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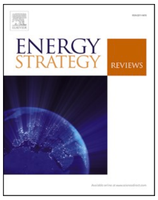

Selection of the best dispatch strategy considering techno-economic and system stability analysis with optimal sizing

Sk. A. Shezan [a,b], Md Fatin Ishraque [c,g], S M Muyeen [d,*], Ahmed Abu-Siada [e], R. Saidur [f], M.M. Ali [g], M.M. Rashid [g]

[a] Dept. of Electrical Engineering, Engineering Institute of Technology, Melbourne, Australia
[b] Dept. of Electrical and Electronic Engineering, Green University of Bangladesh, Mirpur, Bangladesh
[c] Dept. of Electrical, Electronic and Communication Engineering, Pabna University of Science and Technology, Pabna, 6600, Bangladesh
[d] Department of Electrical Engineering, Qatar University, Doha, 2713, Qatar
[e] Faculty of Science and Engineering, Curtin University, Perth, Australia
[f] School of Engineering, Sunway University, Kuala Lumpur, Malaysia
[g] Dept. of EEE, Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh

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ABSTRACT

In this paper, optimized hybrid off-grid renewable energy systems (HRES) have been designed for two divisional locations in Dhaka and Khulna in Bangladesh. An analysis is conducted using five different load dispatch strategies to find the best dispatch strategy for a cost-effective and technically feasible Islanded hybrid microgrid that will support the growing power demand. A comparative analysis among the various dispatch strategies is also presented to find out the best and worst dispatch strategies for the proposed HRESs. The two HRESs consist of solar PV, a backup diesel generator, wind turbine, load demand of 23.31 kW, and a battery storage system. HOMER predictive strategy, Generator Order, Load Following, Combined Dispatch, and Cycle Charging dispatch strategy has been adopted for evaluation. The two HRESs are optimized for CO_2 emission, Levelized Cost of Energy, and Net Present Cost minimization along with a feasible and stable voltage-frequency response on basis of the five dispatch techniques. The techno-economic analysis of the two HRESs is conducted using the HOMER Pro software platform. For the power system response analysis, MATLAB/Simulink is used. This study provides a complete guideline for determining the optimum component sizing ensuring optimum operation and possible costing estimation for the optimized performance of the two HRESs for different dispatch techniques. Also, a comparative study among the designed HRESs, other hybrid systems, and conventional power plants is conducted to prove the significance of this research work.

1. Introduction

The fossil fuel stock of the world is going to deplete within a very short time. Thus, renewable energy-based power generation may be the solution to future energy problems. Burning fossil fuel causes the emission of greenhouse gases (GHGs) which emphasizes the use of renewable sources like wind and solar. Hybrid Renewable Systems (HRES) can be considered as a feasible and efficient option for the inclusion of these renewable distributed sources [1]. For a remote area, the establishment, as well as conventional grid extension often become more expensive than installing a standalone HRES [2,3].

The electricity demand is increasing day by day. Harmful gas emission from conventional fuel-based plants causes a diversion of research interest towards renewable energy sources like hydro, geothermal, wind, biomass, wave and solar energy. In the present day, wind and solar energy technologies are more available and developed. Thus, a rise in the use of these energy resources in HRESs can be observed [4]. HRESs are highly effective and thus, in recent years, researchers have been interested in this topic [5,6].

HRESs, in general, contain distributed sources and loads. HRES have both AC and DC buses and different types of integrated generation sources. HRES can thus integrate both AC and DC loads and sources. For power generation and distribution in a remote area in a decentralized fashion, wind and solar-based stand-alone HRESs can be a suitable solution although their operation becomes challenging due to the intermittent characteristics of wind and solar. As the amount of power generation, as well as the load demand, is always variable, for a stand-

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* Corresponding author. Department of Electrical Engineering, Qatar University, Doha, 2713, Qatar.
E-mail address: sm.muyeeen@qu.edu.qa (S.M. Muyeen).

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Nomenclature

HRES	Hybrid Renewable Energy System
HOMER	Hybrid Optimization of Multiple Energy Resources
GHG	Green House Gas
AC	Alternating Current
DC	Direct Current
IES	Integrated Energy Systems
ED	Economic Dispatch
BESS	Battery Energy Storage System
PV	Photovoltaic
LED	Light Emitting Diode
EV	Electric Vehicle
IHMS	Integrated Hybrid Microgrid System
NPC	Net Present Cost
LCOE	Levelized Cost of Energy
VSC	Voltage Source Converter
IGBT	Insulated-Gate Bipolar Transistor
CDF	Cumulative Distribution Function
LF	Load Following
PS	Homer Predictive Dispatch Strategy
CD	Combined Dispatch
CC	Cycle Charging
GO	Generator Order
WT	Wind Turbine

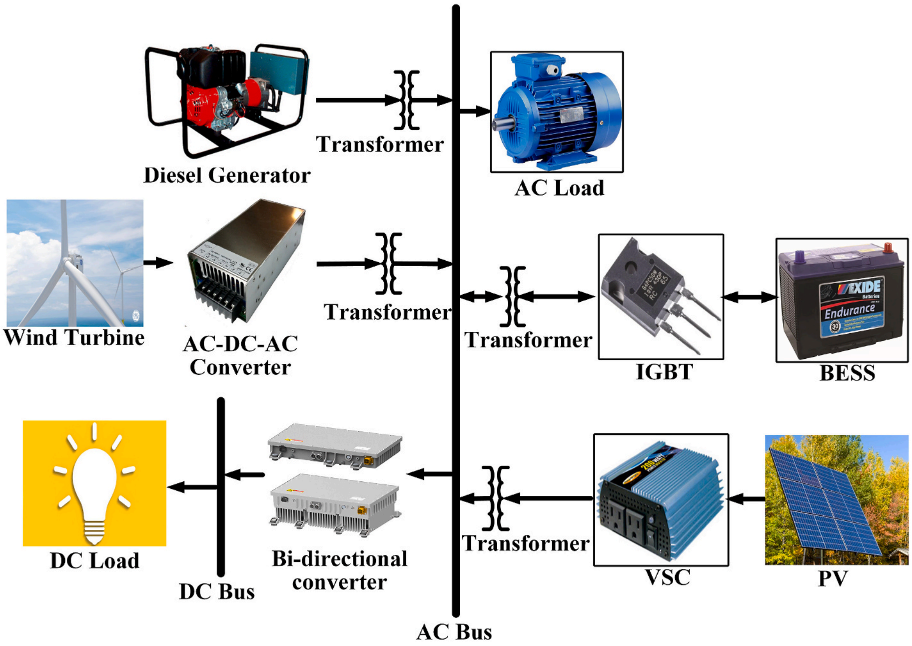

Fig. 1. Block model of the proposed HRES.

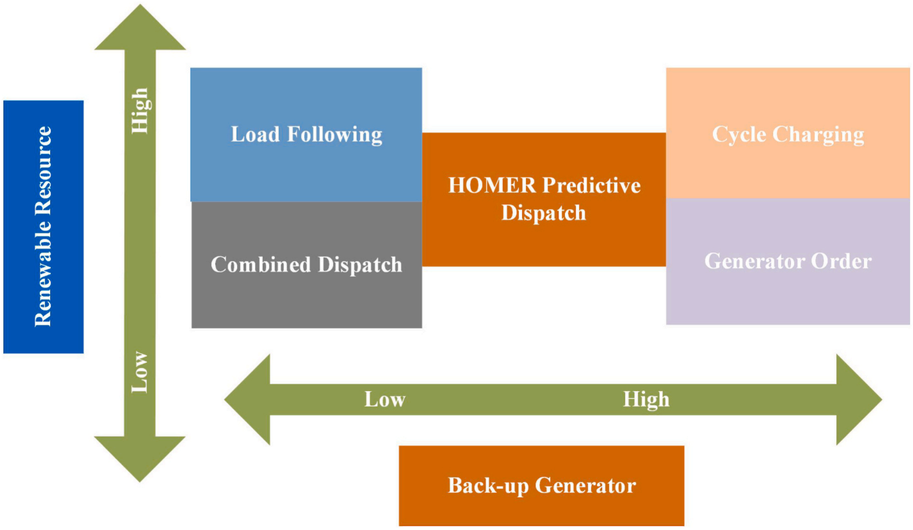

Fig. 2. Influence of renewable sources and diesel generator on basis of dispatch techniques for HRES.

Table 1
Brief chart of energy consumption according to the load capacity.

Apparatus	Unit capacity	Quantity	Capacity
Light Bulb	40 W	124	4.96 kW
Fan	90 W	80	7.2 kW
Water Pump	1500 W	5	7.5 kW
Television	100 W	17	1.7 kW
Fridge	130 W	15	1.95 kW
Total			23.31 kW

alone HRES, power system stability and reliability have always been critical issues. The current work proposes and investigates a revolutionary large-scale biomass-based heat-driven building cooling system for various Indian locations. A thorough benchmarking analysis of various scenarios (a total of 24 scenarios) is included in the study to assess the impact of different types of biomass, different cooling system configurations, and different biomass heater layouts on the thermodynamic, economic, and environmental aspects of the proposed solution [7,8]. In a distribution network, if there is a sudden or rapid change in the load demand or generation, the frequency and voltage fluctuation, referring to instability, may be observed in the system [9].

HRESs, usually generate and distribute electricity in a localized fashion. The integration of different distributed generation units has a valuable impact on the system. Thus, the management of these sources requires new and efficient methods. Because of their great flexibility and resilience, distributed algorithms are increasingly being employed to tackle the economic dispatch problem of integrated energy systems (IESs), however, those algorithms also increase the danger of cyber-attacks in IESs. A distributed algorithm is one that runs on a distributed system without requiring the presence of a central coordinator.

A distributed system is a group of processors that share neither memory nor a clock. Each CPU has its own memory and communicates with one another over communication networks.

The coordinator election problem and the value agreement problem are two challenges that require distributed methods (Byzantine generals problem). Election Algorithms, Bully Algorithm and Ring Algorithm are being considered as the distributed algorithms. The transmission of measurement and decision data across communication networks has

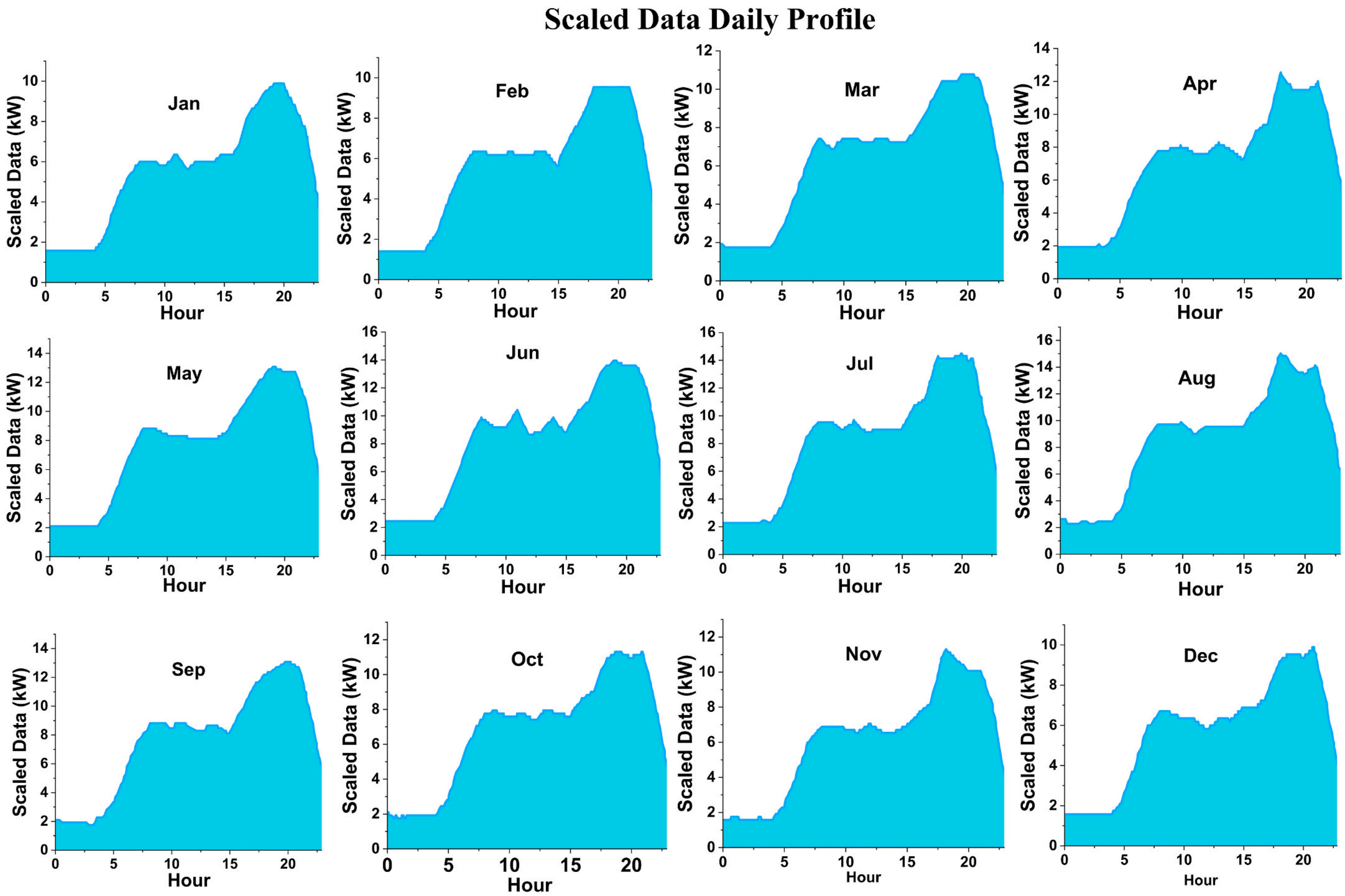

Fig. 3. Load curve for the proposed HRES.

