangladesh [83,84].

Sl/No.	Well Name	Gradient (°C/km)	Sl/No.	Well Name	Gradient (°C/km)
1	Kuchma 1	28.5	20	Fenchuganj 2	20.7
2	Shalbanhat 1	20.8	21	Feni 1	23.8
3	Jaipurhat	25	22	Feni 2	23.5
4	Bogra 1	29.5	23	Kailashtila 1	19.8
5	Singra 1	34.1	24	Kamta 1	23.5
6	Madhyapara	31.6	25	Kutubdia 1	26.4
7	Thakurgaon	34.2	26	Muladi 1	26
8	Barapukuria	48.7	27	Muladi 2	24.4
9	Habiganj 1	20.5	28	Patharia 5	20.4
10	Atgram 1	20.1	29	Saldanandi 1	27.2
11	Bakhrabad 1	23.9	30	Rashidpur 1	21.7
12	Beani Bazar 1	19.8	31	Semutang 1	27
13	Begumganj 1	25.4	32	Shabajpur 1	29.5
14	BINA 1	24.2	33	Sitakund 5	24.7
15	BODC 1	25	34	Sylhet 7	19.9
16	Chattak 1	21.1	35	Titas 11	23.1
17	Cox's bazar 1	25.6	36	SHazipur 1	24.2
18	ARCO AL	26.1	37	Bangora 1	21.2
19	Jaldi 1	20.25	38	Jaldi 3	22.5

There are some operational barriers to setting up a geothermal power plan, such as institutional, regulatory, technical, and financial barriers, and also some useful strategies to overcome these barriers [79].

3.3. Future Development

Bangladesh has not yet achieved full electrification for its population. As the rural communities in Bangladesh are located distant from the electricity distribution line, the power crisis is difficult to solve. The cost and difficulty of building a power grid are higher in coastal and hilly areas, so they do not have access to grid electricity. RE-based microgrids can solve the electricity problem not only in remote hilly or coastal areas, but also in other places. The current portion of renewable power generation in Bangladesh is low compared to the other developing countries. Still, like other developed or developing countries, Bangladesh is preparing for more renewable generation. Some major upcoming solar projects, wind projects, hydropower projects, and hybrid power projects are listed in Table 8.

Table 8. Future RE projects in Bangladesh [85].

Sources	Ongoing		Under Planning	
	Location	**Capacity**	**Location**	**Capacity**
Solar power	Sunamgonj Rangamati Sharishabari Kurigram Solar Street-	650 kW 8 MW 3 MW 30 MW 407 kW	Bidyut Bhaban, Dhaka WAPDA Bhaban Barkal Upazilla Sadar Rajashahi (IPP basis) Chandpur (IPP basis) Swandip Upazilla Thanchi Upazilla Rangunia Bangabandgu Bridge Ishwardi Jhenaidaha	37.5 kW 32.5 kW 10 kW 1 MW 500 kW 500 kW 500 kW 60MW 45 MW 2–3 MW 1–2 MW
Wind power	Muhuri Dam, Feni Mognamaghat, Cox's bazar Kepupara, Borguna Parky Beach, Chittagong Kuakata, Patuakhali	15 MW 15 MW 15 MW 15 MW 15 MW	Parky Beach, Chittagong	50–200 MW
Hydro power	Mirersorai, Chittagong Barkal Upazila, Rangamati	50–70 kW 50 kW		
Hybrid power	Hatiya island, Noakhali	7.5 MW	Kutubdia island	1 MW

There are several ongoing and planned solar projects in Bangladesh organized by BPDB. Bangladesh receives enough solar radiation to collect solar energy. Bangladesh contains such solar radiation on around 94% of its land, which is plenty for acquiring utility from available solar technologies [86]. Both private and public companies have already invested in solar power. Although solar radiation is relatively low during winter and monsoon, it could significantly contribute to energy production in Bangladesh. Among all solar energy technologies, SHS has attracted attention, and grid-connected PV can also be effective, as 50,174 MW of power can be generated from it in Bangladesh. Around 658 tons of greenhouse has can be reduced by 500 kW of grid-connected solar PV [87,88].

Nowadays, most rural Bangladeshi people trust biomass resources to meet their primary electricity needs. Only 44.52 TWh of biomass energy is used, though around 312.608 TWh of potential power is generated from it [5]. Bangladesh has already made considerable progress in the biogas sector. However, there are dormant biomass resources, for example, solid waste, which has enormous potential for generating electricity [89,90]. Heavy winds are available during the summer season, and coastal areas are a possible location for Bangladesh. By using wind energy, regional energy demands can be fulfilled. Hydropower can help meet energy demands as well.

The prospects of RE in Bangladesh are described in Table 9.

Table 9. Prospects of RE in Bangladesh.

Energy Source	Current Investment	Future Prospect	Benefits	Barriers
Solar	Government and private	Bright	Renewable, Environment friendly	Low radiation in winter, availability of land
Biomass & Biogass	Government and private	Bright	available, cheap recycling wastage	Carbon emission
Wind	Government and private	Limited to coastal areas	Renewable, Environment friendly	Low wind speed in winter
Hydropower	Government	Limited to few sites	Reliable, safe	Environment concerns
Nuclear	Government	Under investigation	Low pollution	Maintenance and sustainability concerns
Geothermal	None	To be investigated	Great for heating & cooling	Expensive and maintenance concerns

The government of Bangladesh has developed a master plan to attain 38,700 MW by 2030. According to PSMP, Bangladesh has planned to generate up to 2470 and 3864 MW domestically through RE by 2021 and 2041. To meet this goal, RE solutions should be investigated. Various RE initiatives should be developed for this aim, such as the research and usage of biomass resources, solar power development programs, wind energy studies, and geothermal power generation projects. Hybrid RE systems consisting of multiple RE generation units, such as PV, biogas, biomass, wind, and micro-hydro generators, along with power energy storage systems such as batteries and hydro-pumped storage, will be useful for energy generation.

