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Analysis of Remote PV-Diesel Based Hybrid Minigrid for Different Load Conditions

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Abstract- Lack of quality electricity supply in the remote areas is one of the main hindering factors of global development. Many countries around the world are trying to utilize renewable energy sources for remote electrification including developing countries like Bangladesh. After the renowned Solar Home System (SHS) program, Bangladesh is now focusing on solar PV- diesel hybrid minigrid system to reach more people by providing affordable electricity. Following the availability of electricity in the form of minigrid, a development in industries like sawmills, grinding mills, husking mills is predictable. Therefore, daytime loads might have significant contribution in energy consumption, unlike the usual residential scenario. With this, the irrigation demands are there during the dry season. This study analyzes the techno-economic feasibility of the solar PV-diesel hybrid system with different load conditions. A remote area of southern Bangladesh is taken as the case site. Three case studies are formulated based on the time of using irrigation pumps. HOMER Pro Microgrid Analysis Tool has been used to find the most optimized configuration for each case study. The optimized configurations from each case study are then evaluated based on the cost of electricity (COE), greenhouse gas emissions and renewable energy fraction. The generation profile of solar PV and diesel generators are analyzed for each case study. From the techno-economic evaluation, it is observed that the optimum time to run the irrigation pumps is during the daytime. In this case, the solar PV has the highest contribution to meet the energy demand with the slightly increased cost of electricity.

Keywords-*microgrid; hybrid system; solar PV; irrigation; rural minigrid*

I. INTRODUCTION

Energy is the ultimate bloodline of civilization; every aspect of modern life is one way or another derived from any form of energy. Among all the forms of energy, the most commonly used and the most important in our modern life is the electricity. However, even today a significant portion of the world is without electricity. Most of the remote and rural areas those are geographically or topographically isolated from the urban areas have a scarcity of energy services, leads to lack of modern facilities, which is considered as one of the major obstacles to global development. Therefore, a reliable and continuous supply of electricity is essential not only for the social and economic development of communities but also for vital services like health and education. However, it is not always that straightforward task to bring the remote areas under the regular electricity network. Electricity networks consist of complex entities. It requires a high initial investment cost to expand the grid and regular maintenance cost. But it is not feasible to expand the network if the load density is not high enough. Therefore, the governments around the world are becoming reluctant to invest in expanding the grid to remote areas. Hence, small scale standalone diesel generator based power systems are being used in remote or rural locations. On the other hand, the concern of global warming and finite source of fossil fuels have raised a big question about the sustainability of typical fossil fuel generated electricity. Therefore, the concept of renewable energy sources like solar energy, wind energy, and biomass energy has been emerging for a couple of decades. These renewable energies are recently used in the remote areas either in the local networks or as a single unit. Remote networks consist of diesel generators, and renewable energy sources are reliable, sustainable and even cost effective compared to both grid connected system and only fossil fuel based system [1-4].

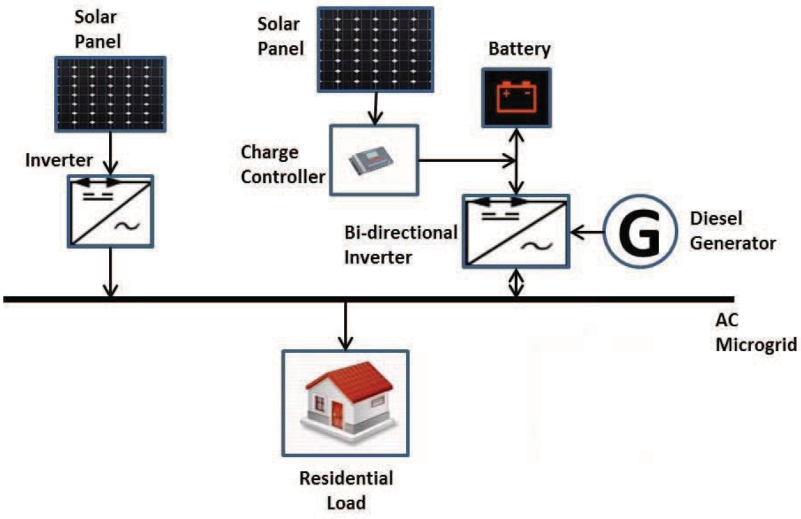
Several countries around the world, such as Australia, Bangladesh, India, South Africa, and Malaysia are involved in extensive research and development on renewable energy based rural electrification which includes standalone unit and microgrid system with distributed renewable energy sources. The addition of renewable energies, particularly solar and wind power into the generation mix can significantly contribute in global Greenhouse Gas (GHG) emission reduction initiative.