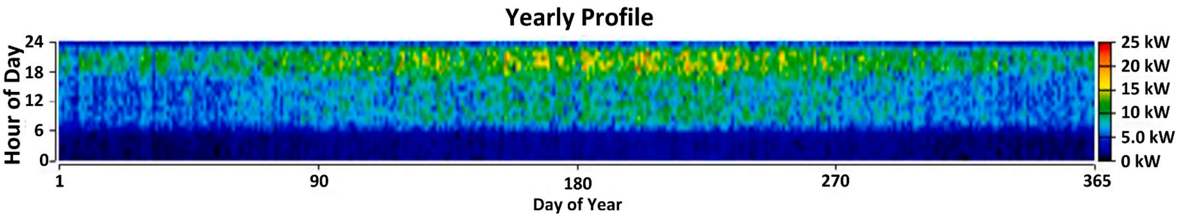

Fig. 4. Load curve yearly profile for the proposed HRES.

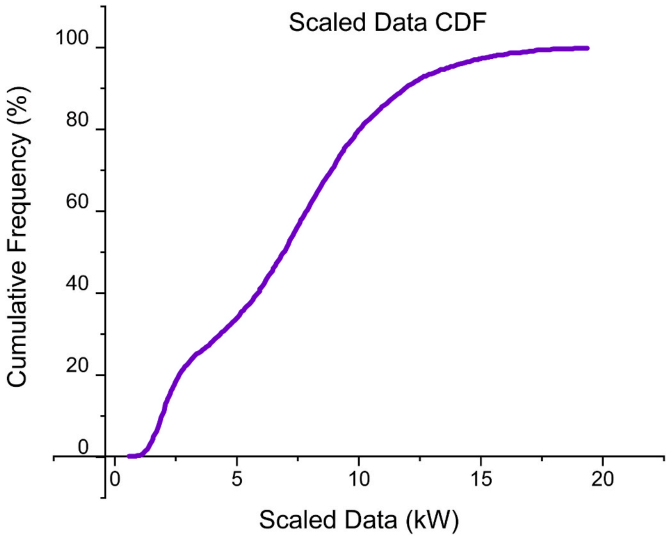

Fig. 5. Demand curve for the proposed HRES in CDF mode.

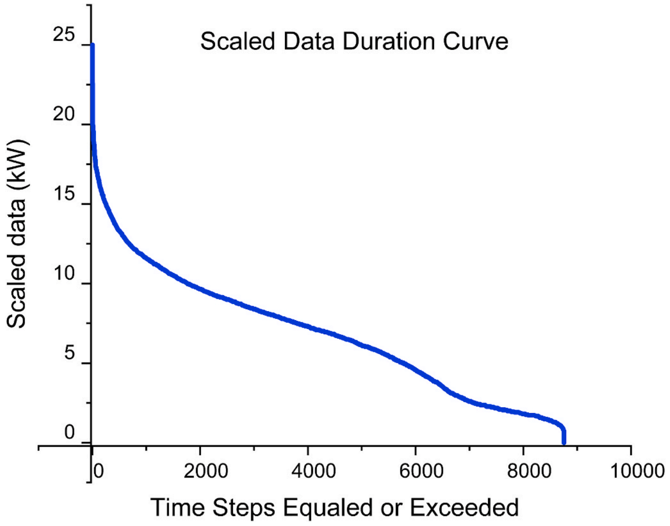

Fig. 6. Demand curve for the proposed HRES in dc mode.

become increasingly common, while the IES's degree of cyber-physical integration has constantly increased. If the IES's communication network is intentionally targeted, it may trigger a chain reaction in its physical network, disrupting the IES's normal operations [10]. There has recently been a surge in interest in researching the consequences of various cyber-attacks on power systems, which mostly include denial of service (DoS) assaults, fake data injection (FDI) attacks, and replay attacks [11]. Those harmful assaults moving over the communication network have the potential to harm the system's economic and safe functioning, as well as disrupt energy supply [12]. This study studies the distributed robust economic dispatch problem of IESs under cyber-attacks to tackle this challenge. First, as the first line of protection

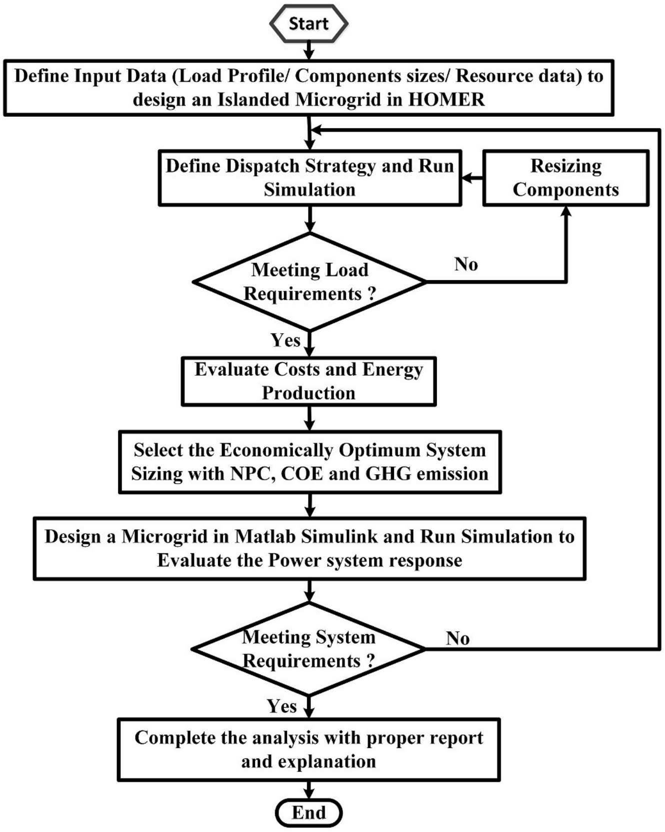

Fig. 8. Optimization and assessment flow chart for the proposed HRES.

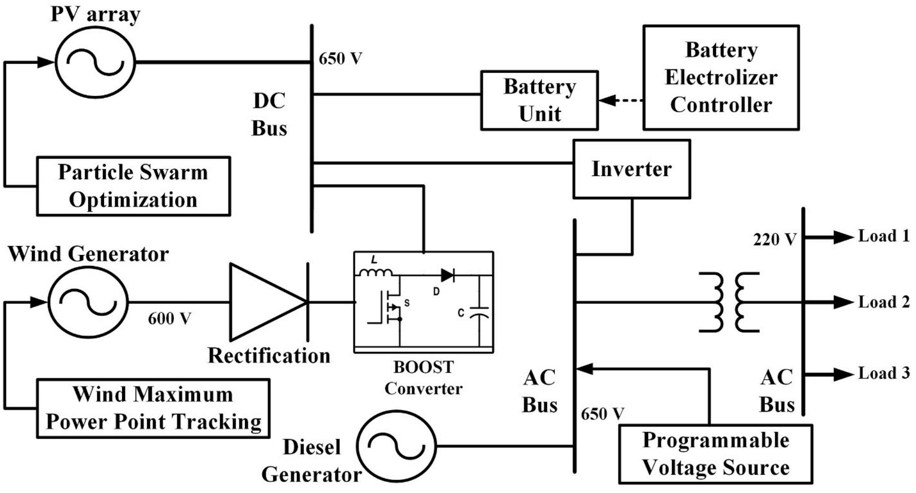

Fig. 7. Simulink model of an HRES for the proposed HRESs.

Table 2
Differences in various parameters for the five dispatch techniques for Dhaka and Khulna.

Dhaka				
Dispatch Techniques	Operating Cost (USD/year)	NPC (USD)	CO_2 Emission (kg/year)	LCOE (USD/kWh)
CC	19,261	307,980	39,131	0.394
CD	15,240	404,093	17,477	0.517
GO	2,930	177,097	0	0.243
LF	4,411	156,181	4,863	0.213
PS	10,217	201,487	18,766	0.258
Khulna				
Dispatch Techniques	Operating Cost (USD/year)	NPC (USD)	CO_2 Emission (kg/year)	LCOE (USD/kWh)
CC	19,549	316,477	39,415	0.405
CD	18,616	468,187	23,418	0.600
GO	3,346	192,072	0	0.264
LF	3,706	162,813	3,051	0.223
PS	10,532	206,363	19,507	0.264

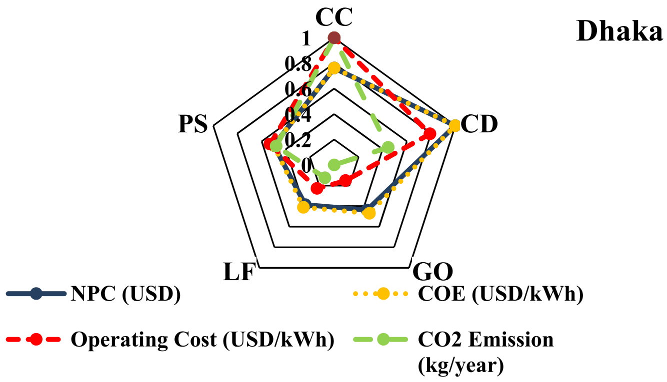

Fig. 9. Different costs for Dhaka HRES for different dispatch techniques.

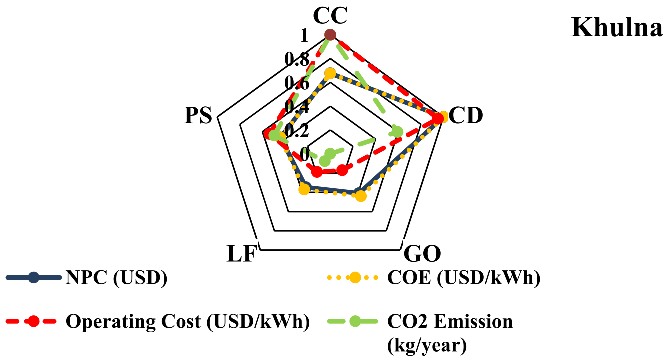

Fig. 10. Different costs for Khulna HRES for different dispatch techniques.

Table 3
Optimum Component Sizes from HOMER study.

