Heliyon 9 (2023) e17990

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Optimal designing of grid-connected microgrid systems for residential and commercial applications in Pakistan

Syeda Sakina Zaidi *, Syed Sajjad Haider Zaidi, Bilal Muhammad Khan, Lubna Moin

National University of Sciences and Technology, PNEC Campus, Karachi, 75350, Pakistan

ARTICLE INFO

Keywords:
Grid-connected microgrid
Cost of energy
Renewable share
Greenhouse gases
Reliability
Sustainability

ABSTRACT

Conventional energy sources (CESs) are currently serving most of the global energy demands, but they will be substantially depleted as moving towards the end of this decade. The generation of electricity from such sources is causing the emission of greenhouse gases that is resulting in deleterious effect on the environment along with changing climatic and energy patterns of the planet. Therefore, the world is heading toward decentralization, and microgrids are playing a key role in this process. The advantages of renewables, which are acknowledged globally as benign, eco-friendly, economical, and inexhaustible resources available worldwide, are to credit for such a massive surge in the utilization of renewable resources in microgrid technology. Despite having an enormous renewable energy potential, Pakistan spends a sizable portion of its budget on energy imports of coal, oil, and liquefied natural gas, however, with good planning, current energy crises might be eliminated or at least mitigated to a greater extent, assuring energy security, economic prosperity, and lower carbon emissions inside the country. This study considers the optimal component planning in a grid-connected microgrid with five objectives to achieve that are to reduce the cost of energy, increase the renewable share, cut greenhouse gas emissions, enhance the reliability of power supply and to make electricity generation sustainable in the long run for the country. Different solar PV capacities are tested against the energy cost, renewable share and emission of greenhouse gases in order to attain the trade-off. The cost of energy is minimized by 92.47%, renewable share rises to 85%, and CO_2 emissions are decreased by 48% for residential application. In the case of commercial application, however, the cost of energy is lowered by 48.52%, the renewable energy share rises to 71.1%, and CO_2 emissions are reduced by 61% through incorporating solar PV into the current power system.

1. Introduction

Increase in energy demand has been observed with rapid technological advancements and industrialization. Currently, most energy demands throughout the world are met by conventional energy sources (CESs), which will be nearly depleted by the end of this decade. With the growing demand for energy and exhaustion of conventional energy sources (CESs), the shortage of energy resources is anticipated by 2030–2040s, even with the typical growth in energy demand of 1% per year [1]. Along with the anticipated shortage, electrical energy is still not available everywhere; one in every six people on the earth lives without electrical power [2], while the

* Corresponding author.
E-mail addresses: sakina.msee19pnec@student.nust.edu.pk (S. Sakina Zaidi), sajjadzaidi@pnec.nust.edu.pk (S.S. Haider Zaidi), bmkhan@pnec.nust.edu.pk (B.M. Khan), lubna@pnec.nust.edu.pk (L. Moin).

https://doi.org/10.1016/j.heliyon.2023.e17990
Received 19 November 2022; Received in revised form 29 June 2023; Accepted 4 July 2023
Available online 5 July 2023
2405-8440/

situation is more severe for developing countries where 45% of the rural population has no electrical power [3]. The inaccessibility of electrical energy in rural areas is attributed to the government's limited budget for rural electrification and the requirement of an initial investment cost for the provision of electricity from distant substations.

Owing to demerits of the centralized electrical system, now world is moving towards decentralization and microgrid is playing an important part in the transition. A microgrid can be described as an electrical distribution system encompassing distributed energy resources (DERs) and loads that function in a controlled and organized manner, whether in grid-connected or standalone mode [4]. The main justification to deploy microgrid in the city area (grid-connected) where electricity is easily accessible includes enhancement of energy reliability and resilience, reduced energy cost and environmental sustainability [5]. Photovoltaic arrays, wind turbines, hydro-generation, batteries, flywheels, supercapacitors, and diesel generators are some of the distributed energy resources used in the microgrids.