4. The Proposed Microgrid for a Remote Island

RE-based hybrid microgrids are increasingly being utilized to integrate distributed generation in both grid-connected and isolated power systems. From the above review, solar power can be considered as the most viable RES for Bangladesh in both off-grid and on-grid systems. As solar power is only accessible during the day, power must be conserved for nighttime load fulfillment. In this case, BESS and FC may be viable options. According to Table 8, Bangladesh already has ongoing and planned hybrid power systems in Hatiya island, Noakhali, and Kutubdia island. A 100% hybrid renewable microgrid comprising PV, BESS, FC, and an EP has been suggested for powering St. Martin island by our case study, which shows the effectiveness of RE on a remote island.

St. Martin's Island is Bangladesh's lone coral island, located in the Bay of Bengal's north-eastern corner, roughly 500 km from the capital Dhaka and 10 km from the mainland [91]. On this little island with a surface area of 12 square kilometers, about 8000 people dwell. It is Bangladesh's most beautiful vacation island. Approximately 3000 people visit this little island on a daily basis from November to February, well exceeding the island's capacity [92]. The island's residents rely on stand-alone diesel generators to supply their energy needs. They do not, however, perform wonderfully and are insufficient to satisfy the demand. Furthermore, they light their homes using diesel, kerosene, and wood. Due to geographical constraints, the island has no power supply from the main grid, and it would not be economically viable. The proposed hybrid renewable power system might be a viable option for meeting the growing electricity demand [93]. The map of this island is shown in Figure 2.

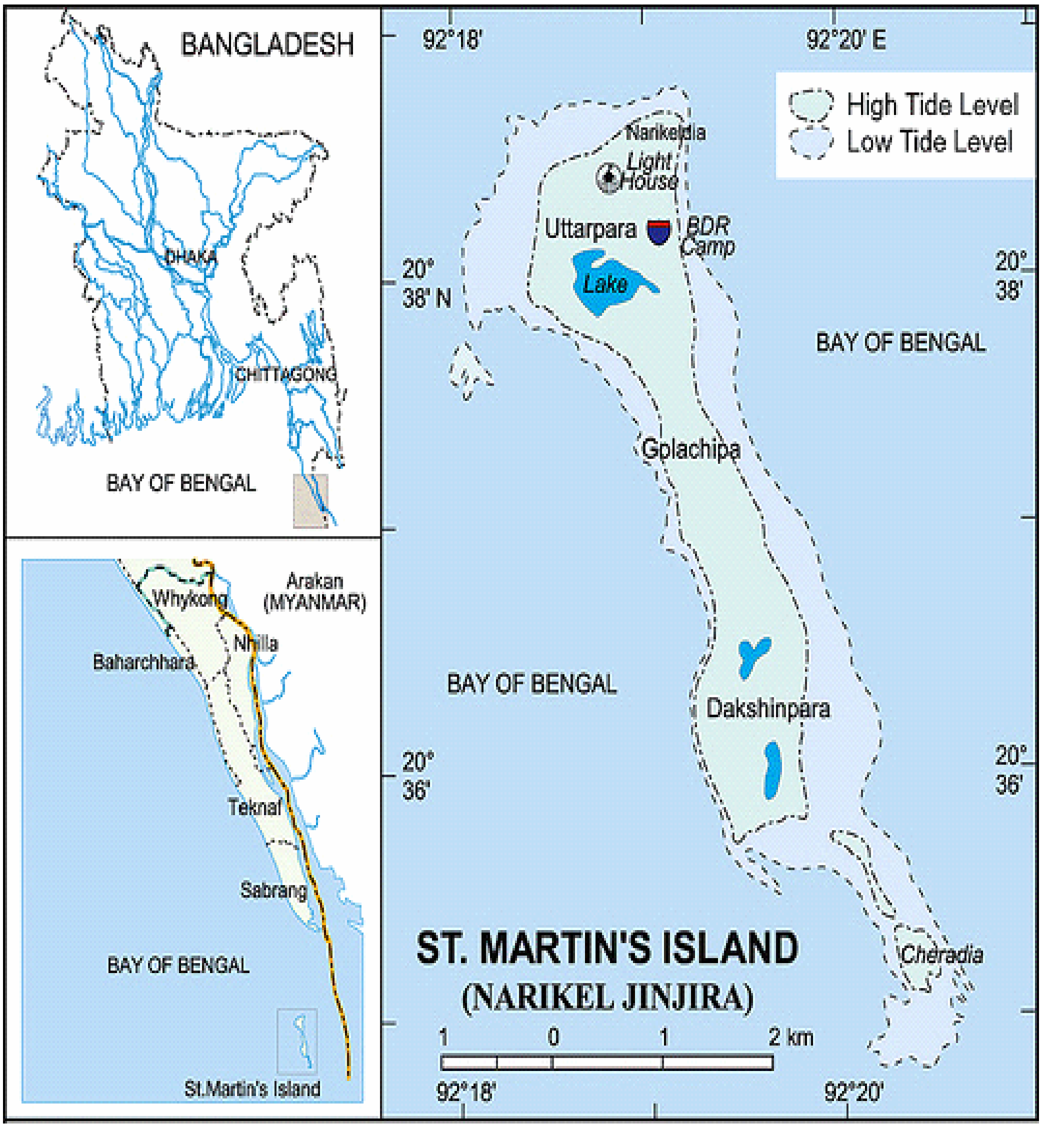


Figure 2. Map of St. Martin's Island [26].