Dhaka					
Dispatch Technique	Converter (kW)	Wind (kW)	PV (kW)	Battery (kWh)	DG (kW)
PS	13.9	1	30	108	7
CD	17.3	2	30	556	12
CC	14.9	1	10	136	8
LF	15.7	1	55	125	4
GO	35.5	1	75	175	1
Khulna					
Dispatch Technique	Converter (kW)	Wind (kW)	PV (kW)	Battery (kWh)	DG (kW)
PS	14.5	1	30	110	7
CD	18.6	15	25	607	12
CC	16.5	2	10	146	8
LF	18.8	1	65	142	3
GO	35.5	1	75	207	1

Table 4
Optimal sizes of HRES components used in Simulink study.

Dhaka					
Dispatch Technique	Converter (kW)	Wind (kW)	PV (kW)	Battery (kWh)	DG (kW)
PS	13.9	1	30	**112**	7
CD	17.3	2	30	**456**	12
CC	14.9	1	10	**132**	8
LF	15.7	**5**	**60**	**639**	**8**
GO	35.5	1	75	**181**	1
Khulna					
Dispatch Technique	Converter (kW)	Wind (kW)	PV (kW)	Battery (kWh)	DG (kW)
PS	14.5	1	30	**111**	7
CD	18.6	15	25	**608**	12
CC	16.5	2	10	**146**	8
LF	18.8	**5**	65	**639**	**8**
GO	35.5	1	75	**180**	1

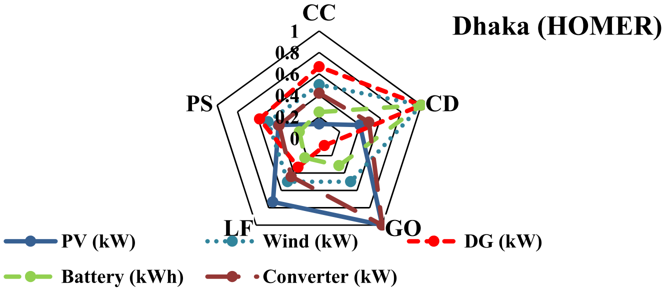

Fig. 11. Optimum component sizes for dhaka division (Homer).

against assaults, a privacy-preserving protocol is created to obscure some critical information utilized for IESs' economic dispatch [13]. A system designer has to face this challenge to satisfy the load demand. "Dispatch Strategy" is the control system's branch that controls the flow of energy among different equipment in the network [2]. The system's overall costing is affected by dispatch strategy and thus helps in designing a more efficient and economic system. The safe and economic function of the HRES can be assured by economic dispatch [14,15].

The main motive of Economic Dispatch (ED) oriented power system problems is to satisfy demand with a reduced cost of operation by output scheduling of the pre-set power generation units. Here the ED problems have to satisfy all of the power generation units' equality and inequality constraints [16]. A proper and effective ED technique can save a lot of money and resource consumption with a minimized emission of harmful gases like CO_2 [17].

Optimal sizing has been becoming revolutionary over the years due to the stochastic nature of the meteorological conditions and convergence rate or the optimizations techniques. A design and demonstration of an islanded HRES with the optimal sizing for a remote school building in Bangladesh has been implemented for remote power supply and hospital maintenance. The optimal sizing approaches considered the meteorological data as well as fuel cost of that area for the diesel

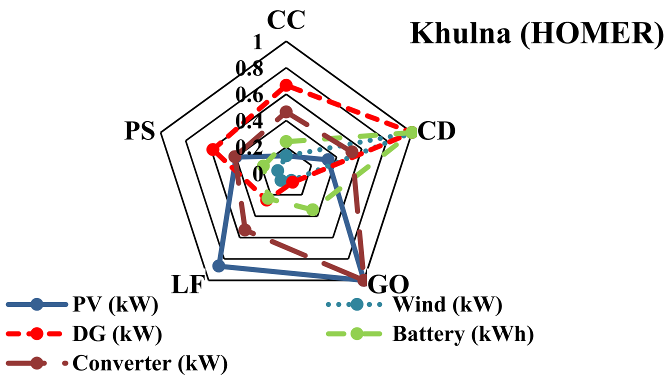

Fig. 12. Optimum component sizes for khulna division (Homer).

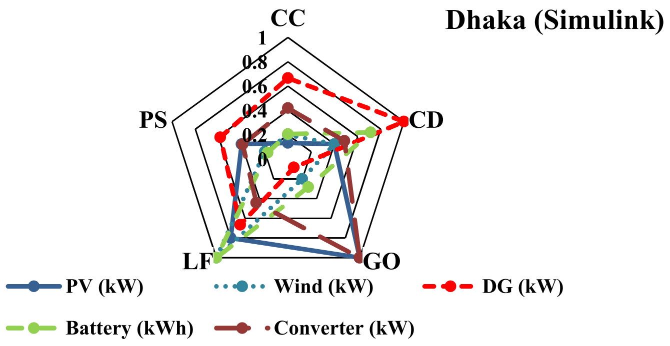

Fig. 13. Optimum component sizes for dhaka division (simulink).

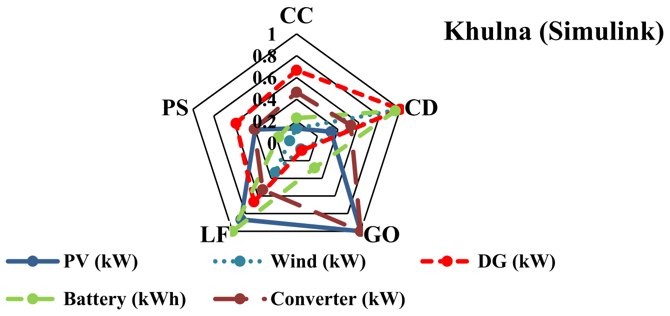

Fig. 14. Optimum component sizes for khulna division (simulink).

generator back-up. A multi-objective-based technique for BESS allocation in distribution networks is presented in this research. The aim function in the proposed work incorporates multiple advantages from energy arbitrage, energy losses reduction, transmission access fee reduction, environmental emission reduction, and BESS development cost reduction [6,18].

Evaluation of the dispatch techniques and optimization algorithms of standalone HRESs have recently attracted increased research interest. The effectiveness of the ED strategy in designing HRESs has been a topic of great interest lately [19–21]. Distributed or centralized control strategy can be utilized in solving ED related problems. In centralized control, a bidirectional communication network is compulsory between the centralized controllers and all the power generation units. Thus, this control strategy is more expensive, has greater communication complexity, and also has higher cyber-attack threats. This study analyses the distributed economic dispatch problem of microgrids. To solve this problem, a distributed delay-free method is provided for efficiently allocating the whole energy demand among local generating units to reduce the aggregated operation cost. Each component may identify its optimum operations by implementing the suggested approach, which only requires local computing and communication [22].

In Distributed control, distributed type controller is utilized which is used to control only a definite area and thus offers simpler control and communication system [23]. Using the consensus algorithm in Refs. [24,25], a unique distributed control technique is suggested to solve ED problems. In the proposed method, the power generators measure the difference between the generation and load. This approximate difference is transmitted to each generation unit and in this way, the amount of power generation is calibrated to recoup for the difference. A dynamic ED model developed in Ref. [14], has an objective of regular operating expense reduction for AC/DC HRESs. A novel fuzzy-swarm optimization approach have been proposed by the researchers in Ref. [26] along with smart grid applications. Demand side management, utilizing flexible dispatch strategies have been studied by several researchers in recent days. An intelligent algorithm for demand response management technique has been proposed by the researchers in Ref. [27]. A novel demand response strategy has been proposed by the researchers in Ref. [28]. Compared to the fixed load strategy, a 20.66% reduction in the size of the hybrid energy system can be obtained by the implementation of demand response management technique. A smart demand response strategy for supplying load demand utilizing pumped hydro energy storage system instead of conventional battery based storage has significant reduction in various costs as proposed by the researchers in Ref. [29]. For this proposed research work in this paper, the demand side management strategies has been kept as a out of scope as the inclusion could defocus the readers from the main contribution of the work which is dispatch strategy based analysis and the inclusion would make the work lengthier.

In [6], and optimized HRES is designed for a remote school. In this work, the dispatch strategy and power system response-based analysis have not been considered. A techno-economic analysis is presented in Refs. [30,31], for islanded solar PV based LED road lighting system in Turkey by optimized designing and sensitivity analysis done in HOMER and DIALux software platform. However, the presented analysis contains no consideration of various dispatch techniques. In Refs. [32,33] the performance of an HRES in a rural site in India comprising various combinations of renewable energy sources is analyzed, based on various dispatch methodologies such as Combined Dispatch, Load Following, and Cycle Charging strategies, on Lithium-Ion (Li-Ion) and Lead Acid (LA) batteries using HOMER Pro platform. A sensitivity analysis is also presented under the three different dispatch strategies. The authors considered three different dispatch techniques excluding Generator Order or Homer predictive dispatch technique. The study consists of sensitivity and performance analysis on LA and Li-Ion based HRES but no power system responses such as voltage/frequency responses of the HRES for different dispatch techniques has been carried out. In Ref. [34], Li et al. designed a renewable energy-based energy management strategy for Electric Vehicle (EV) charging stations. In the analysis, dispatch strategy has not been taken into consideration. In Ref. [35], Shezan et al. designed an off-grid HRES applicable for remote areas. However, the analysis does not contain any dispatch strategy consideration or any power system response analysis. In Ref. [36], the performance of an HRES considering a new dispatch strategy and the power output responses is investigated. In this study, the voltage/frequency responses of the designed HRES have not been discussed [37].

Following the above literature review, it can be observed that the main research gap in this topic is the lack of harmony among the techno-economic study (optimal component sizing, cost analysis, and harmful gas emission) and power system performance analysis on basis of various dispatch strategies. The existing research efforts are either covering up the techno-economic analysis without considering any dispatch strategy or power system responses and not covering a comprehensive study of both. The optimized design of a standalone HRES can be properly evaluated by satisfying two standard measures along with dispatch strategy analysis: (1) techno-economic prospect

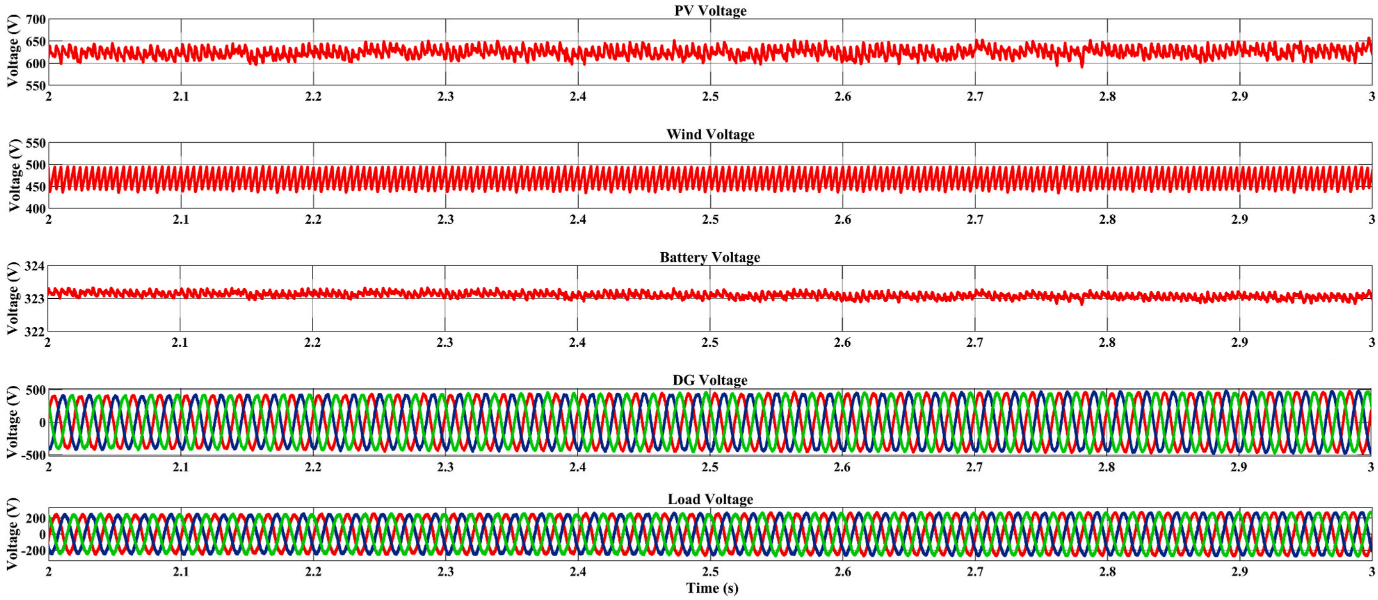

Fig. 15. Voltage responses for dhaka CC.