Being a developing country, Bangladesh is struggling to provide electricity to a major portion of the country; most of them are very remote. Approximately 40% of the population has no access to electricity [5]. However, the government has been trying to utilize the renewable energy sources, particularly solar PV to address the electricity crisis of the remote areas [6]. Bangladesh already has gained worldwide recognition for the solar home system (SHS) based rural electrification program. Under this program, approximately 140MWp system has been installed throughout the country, and their target is to reach 220MWp by 2017 [7]. These small electricity access systems currently consist of a 20 to 100 Wp solar panel, a lead acid battery, a charge controller and basic loads. However, regardless of this success, there are certain limitations of this electrification option that includes- the poorest demographic segment cannot afford the solar home system [8]; there is explicit limitation to utilize the energy for productive purposes [9]; the systems often suffer from excess capacity as they are generally designed over-sized to assure high reliability, excess capacity is the generated energy that gets lost as the battery is full; the systems are not flexible regarding usage patterns and payment methods [10]. Therefore, to allow the off-grid population in Bangladesh to develop further economically, socially, and technologically, a better option for electrification need to be explored. One prospective and flourish option could be the application of rural microgrid or so-called minigrids. Such small grids will provide electricity to rural people and can contribute significantly to improve their quality of life. A detailed study of solar-diesel hybrid minigrid project in Bangladesh is discussed in [11] and [12]. In typical systems as described in [11] and [13], the solar PV panels are connected to the grid in two different ways. One set of panels is connected directly to the grid through grid tie inverter. Another set of PV panels are used for battery charging, and the battery is connected to the grid through a bi-directional inverter. A single diesel generator is acting backup system during the evening and cloudy days. The system is depicted in Fig. 1. With the introduction of the minigrid, a better growth of commercial and industrial loads in the likes of the sawmill, husking mill, grinding mill is expected. Therefore, unlike the regular residential load curve, the daytime load has a significant magnitude in the load curve. Moreover, irrigation pumps can play a vital role in the control and design of the system. The objective of this paper is to analyze techno-economic feasibility of the rural solar-diesel hybrid minigrid with high daytime load and irrigation pumps. The cost-effectiveness and environmental impact of different system designs in relation to different irrigation times are investigated with the help of case studies.

II. RURAL MICROGRID SYSTEM

A remote rural area located at southern part of Bhola (22.0470N, 90.630E), the biggest island of Bangladesh, is taken as the case site for this study. The area consists of a big marketplace, irrigation demand during the dry season, a couple of schools, mosques and general residential load. It is assumed that the daytime electricity demand of the marketplace is high due to several mills and large

Fig. 1. Typical minigrid system[13]



shops. A typical load curve of the area excluding the irrigation demand is shown in Fig. 2. To meet the irrigation demand of the area, 20 pumps of 2KW need to run for on average nine hours a day during the dry season (typically November to April) [14]. The demands of the irrigation pumps are significantly high with respect to the load curve of the area. Therefore, based on the time of running the irrigation pumps three case scenarios have been developed in this paper.

Case-1: Irrigation pump is considered as the deferrable load in addition to the primary loads curve. Deferrable load is electrical load that must be met within some time period, but the exact timing is not important [15].

Case-2: irrigation pumps operate only during the day, from 8am to 4pm.

Case-3: Irrigation pumps work only during night, from 10pm to 6am.

The climatic data of the study area, e.g. solar radiation, temperature, are collected from NASA Surface metrology and Solar Energy [16].