4.1. System Description

Figure 3 depicts the power system model developed for St. Martin's Island, which has a peak load of 30 kW. The power generating and storage system consists of a small PV area, a BESS, an FC, and an EP. The electricity generated by the PV is distributed to the end-users. If the generated power is greater than the demand, the excess power will be utilized to charge the BESS and EP. If there is a power shortfall, however, it is remedied by drawing electricity from BESS. When other power production methods are unable to satisfy the load requirement, FC is used to generate electricity. In addition, the ADLC is used with rooftop PV to achieve high-efficiency operation.

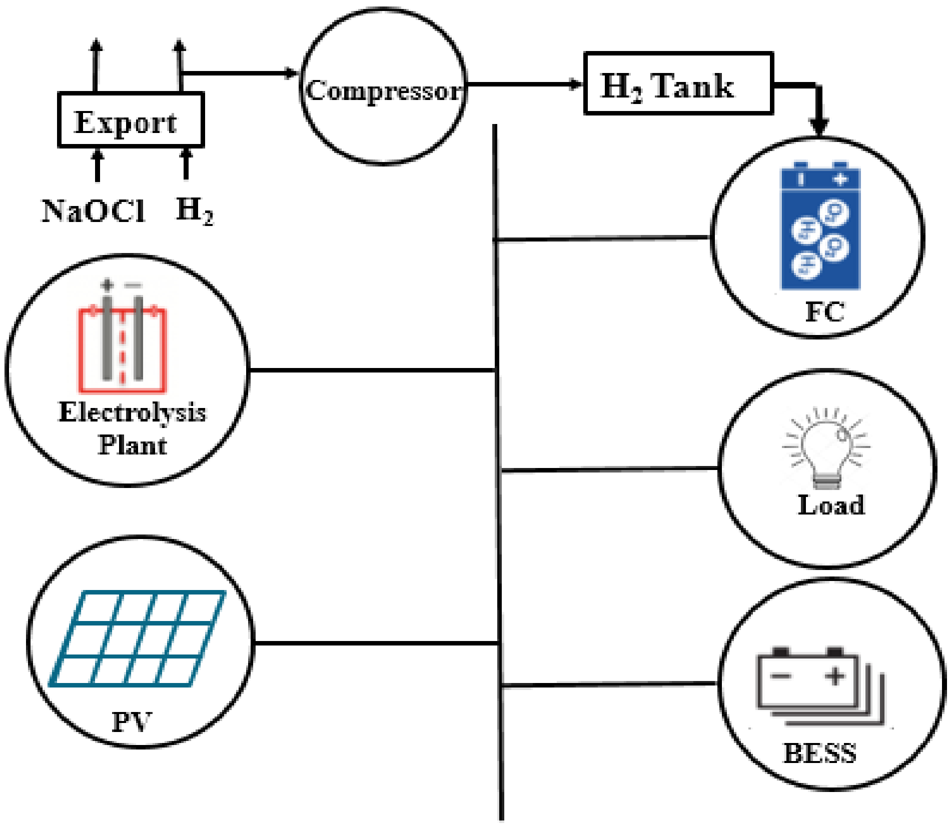


Figure 3. Proposed power system model.

4.1.1. Modeling of Installed Equipment

For the assessment of load demand, a total of 50 households, 15 stores, 5 restaurants, and 5 hotels were chosen at random. One energy-efficient lamp (compact fluorescent light (CFL), 20 W each), one ceiling fan (75 W), and one television (200 W) were considered for every house. Two CFL and one ceiling fan were considered for every shop. Fifteen CFL, eight ceiling fans, one television, and one refrigerator (250 W) were considered for each restaurant. Sixty CFL, 30 ceiling fans, 20 televisions, 2 refrigerators, and one water pump (2000 W) were considered for each hotel. The total load was calculated as 31.625 kW.

According to the geographical location of St. Martin's, the area is well suited for maximizing solar energy consumption. Solar energy is radiated at a rate of 100–300 W/m^2 every year [94]. Hourly power generation from PV in St. Martin's was obtained from the pvwatts calculator, as these data are not available.

Compressed gas storage is used in the proposed method due to being an inexpensive technique for storing hydrogen. The compressor and pressure vessel costs make up the capital cost of compressed gas storage. The compressor cost is proportional to the compressor's power and outlet pressure [95].

The power generation, lifetime, installation cost, and other parameters of installed equipment are listed in Table 10.

Table 10. Parameters of installed components [96–99].

Equipment	Parameters	Values
PV	Rated power (kW)	25
	Lifetime (Years)	25
	Capital cost ($/kW)	1000
	O&M cost ($/kW-year)	60
	Replacement cost ($/kW)	-
	Efficiency (%)	12.3
BESS	Rated power (kW)	6/24 kWh
	Max SoC	0.8
	Min SoC	0.2
	Charging efficiency	0.8
	Discharging efficiency	0.8
	Lifetime (Years)	15
	Capital cost ($/kW)	400
	O&M cost ($/kW-year)	80
	Replacement cost ($/kW)	400
FC	Rated power (kW)	5
	Lifetime (Years)	25
	Capital cost ($/kW)	3000
	O&M cost ($/kW-year)	175
	Replacement cost ($/kW)	-
EP	Lifetime (Years)	25
	Capital cost ($/kW)	2500
	O&M cost ($/kW-year)	175
	Replacement cost ($/kW)	-
Compressor	Lifetime (Years)	25
	Capital cost ($/kW)	1000
	O&M cost ($/kW-year)	-
	Replacement cost ($/kW)	-
Tank	Lifetime (Years)	25
	Capital cost ($/kW)	1323
	O&M cost ($/kW-year)	-
	Replacement cost ($/kW)	-

4.1.2. Modeling of ADLC

An incentive-based DR, ADLC, is presented to bridge the gap between supply and demand curves. We assumed that this contract would be signed by consumers who have rooftop PV. Following the agreement, consumers consent to power outages when there is a power deficit. Each contracted house will be subjected to a maximum of 2 h of power outage per day, with $0.09 compensation for each kW of the outage.