Installed power capacity of renewable energy raised by more than 256.6 GW in the year 2020 aiding the worldwide total renewable installed power capacity to reach an all-time high of 2839 GW, where capacity installation and major investments were observed even in developing countries despite Covid-19 pandemic. Fig. 1 shows the worldwide technology-wise annual additions of renewable power capacity from 2016 to 2021 [6]. The advantages of renewables, which are acknowledged globally as benign, eco-friendly, economical, and inexhaustible resources available worldwide, are to credit for such a massive rise in the usage of renewable energy resources in microgrid technology. Future smart grids hold a variety of roles for microgrids depending on their control capabilities., such as disconnection from the central grid to function in standalone mode, if necessary. It can act as a grid resort to attain quick system response, aid in system recovery, reinforce grid flexibility, and ensure supply security [7]. Fig. 2 depicts different types of microgrids and the underlying drivers to deploy them in real-world applications [8].

Coal, oil and natural gas are currently the leading sources of generating electrical energy; nevertheless, power generation from these conventional energy sources is the prime source of greenhouse gas emissions (GHGEs), resulting in a negative impact on the environment [8,9]. GHGEs have been changing the climatic and energy patterns of the earth [10]. Carbon dioxide emissions are the primary driver of global climatic change. In 2017, worldwide CO_2 emissions were 36.2 billion tons where Pakistan emitted 199 million tons of carbon dioxide [11]. Reduced GHGEs or negative emission cities can be realized with incorporating specific renewable energy sources in the microgrid systems for urban regions, where more carbon is caught than is emitted in total by generating carbon-free electrical energy [12]. Biomass is frequently assigned a key role as a carbon sink in future energy system settings, allowing for negative greenhouse gas emissions (GHGEs) through carbon trap and biogenic carbon dioxide storage in biomass-fueled power plants [13]. The Paris agreement 2015 quests to achieve the global average temperature below 2 °C by adjusting the ratio of fossil fuels and renewable energy by majorly utilizing renewable generation sources [14].

Rapid population expansion and industrialization have increased energy consumption in Pakistan, which has resulted in increased greenhouse gas emissions as a consequence of country's heavy reliance on fossil fuels for energy generation [15]. The country spends a sizable portion of its budget on energy imports of coal, oil, and liquefied natural gas (LNG) [16]. Pakistan holds the enormous potential of renewable energy sources and with properly planned utilization of these resources, prevailing energy crises may be eradicated or at least reduced to a greater extent that will eventually ensure energy security, economic growth and reduced GHGs emissions within the country [17]. Though the total installed capacity in Pakistan was increased at a growth rate of 2.57% from 33,433 MW (2017-18) to 34, 282 (2018-19) and electricity generation was raised from 85,522 GWh to 87,324 GWh at a rate of 2.1%, demand and supply gap of 120, 392 GWh was still observed. Comparison of power demand and generation is depicted in Fig. 3 [18]. Energy source wise share in electricity generation is presented in Fig. 4 whereas sector wise share in energy consumption is shown in Fig. 5 for the year 2021 [19].

The most significant obstacle to the widespread adoption of RESs is their reliance on environmental conditions, which have a considerable impact on energy output levels. The integration of conventional energy generation system with renewable energy

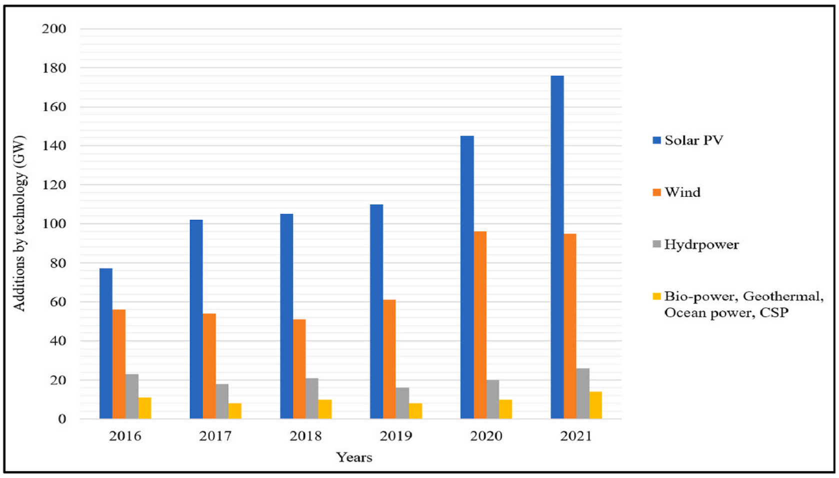


Fig. 1. Technology-wise annual additions of renewable power capacity, 2016–2021 [6].