III. SYSTEM DESIGN

HOMER Pro Microgrid Analysis Tool 3.6.1 [15] is used as the simulation platform for this work. The system consists of solar PV, battery, diesel generators, converters, and loads. Unlike the system proposed in [13], all the PV panels are connected to the grid through an inverter and the battery is connected to the grid through the bi-directional inverter. It is observed from the preliminary simulations that using two different diesel generators instead of one is more economic. It will increase the reliability of the system and decrease the overall fuel consumption. Therefore, instead of a single large generator multiple small generators are used in the system design. The system showed in Fig. 3 is used for all the simulations.

Fig. 2. Load Curve without irrigation load

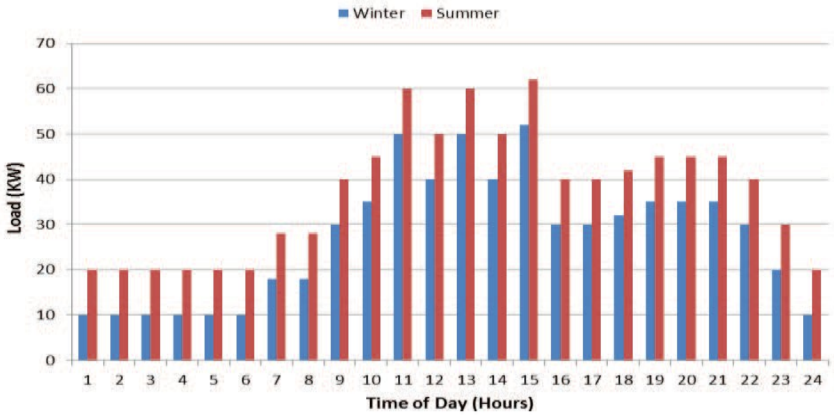
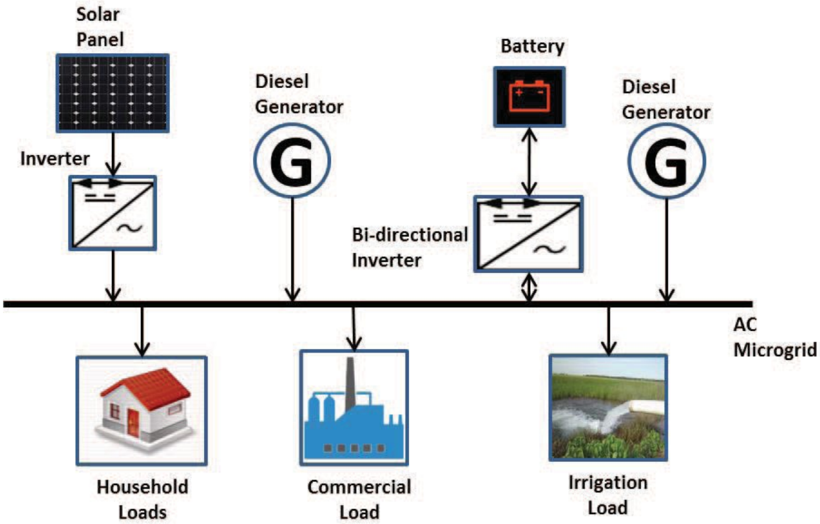


Fig. 3. Proposed system



The case studies are simulated considering few constraints to maintain the system reliability and quality. The constraints are-

a. No annual capacity shortage is allowed. The system should meet the entire load.

b. 40% of the annual energy needs to come from renewable energies. The cost of electricity increases with higher renewable fraction. Therefore, a conservative limit of 40% is considered here. With the declining cost of renewable sources, particularly solar PV, it would be easier to increase the renewable fraction with lower cost in the future.

c. For continuous, reliable operation and to sustain in a sudden incident every system should have an operating reserve. Due to the intermittency of solar energy, system with solar PV has additional operating reserve. In this study, the operating reserve is considered as 10% of the current load and 25% of the solar power output of any time step.

The systems are simulated in two types of dispatch strategy, load following (LF) and cycle charging (CC). In the load following strategy the generators only produce electricity to meet the primary load. Renewable energy sources are responsible for charging the battery storage and serving deferrable loads. On the other hand, in cycle charging strategy the generators charge the battery storage or serve deferrable loads with the surplus electricity after meeting the primary load. In cycle charging strategy, there is a provision to apply a set-point state of charge of the battery. The generators will charge the battery until it reaches the set-point state of charge. However, for all the cases of this study the dispatch strategy is left for HOMER to select optimally. The set-point state of charge is assigned as 80%, and the diesel generators are allowed to run simultaneously and run off. The generators are set to take at least 30% of their capacity, and it will run minimum 20 minutes once it is started.