- IL function in ADLC: Equation (1) defines the content of IL in this suggested method.

$$0 \leq IL(kWh) \leq IL_{max}(kWh) \quad (1)$$

where IL_{max} is the maximum quantity of IL in each hour.

- Compensation function in ADLC: In ADLC, the compensation cost is calculated by the Equation (2):

$$compensation = \sum_{t=1}^{n} IL_t(kW) * PR_{comp}(\$/kW) \quad (2)$$

where IL_t is the IL in hour t and PR_{comp} is the compensation money per kW, which is considered $0.09 here.

4.1.3. Procedure of Seawater Electrolysis

Seawater is electrolyzed to produce hydrogen and sodium hypochlorite (about 3% saltwater). The hydrogen is stored in a hydrogen tank and used to generate electricity via FC in the time of energy shortage. The following is a summary of the chemical reactions in an EP [100].

$$Salt + Water + Energy = Hypo + Hydrogen \tag{3}$$

$$NaCl + H_2O + 2e = NaOCl + H_2 \tag{4}$$

Table 11 shows the price and quantity of hydrogen and sodium hypochlorite generated by seawater electrolysis per 1 kWh.

Table 11. Price and quantity of chemical product.

Chemical Product	Price	Quantity
H_2	0.196 [$/Nm^3]	0.0941 [Nm^3/kWh]
NaOCl	0.364 [$/kg]	312 [g/kWh]

5. Objective Function and Constraints

5.1. Objective Function

The electricity generated by PV is expected to be proportionate to the number of PV installed. The objective function's purposes are to minimize the entire life cycle cost (LCC) of installed equipment (case 1), as shown in Equation (5), and to reduce the disparity between LCC and total profits from chemical product sales (case 2, 3, 4) as shown in Equation (6).

$$Min : LCC = C_F + \sum_{y=1}^{Y} \frac{C_{O\&M}(y) + C_{RP}(y)}{(1+D)^y} \tag{5}$$

$$Min : LCC = C_F + \sum_{y=1}^{Y} \frac{C_{O\&M}(y) + C_{RP}(y)}{(1+D)^y} - P_C \tag{6}$$

where C_F is the initial/fixed investment cost [$]; $C_{O\&M}(y)$ the operation and maintenance cost; and $C_{RP}(y)$ the replacement cost in year y (yen) for the PV, BESS, FC, hydrogen tank, and compressor. Y is the total lifetime (year) of the project, which is considered 25 years in this paper. D is the discount rate, which is assumed to be 3% in this paper. P_C is the total profits from the selling of chemical products.

MILP is used to calculate the optimal numbers of installed PV, BESS, FC, hydrogen tanks, and compressors; and the operating schedules for BESS discharging and charging, and seawater electrolysis. Hydrogen will be sold until the hydrogen filling rate (HFR) of a pressure vessel comes to 50%.

5.2. Constraints

i. Constraints for charging and discharging of BESS are given below:

$$B_c(t) + B_d(t) \leq 1 \tag{7}$$

where B_c and B_d are the charging and discharging state of BESS, respectively.

$$SOC_{min} n_B C_B \leq \sum_{t=1}^{T} \left(\eta_{cB} E_c(t) - \frac{1}{\eta_{dB}} E_d(t) \right) + SOC_i \tag{8}$$

$$\sum_{t=1}^{T} \left(\eta_{cB} E_c(t) - \frac{1}{\eta_{dB}} E_d(t) \right) + SOC_i \leq SOC_{max} n_B C_B \tag{9}$$

ii. Maximum output power of BESS and FC:

$$E_c \leq n_B E_c^{max} \tag{10}$$

$$E_d \leq n_B E_d^{max} \tag{11}$$

$$E_{FC} \leq n_{FC} E_{FC}^{max} \tag{12}$$

iii. Constraints of hydrogen filling rate:

$$0.5 n_T C_T \leq \sum_{t=1}^{T} \left(a E_{EP}(t) - \frac{1}{b} E_{FC}(t) \right) + HFR_i \tag{13}$$

$$\sum_{t=1}^{T} \left(a E_{EP}(t) - \frac{1}{b} E_{FC}(t) \right) + HFR_i \leq 0.95 n_T C_T \tag{14}$$

iv. Limitation of the flow rate of the hydrogen tank and compressor:

$$a E_{EP}(t) \leq n_T Q_{H_2}^{max} \tag{15}$$

$$a E_{EP}(t) \times 2.2 \times \frac{ln(ER_F/0.1)}{ln(20/0.1)} \leq n_{CP} E_{CP} \tag{16}$$

v. Power balance limit:

$$\begin{aligned} &n_{PV} E_{PV}(t) + n_{FC} E_{FC}(t) + n_B (E_d(t) - E_c(t)) \\ &- E_{EP}(t) - E_{CP}(t) - E_{sr}(t) - E_{IL}(t) = E_L(t) \end{aligned} \tag{17}$$

where, n_{PV}, n_B, n_{FC}, n_T, n_{EP} and n_{CP} are the number of each installed equipment. C_B and C_T the per unit capacity of BESS and hydrogen tank, respectively. η_{cB}, η_{dB} are charging and discharging efficiency which have taken by 80% in this paper; E_{PV}, E_{FC}, E_{EP} and E_{CP} are the generated or consumed power [kW] of each installed equipment. E_d and E_c are the discharging and charging power of BESS. E_d^{max}, E_c^{max} are the maximum discharging and charging power [kW] of BESS. E_{FC}^{max} is the maximum output power [kW] of FC and E_{sr} is the surplus power [kW]; SOC_i is the initial state of the SOC of BESS; a and b are the coefficients, $Q_{H_2}^{max}$ is the maximum hydrogen flow rate per unit [kg/h]. E_{IL} is the amount of IL [kW] and E_L is the load demand [kW].