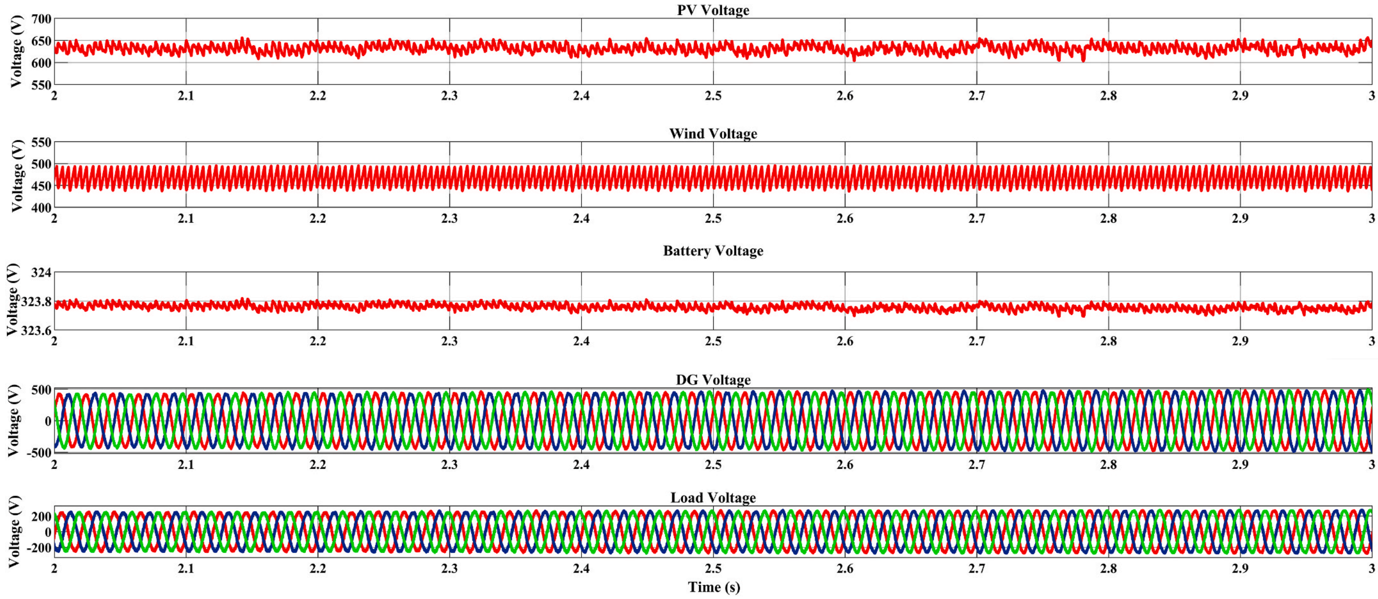

Fig. 16. Voltage responses for dhaka CD

evaluation and (2) power system feasibility along with stability evaluation. The precise harmonization and evaluation of these two standards for a standalone HRES design and optimization for the proposed locations is the key contribution of this paper which has not been considered in the current literature yet [38,39]. In this paper, as test sites, two divisional areas located in the southern part of Bangladesh have been picked. The meteorological data such as solar radiations, wind speed, and temperature for the two investigated sites are shown in the Appendix.

The core target of this study is to develop and assess a PV/diesel generator/wind turbine/battery stand-alone HRES along with an existing distribution system for Bangladesh's Dhaka and Khulna divisions. The main contribution of this paper can be summarized as below:

- Using HOMER Pro HRES platform, to determine the optimum sizes and combinations for the proposed integrated hybrid microgrid system (IHMS) components for its optimal operation which secures minimum CO_2 discharge, net present cost (NPC), Levelized cost of energy (LCOE) considering different dispatch techniques;
- Ensuring feasible and stable operation of the designed HRESs by evaluating the power system response (frequency and voltage outputs of the designed IHMS) in MATLAB/Simulink platform;
- Identifying the best and worst dispatch controls for the designed HRESs based on system costs, power system performances, and hazardous gas discharge;
- Comparing the performance of the proposed HRESs with existing designs and traditional power plants.

2. Modelling of stand-alone HRES

Fig. 1 depicts a block model of a stand-alone HRES along with the system equipment and their correlations. The proposed Dhaka and

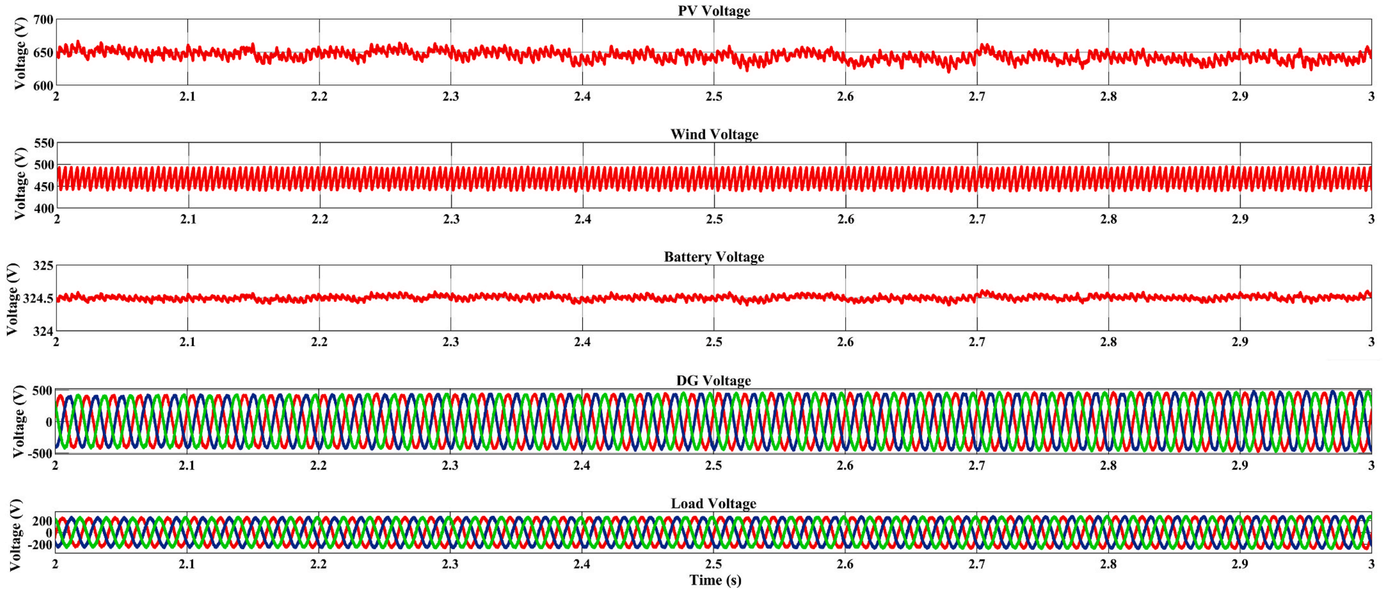

Fig. 17. Voltage responses for dhaka GO

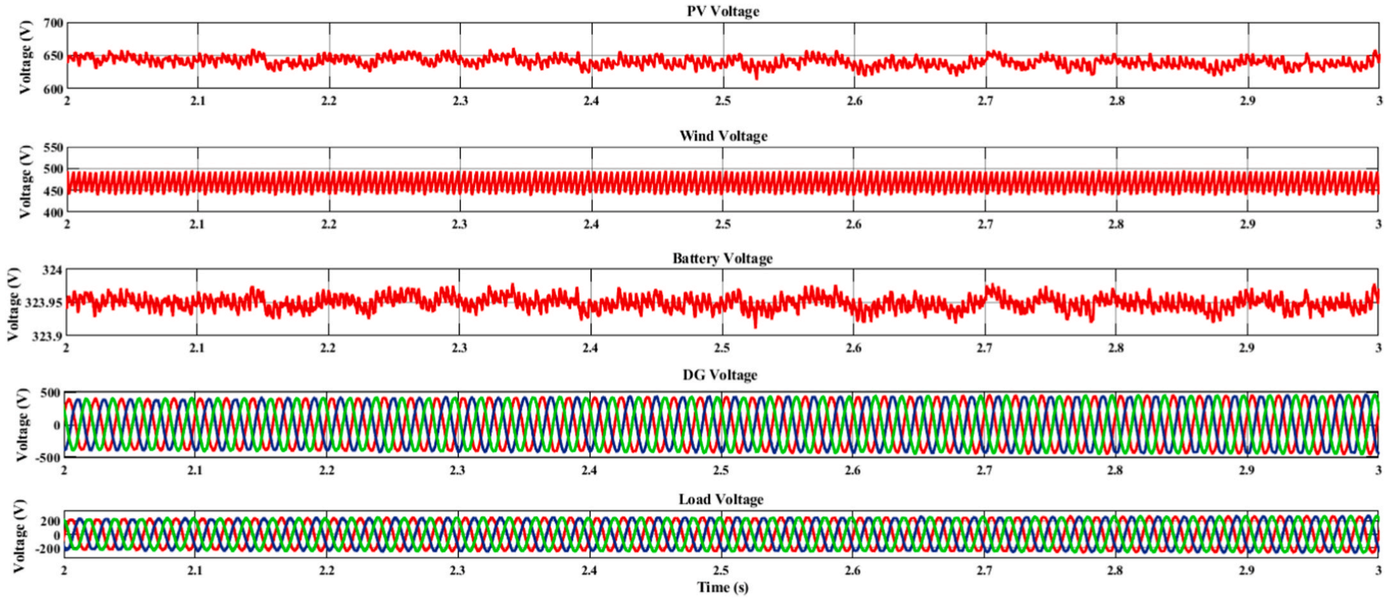

Fig. 18. Voltage responses for dhaka LF

Khulna HRESs consist of diesel generators (DG), wind turbines (WT), solar PVs, battery energy storage systems (BESS), loads, and bi-directional power converters. The required meteorological data used in HOMER analysis are collected from the NASA Surface meteorology and Solar Energy database [40].

3. Methodology

3.1. Dispatch control strategies

Dispatch strategy is known as some rules to control the generator and the storage unit operation whenever there are insufficient renewable resources to supply the load. According to demand profile, amount of power generation, and meteorological circumstances, optimization strategy follows different dispatch techniques while being implemented for HRES design.

Five dispatch techniques are used and assessed in this study: (i) load following (LF), (ii) combined dispatch (CD) (iii) cycle charging (CC), (iv) generator order (GO) and v) HOMER Predictive Dispatch (PS) approach.

In LF dispatch, the generators are operated with a capacity that is enough for satisfying the demand. According to this technique, the demand needs to be fulfilled by using renewable energy sources to keep up the system's feasibility and stability.

In CD dispatch strategy future net-load approximation is avoided and present total load is calculated to decide whether to charge the battery storage utilizing the generator or not. When the demand is low, this technique avoids using the generator. CD strategy selects the cheapest choice to follow the CC or LF control in each time step [41].

In GO dispatch, among several predefined generator combinations, a combination of generators which fulfills the demand and meets the operating capacity in the first place is selected.

PS technique estimates future resource (e.g. wind speed and solar radiation) availability and the future possible load demand. Thus, PS can minimize overall system operating costs [42,43].