A. *Case Study-1*

In this case study, the irrigation pumps are considered as a deferrable load. Deferrable loads must be met within some time period, but the exact timing is not critical [14]. Therefore, the irrigation pumps are assumed to run based on the situation of the other loads and generations. Considering the system primary load and irrigation load, the system components are optimized considering all the constraints to reach the minimum cost of electricity. The system designed in HOMER for case study-1 is showed in Fig. 4. Generic 2V lead-acid battery is considered for the system. 24 batteries are connected in series in a string to make the DC bus voltage 48V.

The considered capacities of each component are showed in Fig. 5. However, these values are considered based on the knowledge gained from several trials. This search space is used for case study-2 and case study-3 also.

The optimization results are given in Fig. 6. The optimization outcome reveals that the system with large PV of 147KWp with two generators of 50KW and 30KW and a single string of battery is the most economical. However, the system without any battery is feasible but marginally costly; the extra cost may be coming from the additional use of fuel.

Fig. 4. System design for Case Study-1

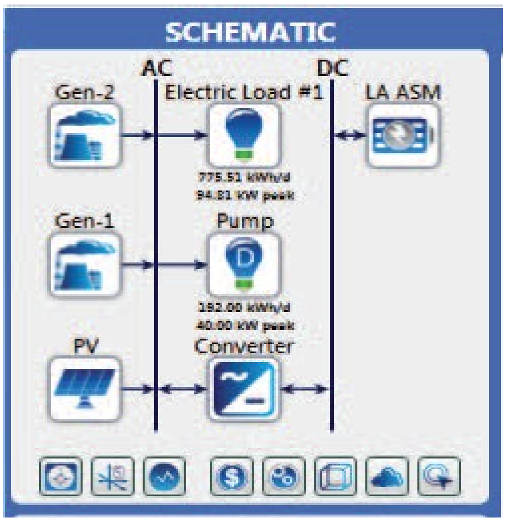
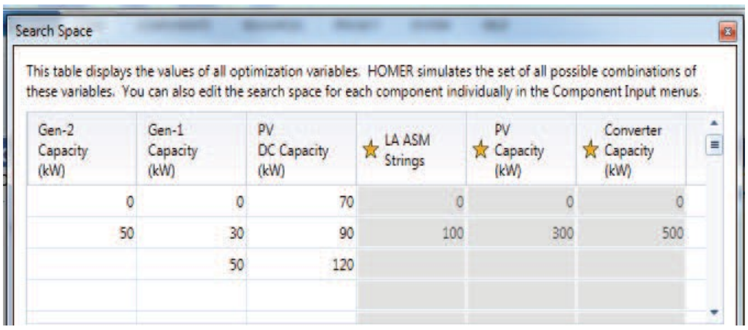


Fig. 5. Search Space to select the optimized size

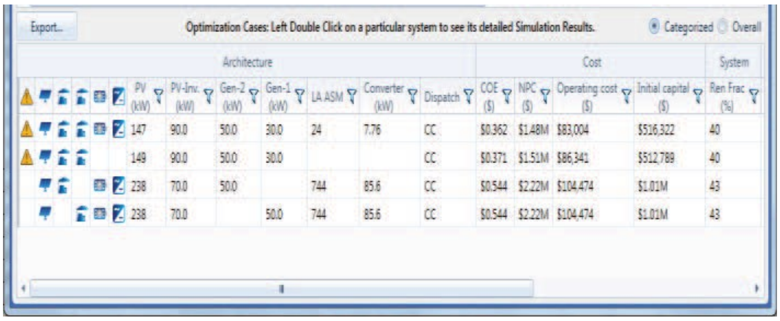


Search Space

This table displays the values of all optimization variables. HOMER simulates the set of all possible combinations of these variables. You can also edit the search space for each component individually in the Component Input menus.