6. Results

The goal of this study was to achieve optimal sizing of the generating unit and storage system in order to meet electric load demand at the lowest possible cost using 100% RESs. The MILP optimization approach was used to carry out the simulations in MATLAB®. Four different cases were considered with combinations of PV, BESS, and FC with the EP for the system to fulfill consumers' electric demand, which will be described in following paragraphs.

i. Case 1: To demonstrate the efficacy of the suggested technology, an initial power system design consisting of PV as a generating unit and BESS as a storage system was considered in this case. Table 12 illustrates the optimal result of this case. Figure 4a shows the one month PV generation. Deviation of PV generation and load demand is shown in Figure 4b. Figure 4c shows 5 days optimal configuration of installed equipment .

ii. Case 2: In this case, EP was considered with PV, BESS, and FC. The results of this case are shown in Table 13. Figure 5a shows the one month PV generation. Trends of PV generation and load demand are shown in Figure 5b. The 5-days optimal configuration of installed equipment and the production of NaOCl are shown in Figure 5c,d respectively.

Table 12. Simulation results of case 1.

Parameters	Number of Unit
PV	5
BESS	20
Total cost ($)	2491.3
Surplus power (kWh/month)	2572.4

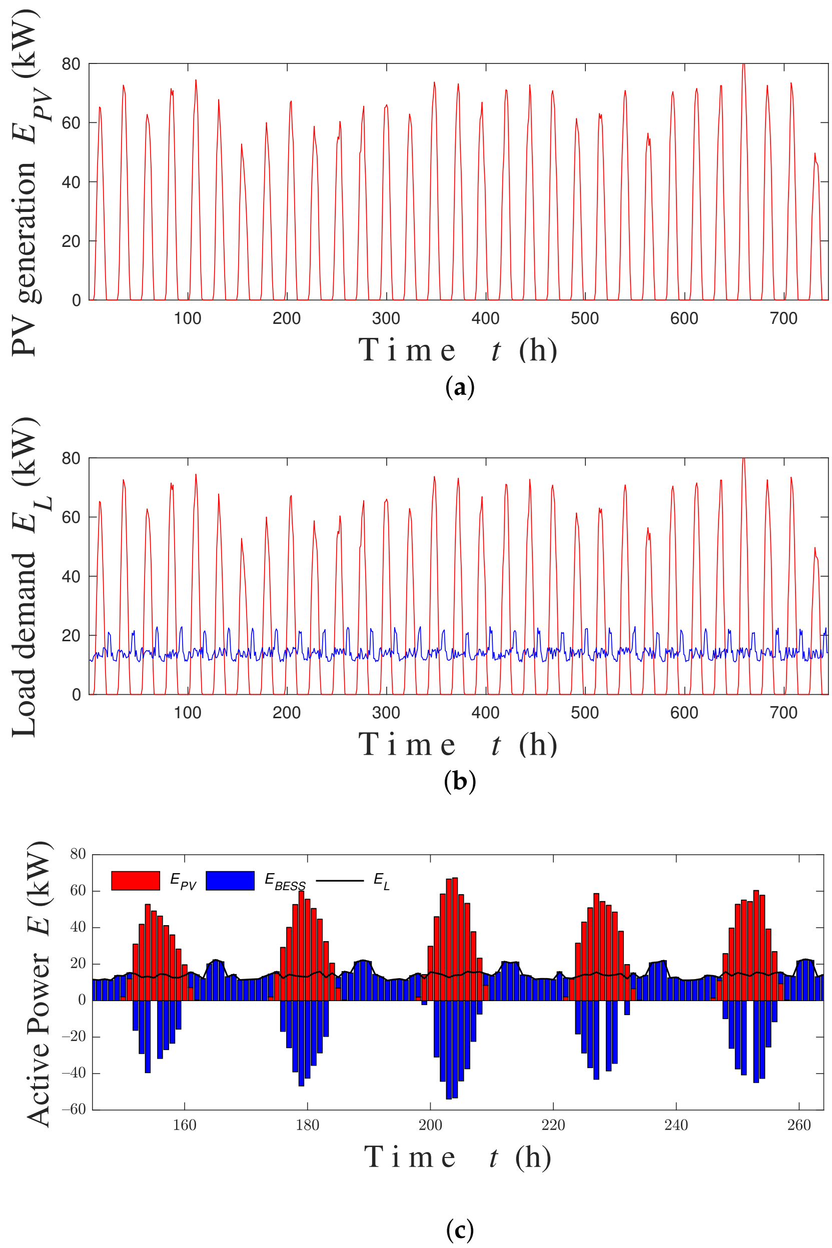
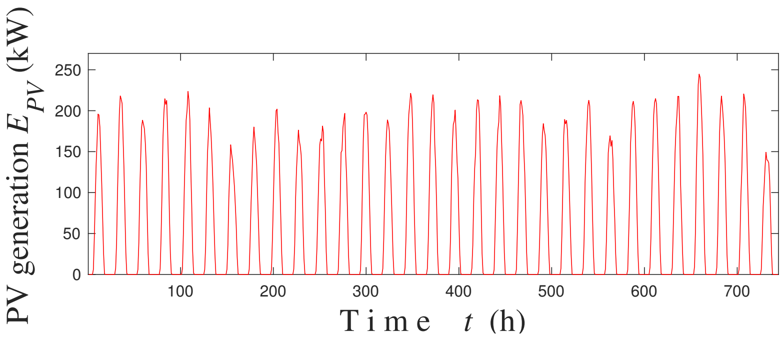


Figure 4. Simulation results of case 1. (**a**) The per hour PV generation. (**b**) The trends of PV power and load demand. (**c**) The simulation results for 5 days.

Table 13. Simulation results of case 2.