Commercial and Industrial
• Reduce energy cost • Increase reliability
University Campus
• Decrease greenhouse gas emission • Reduce energy cost • Increase reliability
Public and Institutional
• Increase reliability for hospitals, schools, and public buildings
Military
• Provide high reliable energy supply
Rural
• Provide energy supply for off-grid consumers

Fig. 2. Different types of MGs and the underlying drivers to deploy them in real-world applications [8].

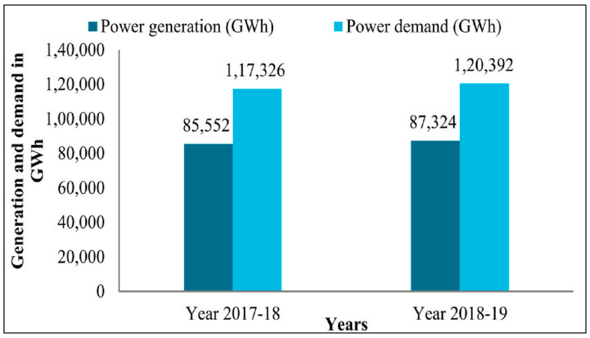


Fig. 3. Comparison of power generation & demand [18].

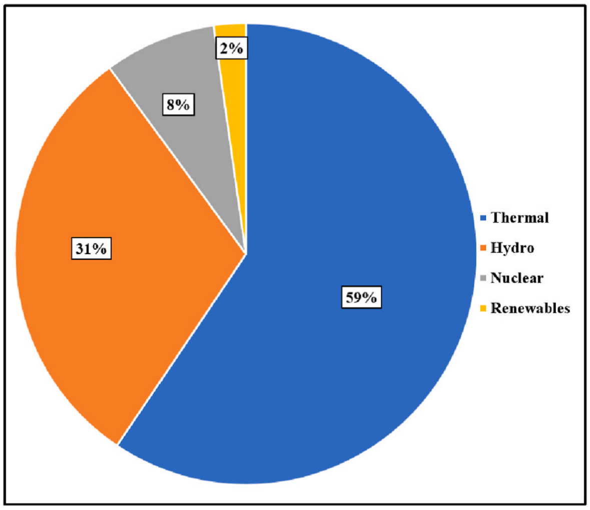


Fig. 4. Energy source wise share in electricity generation in 2021 [19].

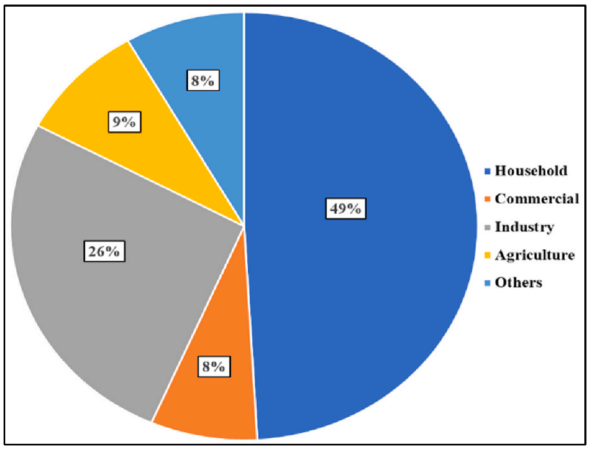


Fig. 5. Sector wise share in electricity consumption in 2021 [19].

resources, can be termed as hybrid energy system (HES), provides a reliable, sustainable, and environmentally affable alternative to address the drawbacks of individual renewable sources of energy [20].

The main purpose of this research is optimal designing of grid-connected microgrid systems for residential and commercial applications in Pakistan. The prime focus is to reduce cost of energy, increase renewable penetration, cut greenhouse gas emissions, enhance reliability of power supply, and to ascertain long-term sustainable generation of electrical energy.