Gen-2 Capacity (kW)	Gen-1 Capacity (kW)	PV DC Capacity (kW)	LA ASM Strings	PV Capacity (kW)	Converter Capacity (kW)
0	0	70	0	0	0
50	30	90	100	300	500
	50	120			

Fig. 6. Optimization outcome of Case Study-1



Export... Optimization Cases: Left Double Click on a particular system to see its detailed Simulation Results. Categorized Overall

Architecture							Cost				System
PV (kW)	PV-Inv. (kW)	Gen-2 (kW)	Gen-1 (kW)	LA ASM	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
147	90.0	50.0	30.0	24	7.76	CC	$0.362	$1.48M	$83,004	$516,322	40
149	90.0	50.0	30.0			CC	$0.371	$1.51M	$86,341	$512,789	40
238	70.0	50.0		744	85.6	CC	$0.544	$2.22M	$104,474	$1.01M	43
238	70.0		50.0	744	85.6	CC	$0.544	$2.22M	$104,474	$1.01M	43

B. *Case Study-2*

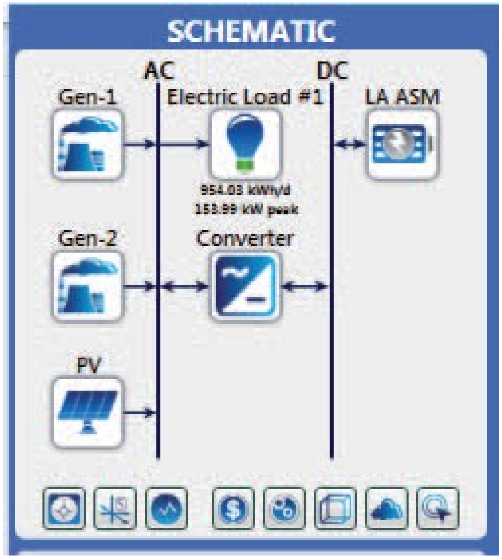
In this case study, the irrigation pumps are merged with the primary load curve with an assumption that the pumps can only run during the daytime. Therefore, the overall load pattern along with the peak load has been changed. The peak load is 154kW for this case. The system is given in Fig. 7.

Similar to the first case study, simulation is performed to find the optimized system with the new load. In this case, the PV capacity and number of batteries have increased compared to the case study-1 for the system with least electricity cost.

C. *Case Study-3*

The irrigation pumps are merged with the primary load curve with an assumption that the pumps can only run in the off-peak hours, during the night. The modified load curve is fed to the HOMER system to calculate the optimized system for this case. The system design is similar to Fig. 7 with the different primary load profile. The system peak load has significantly decreased compared to case study-2. The optimized system with least cost has similar PV capacity but a slightly higher size of battery and diesel generators compared to Case Study-2.

Fig. 7. System design for Case Study-2



IV. RESULT ANALYSIS

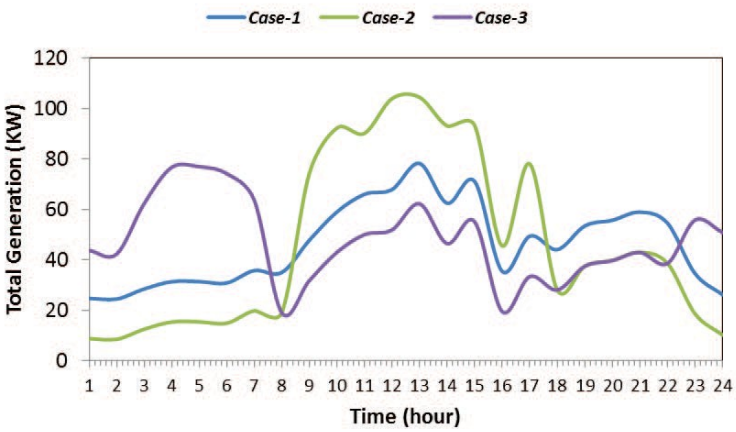
The three case studies of solar PV-diesel hybrid minigrid based on the time of irrigation are developed in HOMER simulation tool. After the optimization analysis for the minimum levelized cost of electricity, the most optimum configuration from each case study is taken for comparison. The component sizes and key parameters of the best system from each system are given in TABLE I. The COE of Case Study-1, and Case Study-2 are 0.366 $/KWh and 0.384 $/KWh respectively, which are very close. On the other hand, COE of Case Study-3 is little higher. Case Study-3 apparently needs to use more electricity from the diesel generators as it needs to provide a greater amount of electricity during the night. On the other hand, in case study-2, when the irrigation pumps run in the day time, Solar PV can contribute to the peak demand. That is why in case study-2 maximum solar output is 100 KW, wherein Case Study-1 and case study-3 the value is 90 kW and 80 KW respectively. The total electricity generation in all case studies during a typical day of irrigation season is illustrated in Fig. 8. It is worth to mention that for economic operation, in Case Study-1, the irrigation loads are distributed throughout the whole day. Having almost the same size of Solar PV, generators, and converters, the capital cost of all three systems are similar. However, the small variations are due to the higher number of batteries in Case Study 2 and 3. Fig. 9 illustrates the cost breakdown of the three case studies. Even though having the similar capital cost, case study-3 is comparatively more expensive due to it higher operation and maintenance cost and fuel cost.