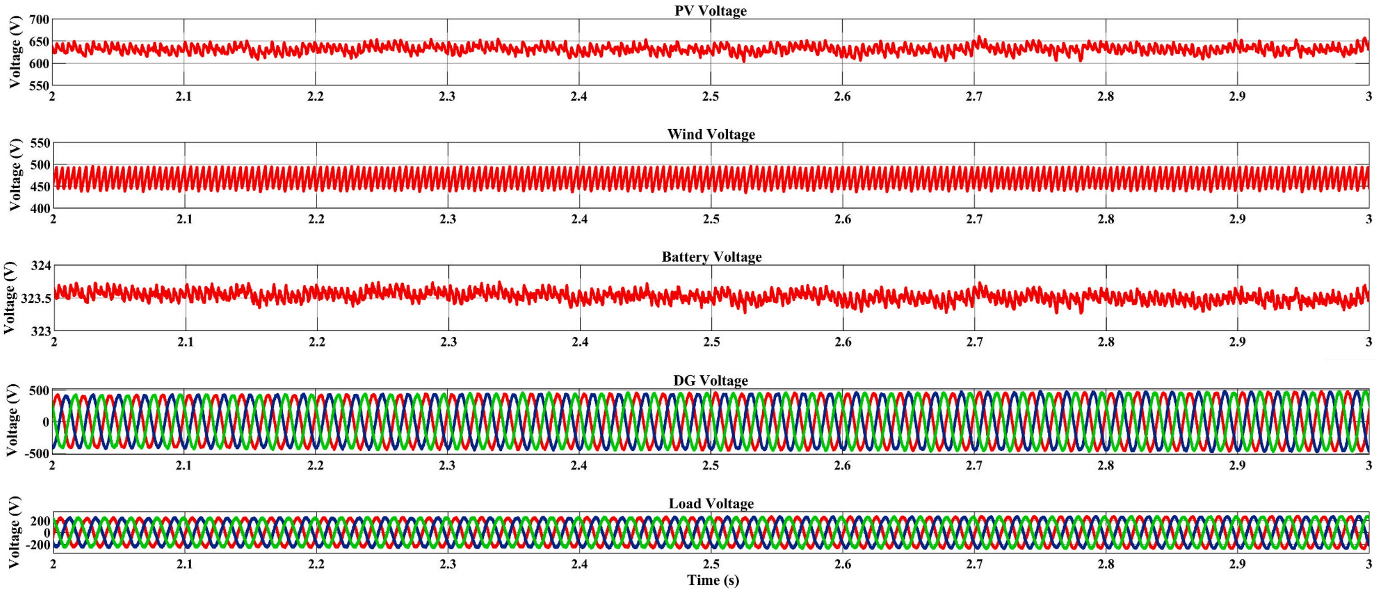

Fig. 19. Voltage responses for dhaka PS.

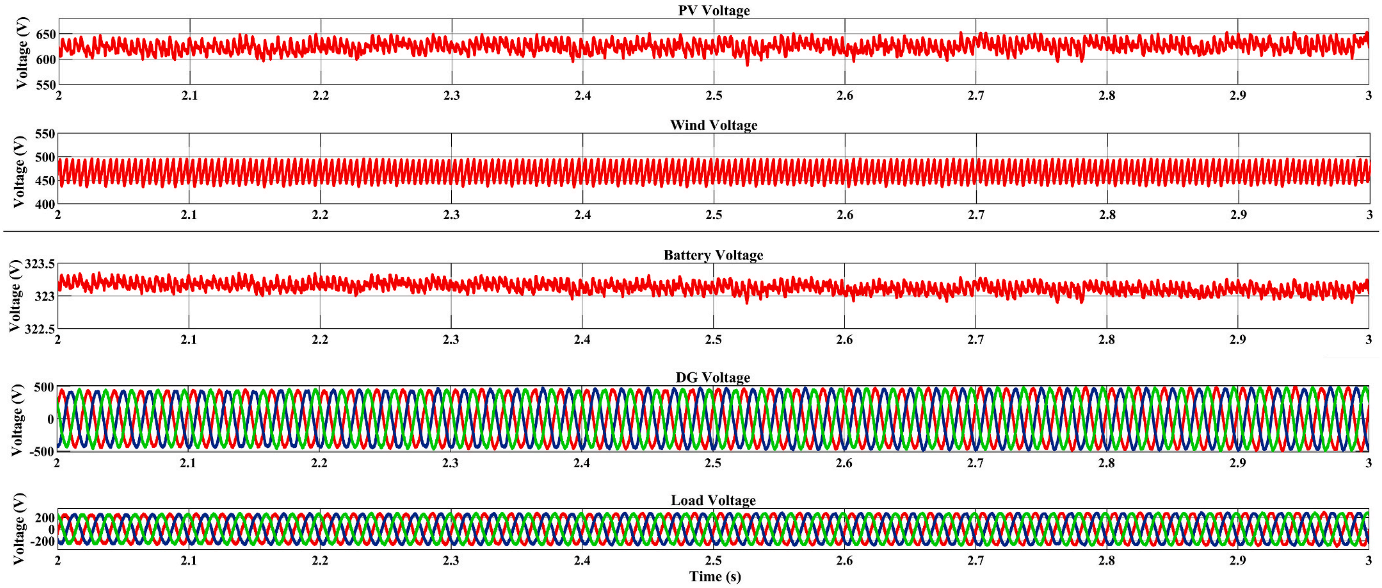

Fig. 20. Voltage responses for khulna CC.

CC dispatch makes the generator operate at its full ability whenever it is requisite. Unused power is utilized for battery charging. CC dispatch is commonly appropriate for networks with zero effective renewable sources.

Fig. 2 depicts the influence of renewable energy sources and diesel generators on electrical power generation for the proposed IHMS using various dispatch techniques. According to the analysis, the LF dispatch has the most effect on the majority of renewable sources, whereas the GO dispatch approach has the greatest influence on the majority of backup generators. All dispatch approaches must consider how to employ generator backup when a critical scenario develops, such as when renewable resource generated power is unknown and load demand changes are uncertain. Fig. 2 also depicts the priority of the operating pattern based on the five methods to show the impact of renewable energy sources and the backup diesel generator.

3.2. *Load profile*

In this work, a community with a market, religious prayer center, residential area has been considered which has a total electrical load of 23.31 kW. This load demand has been approximated in the following manner. Table 1 shows the brief chart of energy consumption according to the load capacity.

Figs. 3 and 4 show the approximated load curve for the proposed HRES for 24 h a day for a year. From the figure, a rough idea can be made of the load demand variation of the proposed HRESs for 24 h a day for a whole year. Figs. 5 and 6 show the demand curve for the proposed HRESs.

3.3. *Formulation of optimization problem*

3.3.1. *Equations related to cost function minimization and optimal sizing*

To find the optimal sizes and the number of required generation

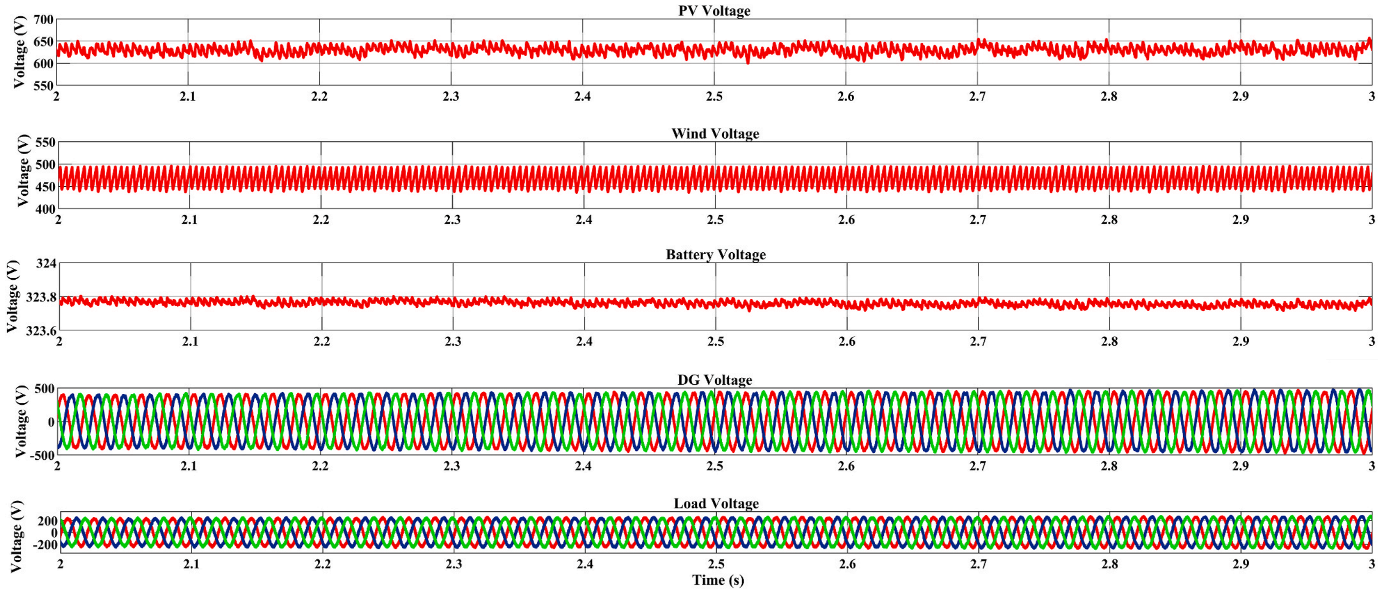

Fig. 21. Voltage responses for khulna CD

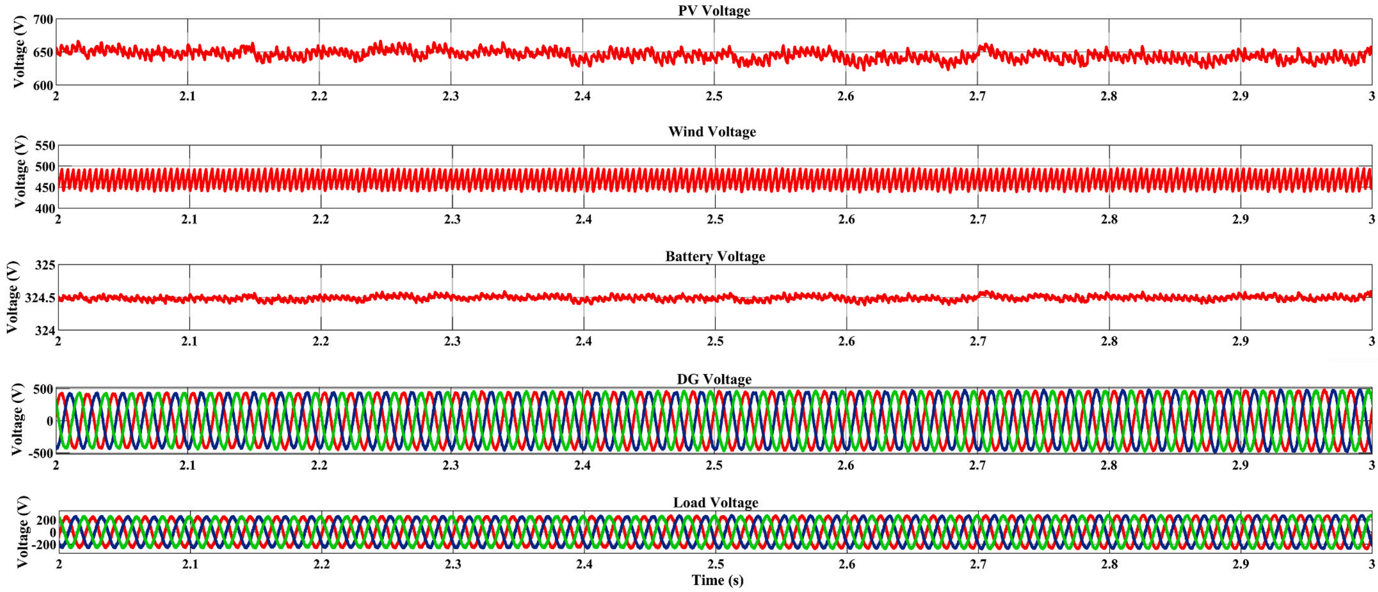

Fig. 22. Voltage responses for khulna GO

units, the optimization problems listed below (equations (1)–(4)) must be solved [44] to get the optimum sizing of the components as well as to ensure the optimum operation of the designed microgrid. Here, to solve the optimization problem, Homer optimizer has been utilized which is a deterministic approach. In the mentioned equations, *a, b, c,* and *d* refer to the respective different equipment sizes, and f_1, f_2, and f_3 express the weights to emphasize the significance of the respective equipment. *NPC* refers to the net present cost, *LCOE* refers to the levelized cost of energy and *GHG,* and *e.* CO_2 refers to the quantity of greenhouse gas and carbon discharge from the diesel generator respectively.

$$\frac{min}{a,b,c,d,f_1 \in N^\circ}(f_1(a.LCOE_{PV}+b.LCOE_{WT}+c.LCOE_{DG}+d.LCOE_{BT})) \tag{1}$$

$$\frac{min}{a,b,c,d,f_2 \in N^\circ}(f_2(a.NPC_{PV}+b.NPC_{WT}+c.NPC_{DG}+d.NPC_{BT})) \tag{2}$$

$$\frac{min}{e,f_3 \in N^\circ}(f_3(e.CO_{2_{DG}})) \tag{3}$$

$$\frac{min}{f_1f_2f_3 \in N^\circ}\left(f_1LCOE_{Total}+f_2NPC_{Total}+f_3GHG_{Total}\right)) \tag{4}$$

3.3.2. Equations for LCOE

In HOMER, the LCOE for a HRES may be estimated from Ref. [45]:

$$\mathrm{LCOE}=\frac{\mathrm{C_{annual}}}{\mathrm{L_{primary}}+\mathrm{L_d}+\mathrm{E_{gs}}} \tag{5}$$

where, $\mathrm{C_{annual}}$ = total yearly cost, $\mathrm{L_{primary}}$ = amount of primary load, $\mathrm{E_{gs}}$ = annual energy sold to the traditional grid, $\mathrm{L_d}$ = amount of deferrable load.