Parameters	Number of Unit
PV	15
BESS	0
FC	5
Hydrogen tank	1
Hydrogen compressor	1
Total cost ($)	14,316
Surplus power (kWh/month)	0
Revenue ($)	43,799



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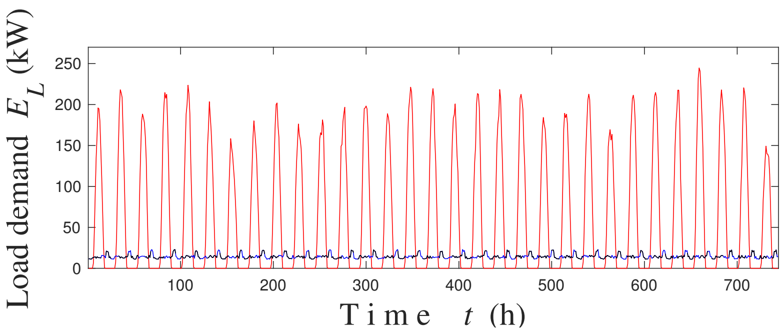

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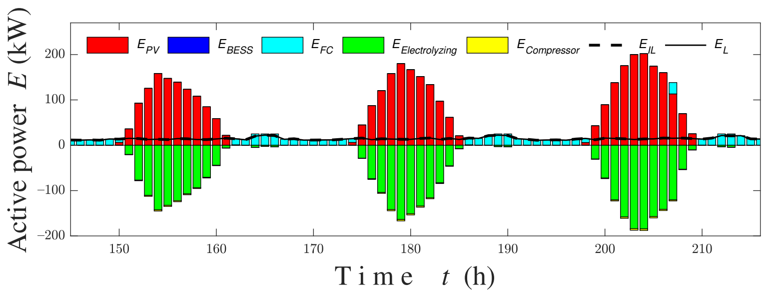
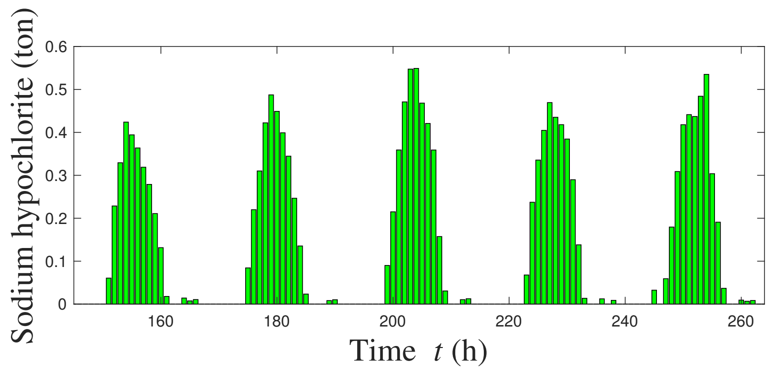


(**c**)

Figure 5. *Cont.*



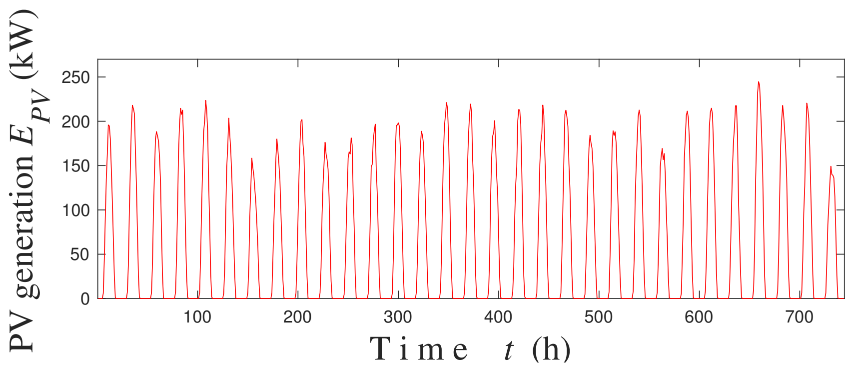
(**d**)

Figure 5. Simulation results of case 2. (**a**) The per hour PV generation. (**b**) The trends of PV power and load demand. (**c**) The simulation results for 5 days. (**d**) The generation of NaOCl in 5 days.

iii. Case 3: In this case, the installed equipment was the same as in case 2, but ADLC was applied. The obtained results are illustrated in Table 14. Figure 6a shows the one month PV generation. Trends of PV generation and load demand are shown in Figure 6b. The 5-days optimal configuration of installed equipment and the production of NaOCl are shown in Figure 6c,d respectively.

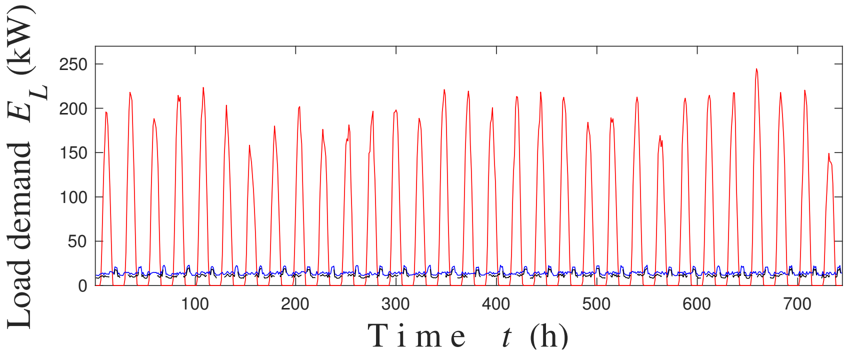
Table 14. Simulation results of case 3.