The remaining paper is ordered as follows: Section 2 encompasses comprehensive literature review regarding similar research conducted worldwide and in Pakistan along with the identification of research gap for conducting the proposed study. Section 3 includes the designed approach to achieve the optimum design of grid-connected microgrid, specification of selected location, details regarding solar irradiation and ambient temperature, load contour, components of the system, hybrid electrical power system setting, and mathematical modelling of the systems proposed in the study. Section 4 displays optimization results as well as discussion related to the achievement of five set objectives, limitations for the actual implementation of the proposed designs, grid-connected microgrid design with energy storage systems, sensitivity analysis and the need to adopt latest energy trends of the world. Section 5 incorporates the conclusions derived from the work done.

2. Literature review

A significant amount of research has been conducted worldwide in the past decade regarding optimal design, sizing, and operation of microgrids in islanded mode. A research on a hybrid energy system incorporating PV, wind turbines, and hydropower was conducted for a distant countryside school in Thailand, and the proposed standalone HES was determined to be a compelling solution from both a technical and economic standpoint [21]. PV panels, wind turbines, and batteries were used to create a hybrid power system for a renewable energy laboratory (off-grid) in the KhshU Site, Iran, where PV/battery and PV/Wind/Battery hybrid energy systems were shown to be the most cost-effective configurations [22]. The size optimization problem with several objectives, including penetration maximization of renewable energy sources, reduction of pollutant emissions, and life-cycle cost, is solved using a genetic algorithm-based technique. Microgrid is built based on optimal sizing, and the proposed design is evaluated using operational data [23]. To find the best off-grid hybrid energy configuration, optimization study is performed using HOMER resulting in PV/Wind/Battery as the best combination to electrify a desert safari camp in UAE [24]. A study on optimal design of HES using HOMER tool for an Indian rural area is conducted in which different mixtures of renewable energy resources are evaluated. Hybrid energy system consisting of PV/Wind/Hydro/Biogas/Biomass provides the finest solution whereas to fulfill future energy demands, combinations of multiple renewable energy systems are found feasible in contrast to relying on single renewable energy source [25].

Likewise, numerous studies have been directed to evaluate the feasibility of grid-connected microgrids. Two existing microgrids (one autonomous and the other interconnected) are investigated in Rafina, Greece, near the coast of Athens. The findings show that the configuration of both microgrids might be improved by adding more PVs and wind turbines, making them more cost-effective and economically viable [26]. Techno-economic and environmental analysis is performed in Isfahan, Iran. The result of analysis shows that in grid-connected PV energy system, optimal configuration generates 68% of electricity from PV panels while the remaining is absorbed from the main grid whereas carbon dioxide emissions are also reduced [27]. Optimal planning and Energy management of microgrid comprising of PV, wind turbine and micro-turbine as generating section whereas battery and fuel cell as storing section has been conducted in Nain, Iran in which designed microgrid meets only one percent of the demand from the central network [28]. The case study is carried out for the urban university campus of Montreal, Canada to attain optimal isolated and grid-connected microgrid system by integrating renewable energy resources. Further, isolated and grid-connected systems are compared on technological and economic grounds. A grid-connected hybrid energy system with no battery storage and a high renewable fraction is shown to be the best alternative, with electricity costs lowered by 50% in contrast to the original grid power pricing in Montreal, Quebec [29].

Similar research has been conducted in Pakistan, however most of the research work has been focused on off-grid microgrids for impoverished rural areas [30–39]. However, a very limited number of studies have been conducted for microgrid working in grid-connected mode. A combined hydro/solar RES is designed for a small village in Muzaffargarh District, Pakistan to tackle energy shortage issue by utilizing the openly available renewables. Hybrid energy system is combined with local grid station to ensure constant supply of electrical energy. Designed system is capable to generate cheaper electricity as compared to electricity supplied by the grid [40]. A case study has been carried out for higher education institution located in Jamshoro, Pakistan for the sizing and optimization of microgrid with aim to generate clean energy from renewable energy penetration. The optimized model generates 63% of electricity from renewables while the remaining energy is to be absorbed from the national grid [41]. In a study conducted for a rural community in Pakistan's Sindh province, combination of solar/wind/grid provides the optimal design solution targeting the net present cost (NPC) and cost of electricity (COE) as the objective function [42].