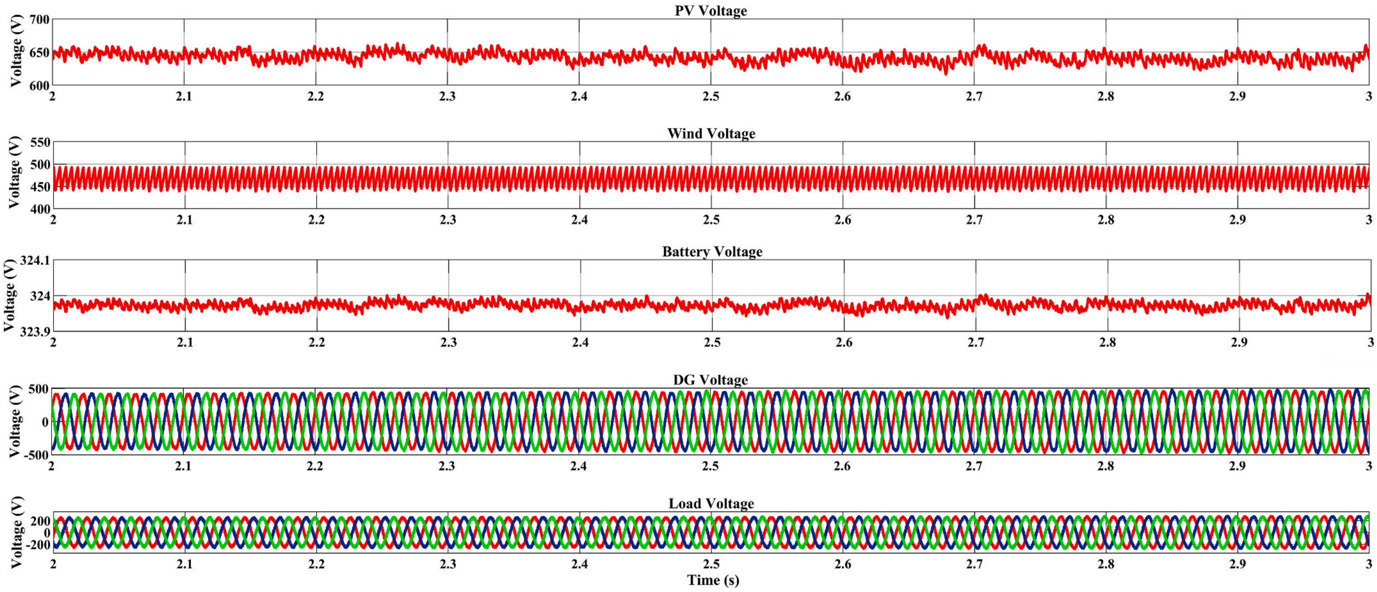

Fig. 23. Voltage responses for khulna LF

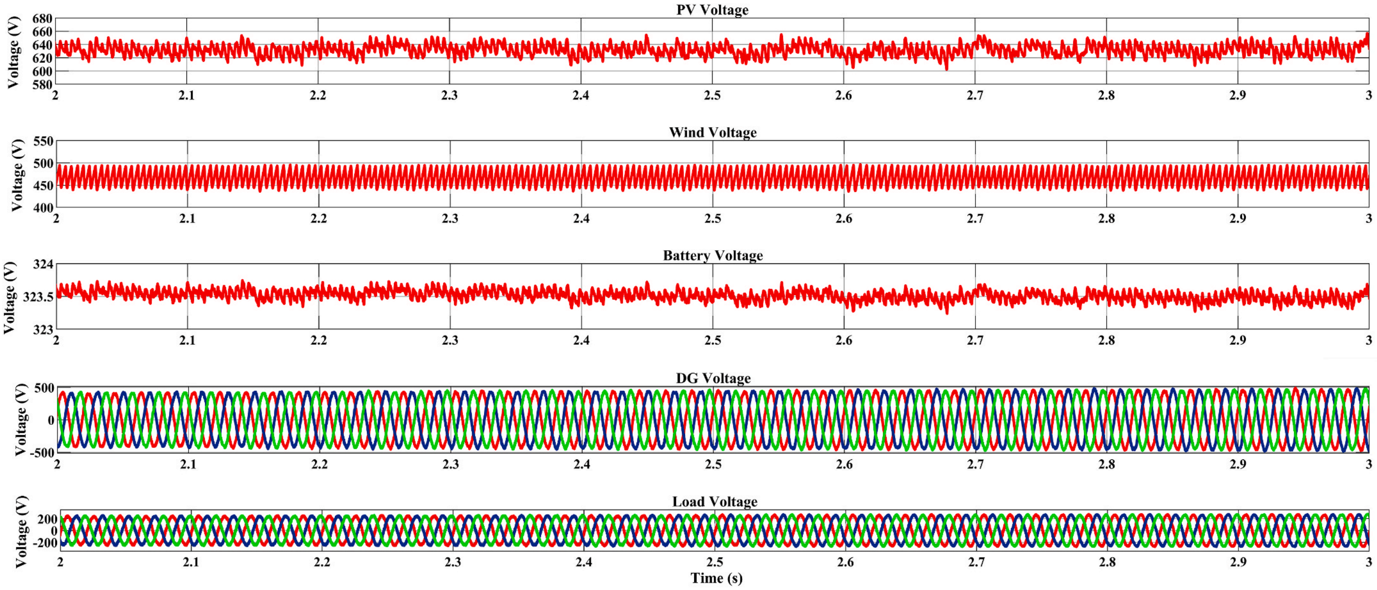

Fig. 24. Voltage responses for khulna PS.

3.3.3. NPC estimation

In HOMER, NPC for the proposed HRES may be found from Ref. [45]:

$$C_{NPC} = \frac{C_{annual}}{CRF\left(i, T_{project}\right)} \tag{6}$$

where, $T_{project}$ = Lifetime of the project, i = interest rate (per annum), C_{annual} = total cost per annum, CRF (.) = Capital recovery factor.

3.3.4. Evaluation of CO_2 emission

Discharge of CO_2 gas from the HRES is evaluated as below [45]:

$$eCO_2 = 3.667 \times m_{fuel} \times FHV \times CEF_{fuel} \times X_c \tag{7}$$

where FHV = Fuel heating value in MJ/L, m_{fuel} = Fuel quantity measured in liter, CEF_{fuel} = Carbon emersion factor measured in ton carbon/TJ, eCO_2 = emersed CO_2 gas from HRES, X_c = Fraction of oxidized carbon. 1 g of carbon is included in 3.667 g of CO_2.

3.3.5. Evaluation of economic dispatch

The economic dispatch problem is formulated as an optimization problem using the below equations [46]:

$$\min_{\mathbf{P}_{\mathbf{G_i}}} \sum_{i} \mathbf{C}_{\mathbf{G_i}} \mathbf{P}_{\mathbf{G_i}} \tag{8}$$

Subject to,

$$\mathbf{P}_{\mathbf{G_i}}^{\mathbf{min}} \le \mathbf{P}_{\mathbf{G_i}} \le \mathbf{P}_{\mathbf{G_i}}^{\mathbf{max}} \tag{9}$$

$$\sum_{i} \mathbf{P}_{\mathbf{G_i}} = \mathbf{P}_{\mathbf{D}} \tag{10}$$

The objective function of (8) minimizes the generation cost of power, in which C_{G_I} = marginal cost of each generator and P_{G_I} = generated power of that particular generator. All generators must stay within their maximum and minimum limitations, according to (9), and all power generation has to be equal to the demand P_D, according to (10).

Table 5
Voltage responses in brief from MATLAB/Simulink study.

Dispatch Techniques	Wind (V)	PV (V)	Load (V, p-p)	Battery (V)	DG (V, p-p)
Dhaka					
PS	440–500	600–650	400	323.30–323.57	1000
CD	440–500	600–660	400	323.70–323.80	1000
CC	440–500	590–600	400	322.90–323.20	1000
LF	440–500	610–660	400	323.91–323.97	1000
GO	440–500	620–670	400	324.50	1000
Khulna					
Dispatch Techniques	Wind (V)	PV (V)	Load (V, p-p)	Battery (V)	DG (V, p-p)
PS	440–500	600–660	400	323.20–323.70	1000
CD	440–500	600–660	400	323.70–323.80	1000
CC	440–500	590–650	400	322.80–323.40	1000
LF	440–500	610–660	400	323.95–324.00	1000
GO	440–500	620–670	400	324.40–324.60	1000

3.3.6. *Stabilization of frequency*

The post-fault RoCoF (Rate of Change of Frequency) and frequency nadir (f^{nadir}) can be kept within their precarious inceptions to achieve a stable HRES frequency, as below [47]:

$$|\mathbf{RoCoF}| \le \mathbf{RoCoF}^{\mathbf{max}},\ \mathbf{f}^{\mathbf{min}} \le \mathbf{f}^{\mathbf{nadir}} \le \mathbf{f}^{\mathbf{max}} \tag{11}$$

The following equation may be used to determine the frequency response of a HRES [47]:

$$2H\frac{\mathbf{d\Delta f(t)}}{\mathbf{dt}} = \sum_{\mathbf{i}} \mathbf{\Delta P_{Gi}(t)} + \sum_{\mathbf{j}} \mathbf{\Delta P_{Sj}(t)} - \mathbf{D\Delta f(t)} - \mathbf{P_M} \tag{12}$$

where D = load damping factor, P_M = HRESs power imbalance, H = HRES inertia, the power variations of synchronous unit i and battery j are represented respectively by ΔP_{Gi} (t) and ΔP_{Sj} (t), Δf (t) = fluctuation in frequency.

3.3.7. *Equations for voltage*

Ideal constant voltage can be governed by the below equation [46]:

$$\min\sum_{\mathbf{i}}\left(\mathbf{V_i} - \mathbf{V_{setpoint,i}}\right)^2 \tag{13}$$

where V_i is the particular node's voltage and $V_{setpoint,i}$ is the node's reference voltage.

Fig. 7 demonstrates a basic model for the two proposed HRES that has been used for Matlab/Simulink analysis. Solar PV, wind turbine module, diesel generator unit, battery, converters, controllers and load, all are included in the model.

The system flow diagram in Fig. 8 depicts the proposed HRES 's optimal design and assessment process which has also been supplied as supplementary material. The optimization procedure begins with the selection of components and input parameters, as well as the technical and economical parameters, load demand assessment, and dispatch technique definition. To test the technical validity of the proposed model, the simulation's identified optimal sizes are applied for the power system response in the Matlab/Simulink model.