The model provides the generation profile of each source to meet the load demand of the optimized systems of each case study. In Case Study-1, as shown in Fig. 10, the solar PV output is enough to meet the load demand during the day. The diesel generators start to run at the end of a day, before sunset. The batteries are fully charged by the solar PV and provide support to the system during transition periods. As the system for Case Study-1 follows cycle charging strategy, the batteries are charged to 80% state of charge (SOC) by generators. This 80% SOC help the batteries to provide support in the morning transition period when the load starts to increase. In this case, the daytime load

TABLE I. SIMULATION OUTCOMES

	Case Study-1	Case Study-2	Case Study-3
Cost of Electricity ($/KWh)	0.370	0.384	0.410
Renewable Fraction	40%	42%	40%
Excess Electricity	9.3%	5.1%	5.7%
Battery Autonomy (hours)	0.49	2.48	3
Dispatch Strategy	Cycle Charging	Cycle Charging	Load Following
PV capacity (KWp)	148	147	145
Generator-1 Size (KW)	30	30	40
Generator-2 Size (KW)	50	50	50
Battery (number of batteries)	24	120	144
Converter Size (KW)	12	23	36
PV Dedicated Converter Size (KW)	90	100	80

Fig. 8. Total generation in a typical day of dry season



is supported by solar PV and generators work after sunset to sunrise. Hence, the size and autonomy of the batteries are small. It is found that even the system without a battery can run economically with bit higher fuel cost.

In case Study-2, as the irrigation pumps are running during the daytime, the day load is very high. Solar PV cannot always meet the demand, leads to the occasional start of the generators as shown in Fig. 11. However, there may be instances with extra solar power, particularly at the beginning of the day. The additional energy is used to charge the batteries. On the other hand, during the late night the load demand becomes too low, therefore, sometimes it is more economical to discharge the stored energy from the batteries than run a generator. Hence, the battery capacity and autonomy are comparatively higher in this case. The higher capacity of the battery becomes handier during the rainy season when the solar PV output becomes more intermittent and generators start frequently.