Parameters	Number of Unit
PV	15
BESS	0
FC	4
Hydrogen tank	1
Hydrogen compressor	1
Interruptible load(kWh/month)	2232
Compensation cost ($)	200.88
Total cost ($)	14,416
Surplus power(kWh/month)	0
Revenue ($)	46,710

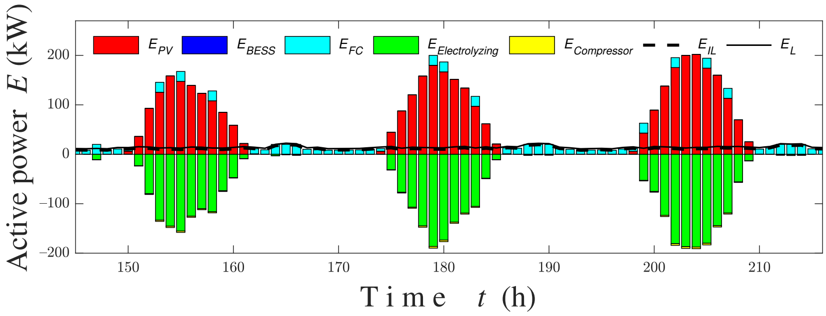


(**a**)

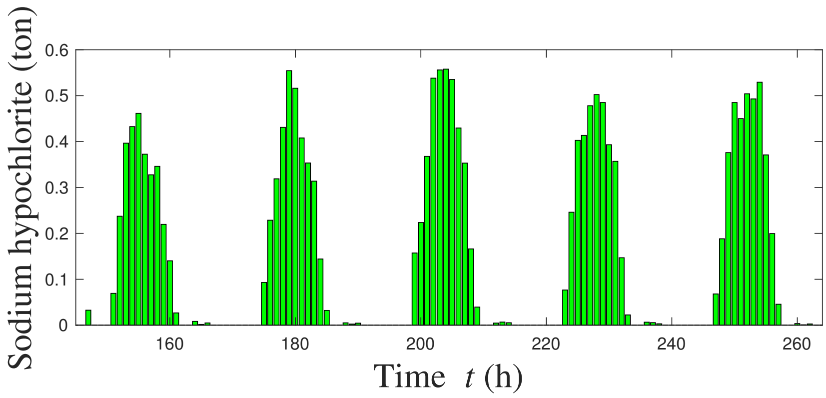
Figure 6. *Cont.*



(**b**)



(**c**)



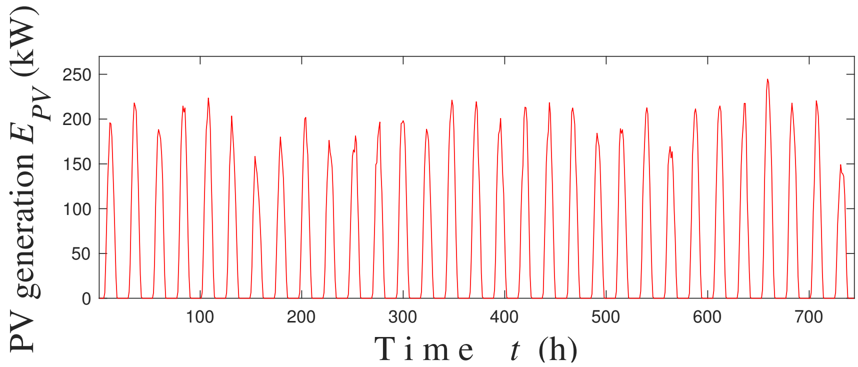
(**d**)

Figure 6. Simulation results of case 3. (**a**) The per hour PV generation. (**b**) The trends of PV power and load demand. (**c**) The simulation results for 5 days. (**d**) The generation of NaOCl in 5 days.

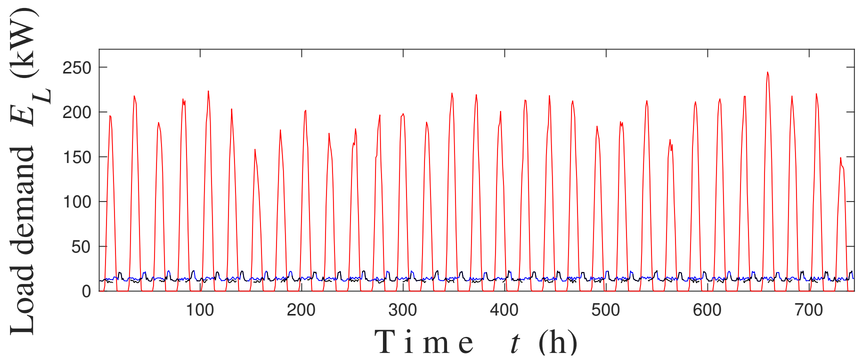
iv. Case 4: In this case, ADLC was applied to the consumers who had rooftop PV. Table 15 shows the results of this case. Figure 7a shows the one month PV generation. Trends of PV generation and load demand are shown in Figure 7b. The 5-days optimal configuration of installed equipment and the production of NaOCl are shown in Figure 7c,d respectively.

Table 15. Simulation results of case 4.

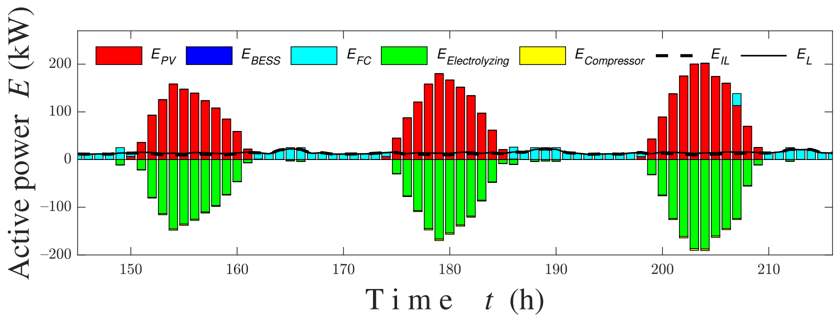
Parameters	Number of Unit
PV	15
BESS	0
FC	5
Hydrogen tank	1
Hydrogen compressor	1
Interruptible load(kWh/month)	853
Compensation cost ($)	76.7
Total cost ($)	14,393
Surplus power(kWh/month)	0
Revenue ($)	44,912