3.3.8. *Results and discussions*

3.3.8.1. *Optimal sizing of proposed HRES.*

The research work has been done in this work to find the optimal component sizing and ensure optimum operation. LCOE, NPC, and CO_2 discharge for five dispatch methods for Dhaka and Khulna HRESs gathered from HOMER are shown

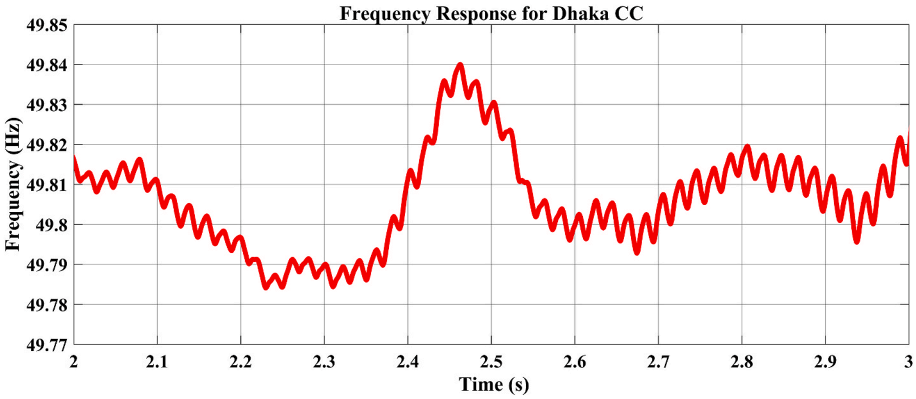

Fig. 25. Frequency response for dhaka CC.

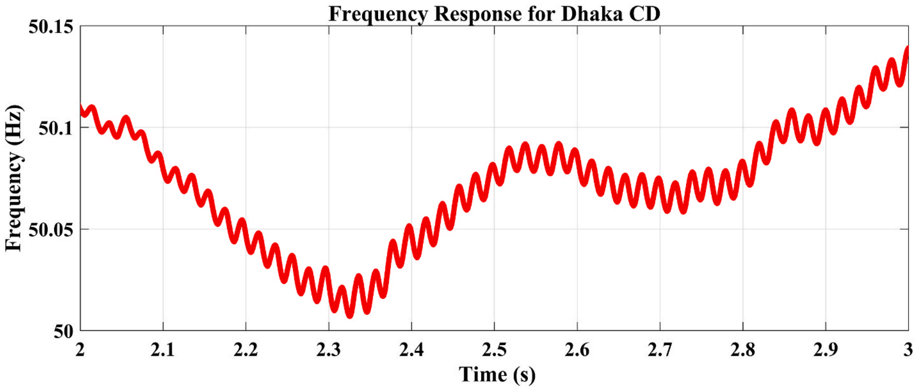

Fig. 26. Frequency response for dhaka CD

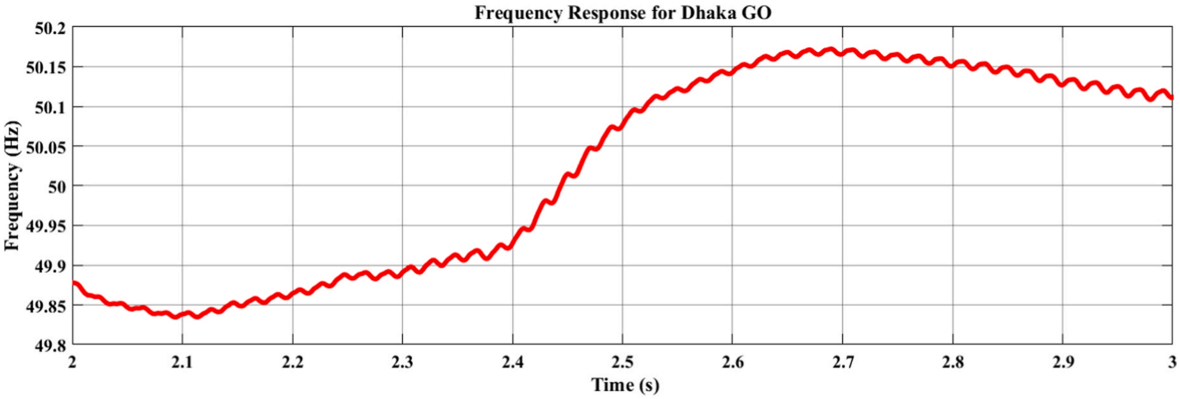

Fig. 27. Frequency response for dhaka GO

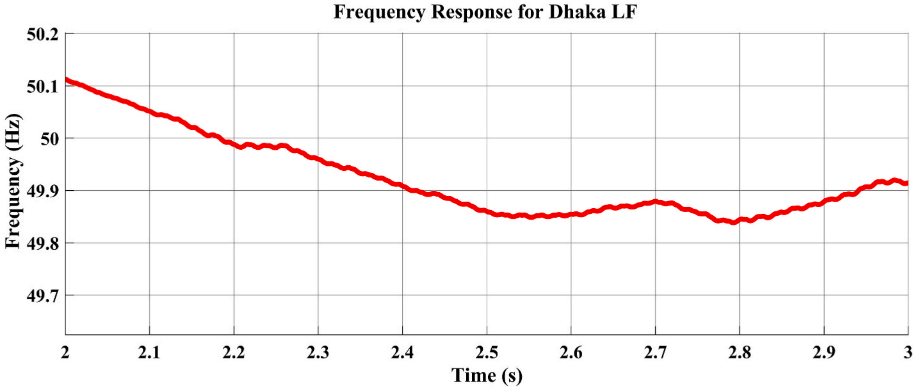

Fig. 28. Frequency response for dhaka LF

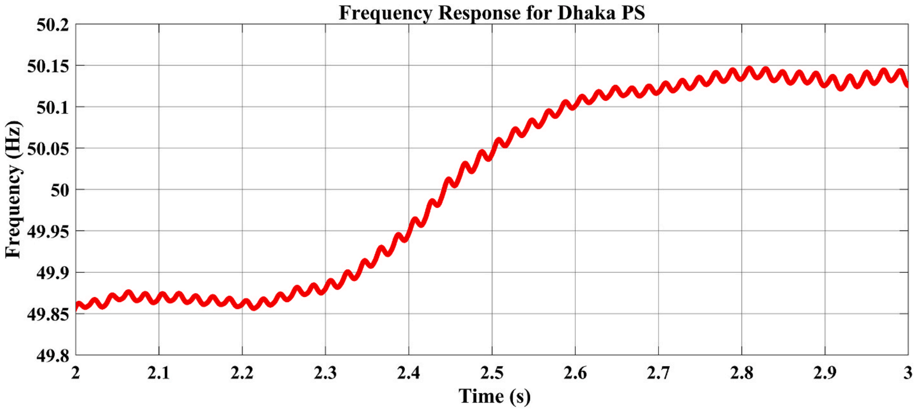

Fig. 29. Frequency response for dhaka PS.

in Table 2. CO_2 discharge, LCOE and NPC are minimum for LF, respectively at 0.213 $/kWh, 156,181 $ and 4,863 kg/year and maximum for CD respectively at 0.600$/kWh, 468,187 $ and 23,418 kg/year for Dhaka and Khulna.

Figs. 9 and 10 show different expenses and CO_2 discharge for various dispatch methods for the two HRESs gathered from the HOMER simulation in a per-unit fashion. Due to the variation in dispatch strategy, the comparative study demonstrates obvious variances in various costs while having the same demand profile. Table 2 is the comparative analysis of all the dispatch strategies. So, when the author chose GO for any particular simulation, it shows hundreds of combinations for only GO, then the author chose the best combination among others. So, according to the mechanism of GO it can be said that The Generator Sequence strategy instructs HOMER to employ the first generator combination that satisfies the Operating Capacity after applying a predetermined order of generator combinations. Only systems with generators, PVs, wind turbines, a converter, and/or storage components are supported by the Generator Order approach.

Table 3 demonstrates the optimal sizes of different HRES components i.e. batteries, diesel generators, converters, solar PVs, and wind turbines found from the HOMER study.

The study found that the optimum sizes of HRES components determined by HOMER simulation for a given site did not always result in a stable, feasible, and reliable power system response. Thus, the HOMER identified optimum sizes in Table 3 has been calibrated as shown in Table 4 (bolded and coloured) wherever necessary using the

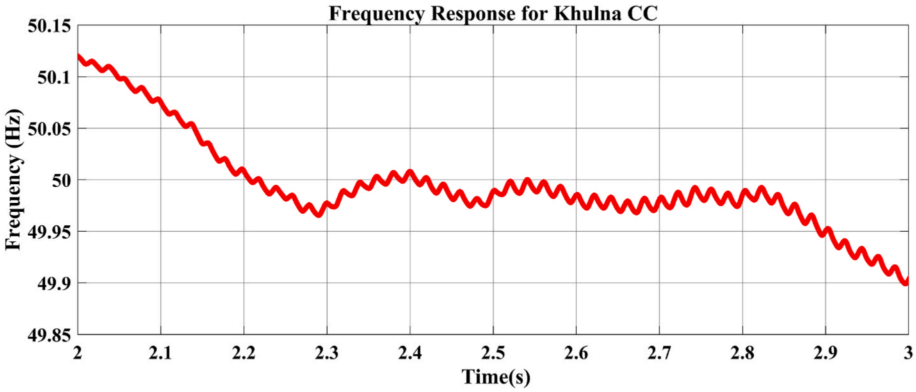

Fig. 30. Frequency response for khulna CC.