Fig. 9. Cost breakdown

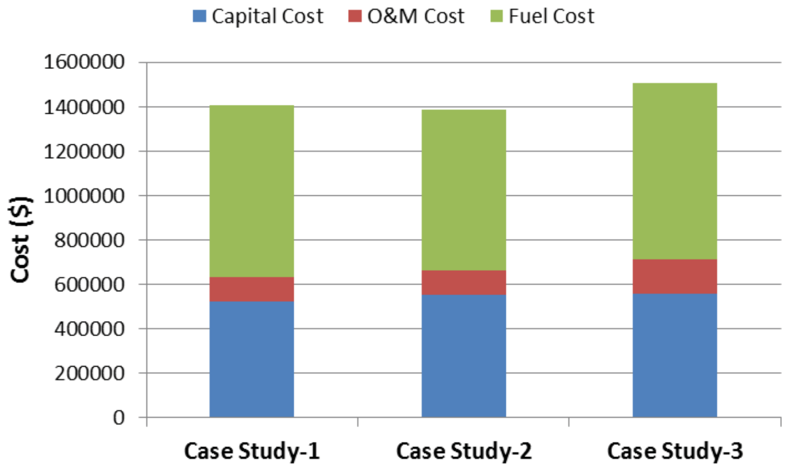
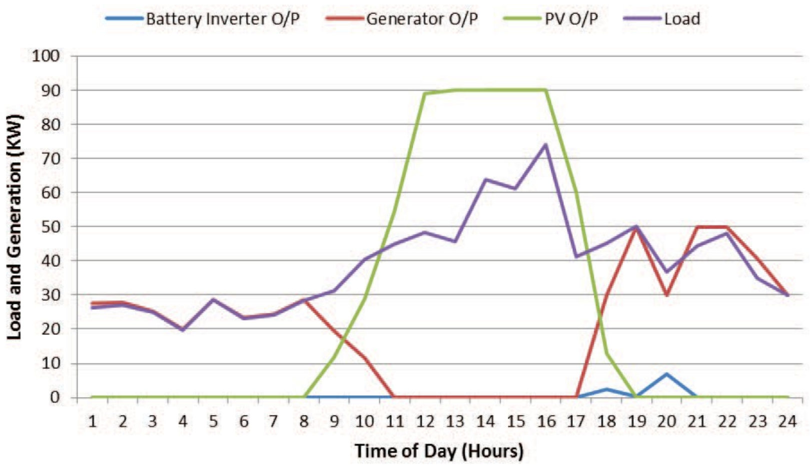


Fig. 10. Load and generations in a typical day of dry season for Case Study-1



The system for the Case Study-3 has a higher capacity of the diesel generators. As shown in Fig. 12, the solar PV output is usually more than enough to meet the load. The maximum load occurs at the late night when the irrigation pumps are running. The batteries store the extra energy from the solar PV to use it during the evening. The 1st generator starts to ramp up in the evening, and the 2nd generator joins when the irrigation pumps start at midnight. Hence, the peak load of irrigation pumping is entirely coming from the generators, which results in higher fuel cost and emissions. However, as the system follow load following dispatch strategy, the batteries are only charged by the solar PV. The emissions incurred from all case studies are shown in Fig. 13.

Fig. 11. Load and generations in a typical day of dry season for Case Study-2

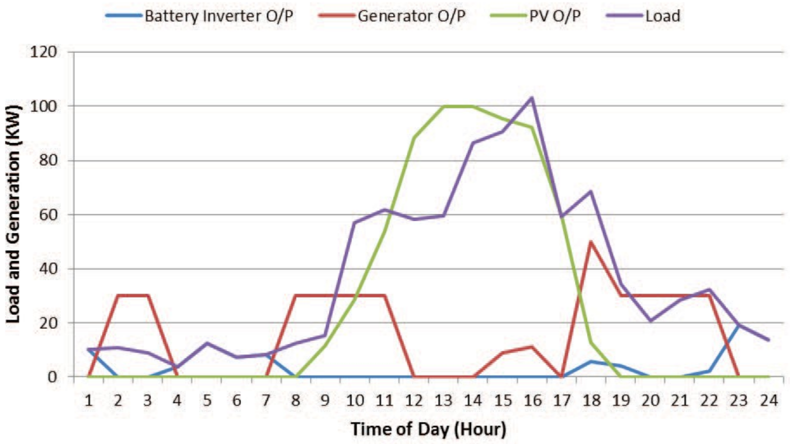
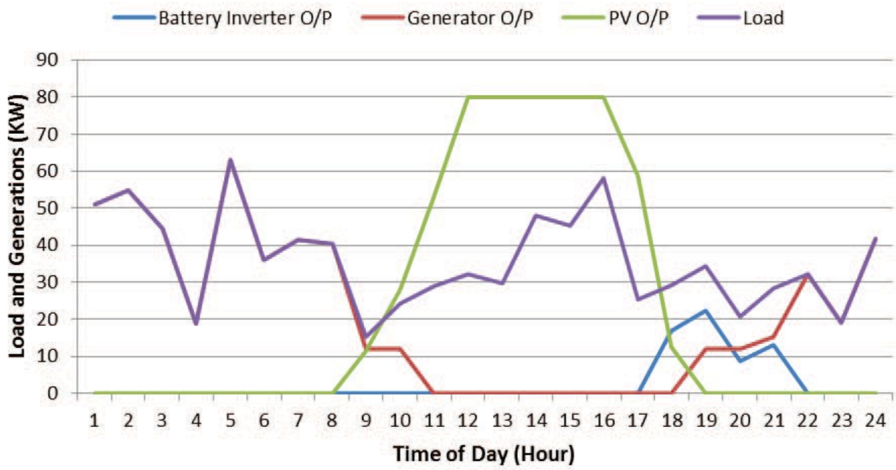
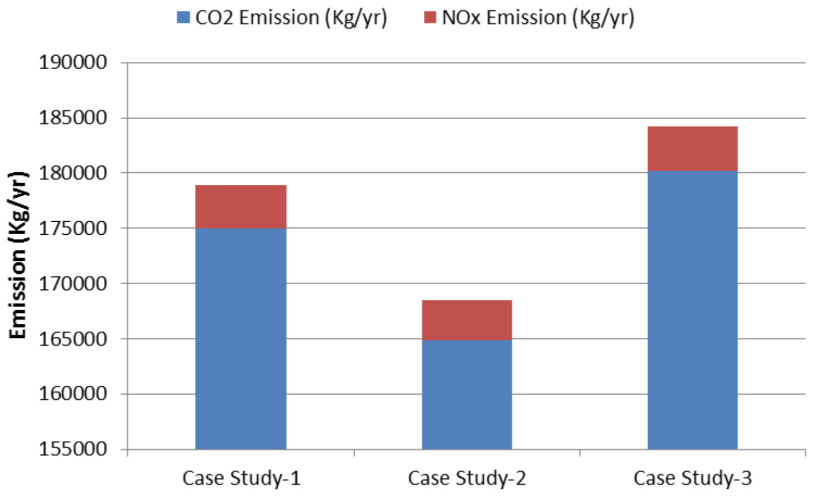