(**a**)

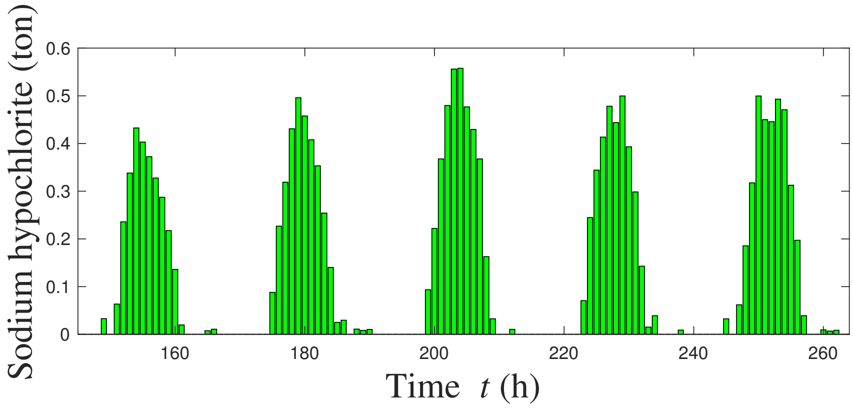


(**b**)



(**c**)

Figure 7. *Cont.*



(**d**)

Figure 7. Simulation results of case 4. (**a**) The per hour PV generation. (**b**) The trends of PV power and load demand. (**c**) The simulation results for 5 days. (**d**) The generation of NaOCl in 5 days.

7. Discussion

For the basic scenario, a DG of 30 kW is considered the ideal architecture; demand, component cost characteristics, and resource availability are taken into account. This scenario is now in use in St. Martin's Island. The cost of electricity for a DG is around $0.465 per kWh. The present diesel-only power system is around 4.1 times more expensive than case 1 of the proposed system. This is mostly due to the current rise in diesel fuel prices. The DG is also responsible for the release of greenhouse gases.

All cases proposed in this paper can fulfill the load demand with appropriate sizing utilizing MILP approaches. In case 1, the load demand can be satisfied with a total cost of 2491.3 dollars per month, which is less than in any other case. However, there is surplus power of 2572.4 kWh each month that will be wasted.

In case 2, FC and EP are introduced to utilize the surplus power for seawater electrolysis to produce NaOCl and H_2 and make a profit from selling these products. The total cost is 14,316 dollars, which is higher than case 1, but there is a profit of 43,779 dollars per month, which is impossible to gain in case 1.

In case 3, the optimal configuration of the same generation units and storage systems as in case 2 is considered in the presence of ADLC. The total cost is 14,416 dollars per month, but the profit increases to 46,710 dollars, which is 2931 dollar more than in case 2. However, in this case, the consumers cannot use electricity during a power outage, which will burden consumers.

In case 4, rooftop PV are considered with the same system configuration as case 3. In this case, ADLC is applied to the consumers who have rooftop PV. This system is more reliable for consumers than case 3, as they can use PV power during power outages. The total cost is also decreased to 14,393 dollars, and the revenue reduced to 44,912 dollars.

Case 1 has a lower installation cost than the other cases, but there is no additional profit, and the surplus power will be squandered. As profits are probable from chemical sales, the installation costs in cases 2, 3, and 4 could be reimbursed in 8.17, 7.72, and 8.01 years, respectively. On the other hand, in these three cases, BESS is not used. Thus, BESS can be ignored while implementing a power system with EP and FC. The revenue of case 3 is 6.23% higher and 3.85% higher than in cases 2 and 4. The amount of IL is 2232 kWh per month in case 2, which is 61.8% higher than in case 4, imposing a burden for consumers. Thus, rooftop PV is considered in case 4 to make the system more reliable by reducing the amount of IL.

8. Conclusions

The electrification of developing countries is in serious jeopardy. Delivering power from the main grid to rural regions is one of the most significant obstacles to achieving 100% energy availability across such countries. Despite having a low per capita energy demand, Bangladesh, a developing South Asian country, suffers this difficulty. Bangladesh is experiencing an energy crisis which is halting the country's economic growth. About 4% of the population is still without electricity, a problem that cannot be solved without addressing the issue of powering distant places. Load shedding affects residents in electrified regions as well. RE, especially solar power, can significantly help meet the demand of Bangladeshi sustainably. The present energy condition, alternative renewable resources, and future possibilities of Bangladesh were explored; and an optimal 100% RE-based off-grid power system consisting of PV, BESS, FC, and EP for St. Martin's Island, Bangladesh, was proposed in this paper in order to fulfill energy demands at the lowest cost and with maximal profit (by selling chemical products created by seawater electrolysis). The MILP optimization technique solved the proposed power system model. Four cases were considered to verify the effectiveness of the proposed method, and the results illustrate that:

- Although case 1 has a lower installation cost than the others, as it consists of only PV and BESS, there is no opportunity for additional profit, and the surplus power will be wasted. The installation costs of cases 2, 3, and 4 are higher than case 1, but these can be made up for in 8.17, 7.72, or 8.01 years, respectively, by the profits from chemical sales. Though case 3 generates 6.23% and 3.85% more profits than cases 2 and 4, respectively, it is not reliable, as the quantity of IL is 2232 kWh per month, which is very high and puts a strain on customers. As a result, in case 4, rooftop PV is used to make the system more dependable by lowering the quantity of IL.
- In case 4, the IL is only applied to the consumers who own rooftop PV, which reduces the system's cost and profits, but makes the system more stable than other cases.

The load demand data for St. Martin's Island were assumed in this paper, which will have caused minor errors in computing the compensation cost due to real-time load uncertainty.

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