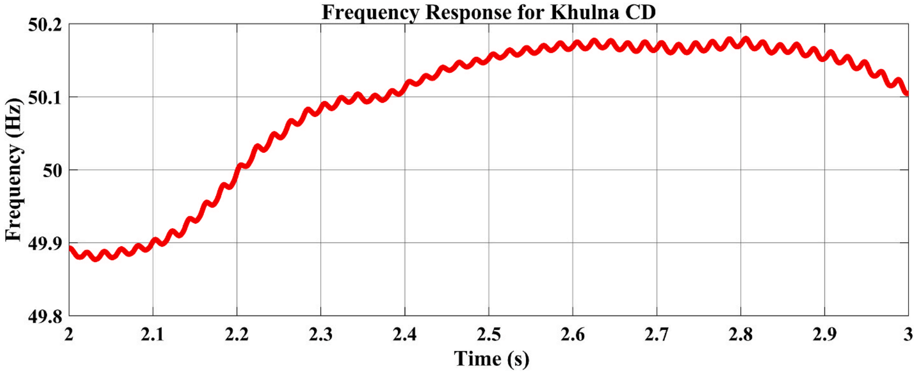

Fig. 31. Frequency response for khulna CD

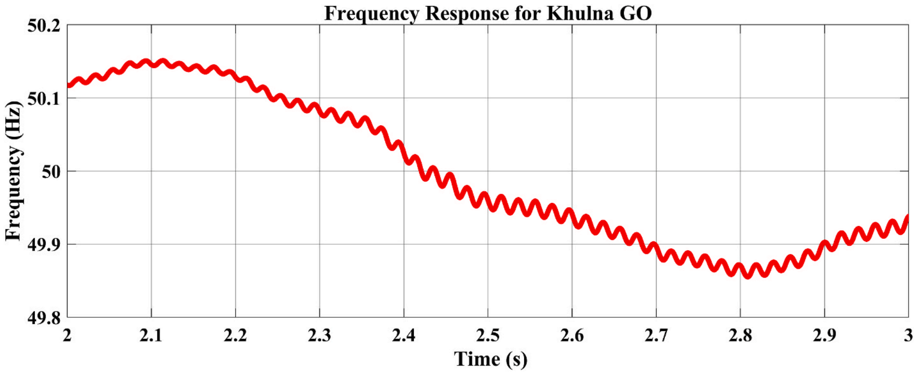

Fig. 32. Frequency response for khulna GO

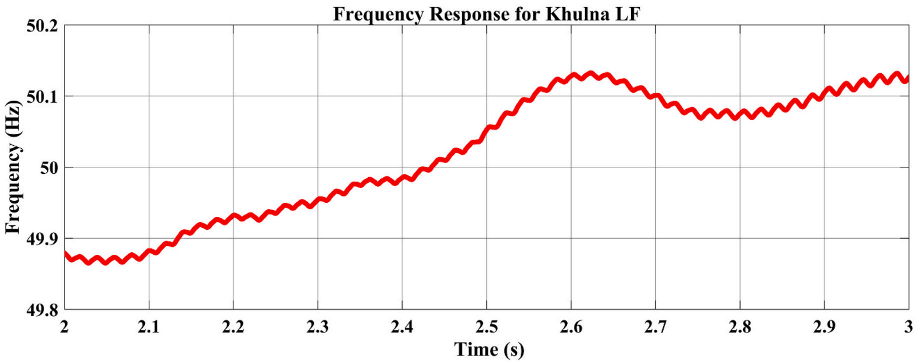

Fig. 33. Frequency response for khulna LF

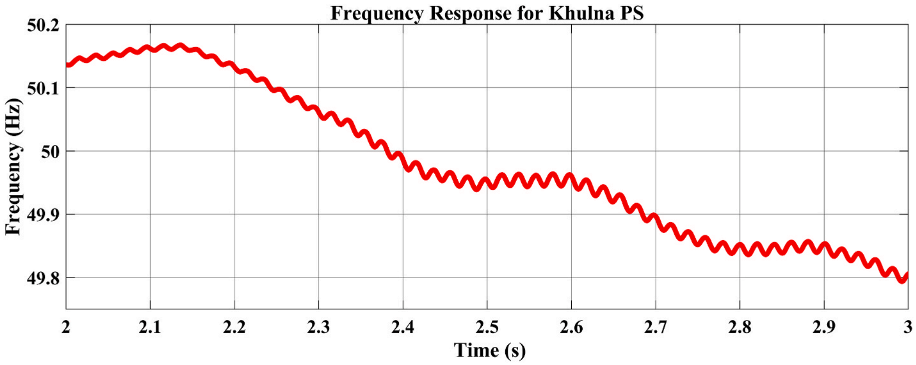

Fig. 34. Frequency response for khulna PS.

Table 6
HRES frequency found in MATLAB/Simulink study.

Dhaka				
Dispatch Techniques	Frequency range (Hz)	Frequency at 2 s (Hz)	Frequency at 3 s (Hz)	Highest Frequency (Hz)
CC	49.78–49.84	49.82	49.83	49.84
CD	50.01–50.14	50.11	50.14	50.14
GO	49.83–50.16	49.87	50.11	50.16
LF	49.91–50.11	50.11	49.91	50.11
PS	49.86–50.15	49.86	50.13	50.15
Khulna				
Dispatch Techniques	Frequency range (Hz)	Frequency at 2 s (Hz)	Frequency at 3 s (Hz)	Highest Frequency (Hz)
CC	49.90–50.12	50.12	49.90	50.12
CD	49.87–50.17	49.89	50.10	50.17
GO	49.86–50.15	50.12	49.93	50.15
LF	49.88–50.14	49.88	50.13	50.14
PS	49.79–50.18	50.14	49.80	50.18

Table 7
Comparison between the proposed and other HRES design.

Parameters		Proposed HRES	Other HRES [45]
CO_2 Emission/Year (Kt)	0.005	198347.984	
LCOE ($/kWh)		0.213	1.877
NPC/Year ($)		156,181	288,194
Operating Cost		4,411	19,516

Table 8
Comparison between proposed HRES and traditional power station.

Parameters	Proposed HRES	Conventional Power Station [45]
NPC/Year ($)	156,181	297,000.00
CO_2 Emission/Year (Kt)	0.005	198,348.00
LCOE ($/kWh)	0.213	0.380

'trial and error' method for real-time power system study in the Simulink HRES model shown in Fig. 7. Table 4 summarizes the optimum sizes of different HRES equipment i.e. wind turbine, diesel generator, solar PV module, storage, and converter sizes used in the Simulink study that keeps the HRES responses i. e frequency and voltage outputs steady and within the tolerable range. Figs. 11 and 12 illustrate the optimal sizes of various HRES components utilized in the Dhaka and Khulna division HRESs, as determined by the HOMER research, per unit respectively.

Fig. 14 depicts the optimum sizes of different HRES equipment for the Khulna division HRES found from MATLAB/Simulink analysis in per unit.

Fig. 13 depicts the optimum sizes of different HRES equipment for the Dhaka division HRES found from MATLAB/Simulink analysis in per unit.

4. Power system performance on basis of five dispatch techniques

The term "power system performance" in this paper refers to a stable voltage output as well as a stable and "within limit" frequency response as determined by the Simulink study. The sizes of various HRES equipment listed in Table 4 were utilized in the Simulink model shown in Fig. 7 to assess the HRES performance. The HRESs are determined to be practical and stable for all of the component sizes listed in Table 4, as indicated in the following sections.

4.1. Voltage response

Fig. 15 through 24 show the voltage responses of HRES components such as Wind Turbines, Solar PVs, Batteries, Diesel Generators and Loads for the Dhaka and Khulna divisions for the assumed five strategies. Table 5 summarizes the responses where it can be found that for the limit of 2–3 s the responses are stable (p-p refers to peak to peak voltages).

4.2. Frequency responses

Fig. 25 through 34 show the frequency responses for Dhaka and Khulna divisions for various dispatch techniques. Though the frequency faces some ups and downs in magnitude, still all the frequency responses are found to be steady for the 2–3 s time duration. The responses are also within the considerable range of 50±2% Hz as can be observed from the figures. Table 6 summarizes the system frequency responses for the two proposed HRESs for several dispatch techniques. According to the comparative analysis, it can be observed that the lowest frequency profile is 49.78 Hz which is captured for the Dhaka division under CC strategy and the highest frequency profile is 50.18 Hz which is captured for the Khulna division under PS strategy.

4.3. Comparative analysis

The proposed HRES offers minimized different costs and harmful gas emissions than other similar HRES designs and conventional grids. In Table 7, a brief comparative analysis on basis of CO_2 discharge and various expenses of the proposed and other HRES is presented.

The relative analysis shows that the LCOE of the proposed IHMS is 88.65%, the NPC is 45.81%, the operating cost is 77.40%, and the CO_2 discharge of the HRES is 99.99% reduced than other hybrid system designs. Moreover, from Table 8, it is evident that the LCOE of the proposed system is 43.95%, the NPC is 47.41%, and the CO_2 discharge of the proposed HRES system is 99.99% less than traditional power stations.

4.4. Main contribution and selection of best and worst dispatch strategy

In this paper, an optimum solution is obtained through conducting a critical study in technoeconomic, power system performance, and environmental pollution aspects by firstly designing the HRES using the HOMER platform and then by applying the optimized solution to the HRES model in Simulink. From the performance evaluation, the LF control technique serves as the best algorithm based on all the evaluation criteria. LF is a dispatch control strategy whereby whenever a generator operates; it produces only enough power to meet the primary demand. Lower-priority objectives such as charging the storage bank or serving the deferrable load are left for renewable power sources. The generator may still ramp up and sell power to the grid if it is economically advantageous [39]. Load following tends to be optimal in systems with a lot of renewable power when the renewable power output sometimes exceeds the load. The CD strategy for the proposed HRES optimization and long-term operation is determined as the worst dispatch technique. Moreover, both PS and CC exhibit long-lasting instability in case of frequency and voltage and thus offer a bad quality power supply for the HRES.

5. Conclusion

In this work, two off-grid hybrid renewable energy systems (HRES) have been optimized and evaluated using wind turbines, battery storages, solar panels, and diesel generators considering five dispatch control strategies. Simulation analysis shows that the load following is the best dispatch technique for the designed HRESs on the ground of minimum levelized cost of energy, CO_2 discharge, net present cost and HRES frequency and voltage stability. Combined Dispatch is found to be the worst dispatch technique on basis of the highest levelized cost of energy, CO_2 emissions, net present cost and system stability performance. For load-following strategy, the net present cost, levelized cost of energy and CO_2 discharge are the lowest (156,181 $, 0.213 $/kWh, and 4,863 kg/year; respectively). On the other hand, they are found to be the highest in case of combined dispatch technique (468,187 $, 0.600 $/kWh, and 23,418 kg/year; respectively). The cost of energy of the proposed hybrid system is 88.65%, the net present cost is 45.81%, the CO_2 discharge is 99.99% and the operating cost is 77.40% less than other hybrid renewable energy systems. It is also evident from the results that the cost of energy for the proposed HRES is 43.95%, the net present cost is 47.41%, and the CO_2 discharge is 99.99% less than traditional power stations. The proposed HRESs have fulfilled technoeconomic feasibility (optimal sizing and costing) and system stability (frequency and voltage stability) to ensure the undisturbed supply of electricity for the desired locations of Dhaka and Khulna. The proposed standalone HRESs will be suitable for applications, especially for isolated and off-grid locations.

6. Future work

The analysis can be taken further ahead by keeping in mind the stochastic nature of the wind and solar resources while optimizing the HRES design. The authors will consider the load transferring in HRESs based on real power flow for future research work.

Author contributions

"Conceptualization, **Sk. A. Shezan** and **Md. Fatin Ishraque**; methodology, **Sk. A. Shezan** and **Md. Fatin Ishraque**.; software, **Sk. A. Shezan** and **Md. Fatin Ishraque**; validation, **S.M. Muyeen**, **R. Saidur** and **M.M. Ali;** formal analysis, **Md. Fatin Ishraque**; investigation, **Sk. A. Shezan** and **S.M. Muyeen**; resources, **Sk. A. Shezan**; data curation, **Sk. A. Shezan**, **Md. Fatin Ishraque**, **M.M. Ali** and **M.M. Rashid**; writing—original draft preparation, **Sk. A. Shezan** and **Md. Fatin Ishraque**; writing—review and editing, **Sk. A. Shezan**, **S.M. Muyeen** and **Ahmed Abu-Siada**; visualization, **Sk. A. Shezan** and **Md. Fatin Ishraque**; supervision, **R. Saidur, M.M. Ali and S.M. Muyeen**; project administration, **Sk. A. Shezan, Ahmed Abu-Siada and S.M. Muyeen**; funding acquisition, **Ahmed Abu-Siada**. All authors have read and agreed to the published version of the manuscript."

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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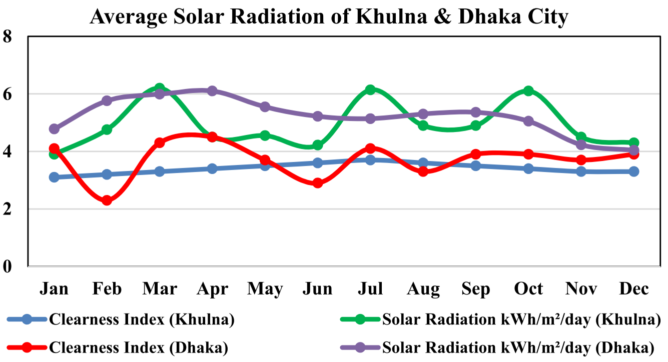
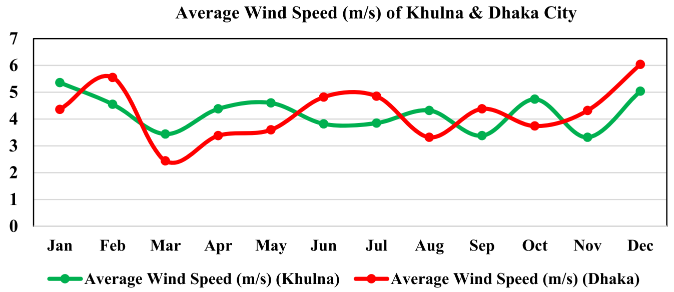
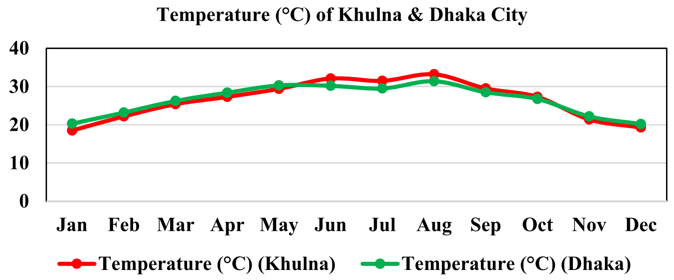
Appendix B. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.esr.2022.100923.

Appendix







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