Fig. 12. Load and generations in a typical day of dry season for Case Study-3



In present condition diesel engines are used for irrigation in remote areas, which results in lots of emissions and of course very costly to afford. As explored from the simulation, the Case Study-3 of this work also uses mainly diesel generators and performing worst regarding emission and cost. On the other hand Case Study 1 and 2 have a similar cost, however, Case Study-2 uses for renewable energy. Moreover, from user's point of view, it is convenient to monitor the irrigation system during the day time.

Fig. 13. Emissions incurred from the systems



V. CONCLUSIONS

To limit GHG emission and for sustainable future, it is crucial to increase the uses of renewable energy and at the same time reduce fossil fuel consumption. Solar PV-Diesel hybrid minigrids are getting attentions for remote electrification in many countries around the globe. Bangladesh is already in a process to utilize the solar-diesel hybrid mingrid to provide quality electricity to the remote areas. On the other hand, being an agricultural country, there are demands for irrigation during the dry season. If properly designed the hybrid minigrid system can replace the currently used diesel engine based irrigation pump and in a process can help to avoid a good amount of GHG emission. This study focuses on the convenient way to meet the irrigation demand by the hybrid minigrid system. Three different case studies are formulated based on the time of irrigation pumps for a site located in the southern part of Bhola, the biggest island of Bangladesh. The operations of irrigation pumps at different times of a day significantly vary the load pattern of the system which results in various optimized system configurations. It is evident from the simulation, as expected when irrigation pumps operate during the daytime, a significant contribution of energy comes from solar PV. Hence, daytime irrigation results in minimum GHG emission. Moreover, the levelized cost of electricity is also competitive with other cases. Therefore, it is economically and environmentally suitable to operate irrigation pumps by solar PV-diesel hybrid minigrid during the day. The outcome of this study is expected to help the researchers and utilities to design the remote minigrids with irrigation loads.

The position of the irrigation pumps and diesel generators are not considered in this study. The voltage quality at different points of distribution line can be varied due the intermittency of the solar PV. There is scope to analyze the voltage and frequency condition of this kind of remote hybrid minigrid system.

Continuous measures should be taken to make the remote minigrid 100% renewable energy dependent. The possibilities to integrate other renewable energy sources like wind and biomass into the remote minigrids can be investigated. Renewable energy based remote grids will play a significant role in the sustainable demographic development of the rural areas.

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