Therefore, there exists a broad gap for research work related to grid-connected microgrid for domestic, commercial, and industrial applications in the urban areas of Pakistan, where a major portion of the electrical energy generated primarily from conventional energy resources is being consumed. Optimum design, sizing, and implementation of grid-connected microgrid for urban areas of Pakistan will have a considerable impact on the renewables share in overall electricity generation. It will serve as an important step towards the reduction of greenhouse gas emissions produced during electricity generation. Moreover, through renewable energy integration, sustainability of electrical energy will be ensured as at present it is fundamentally dependent on imported conventional energy sources.

3. Designed approach

This study has been carried out to accomplish five pre-defined objectives that are to reduce cost of energy, increase renewable share, cut greenhouse gas emissions, enhance reliability of power supply and to make generation sustainable in the long run for the country. With these objectives in mind, the optimal planning of components in grid-connected microgrid system has been performed. The mechanism described in Fig. 6 is proposed to realize five objectives. Various tools for optimizing energy systems are available for instance, HOMER [43–45], TRNSYS [46], iHOGA [47], and RETScreen [48]. HOMER is a comprehensive tool that has been widely utilized over the last century owing to its robust optimization engine and notable competence in designing optimal systems [49]. Therefore, it has been selected to undertake the research.

HOMER simulates energy systems, provides system plans that are cost-effective, and performs sensitivity analysis. It checks the feasibility of different configurations of microgrid based on conditions specified by user and calculates the installation and operating cost of system for multiple configurations possible over the life of project. HOMER presents a list of configurations that are arranged in ascending order with respect to Net Present Cost (NPC) so that user can compare different system designs from technical and economic viewpoint. However, for sensitivity analysis, HOMER iterates the optimization process and simulates different configurations over the range of values for each sensitivity variable defined by the user.

The experiments used in the study were approved by Pakistan Navy Engineering College, NUST Ethics Committee.

3.1. *Details of the selected locations*

Karachi, the largest city of Pakistan is selected for conducting case studies for optimal design of grid-connected microgrid for residential and commercial applications. The cosmopolitan city is the twelfth largest city in the world and the capital of province Sindh of Pakistan. It is located on the coast of Arabian Sea. The city is the commercial and industrial center of the country.

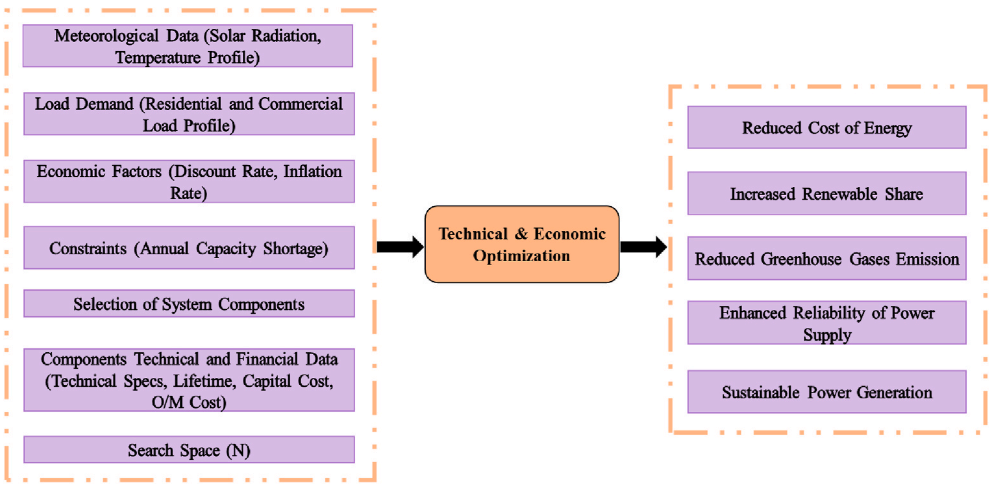


Fig. 6. Methodology for optimal designing of grid-connected microgrid.

3.2. Solar irradiation and temperature profile

The amount of power produced by photovoltaic arrays is primarily dependent on solar irradiation and temperature. The monthly average solar irradiation and temperature are important to consider in this context as required input in HOMER software. Fig. 7 depicts clearance index and solar radiation data of selected location obtained from NASA Prediction of Worldwide Energy Resource (POWER) for the year 2022. Karachi gets an average annual solar irradiation of 5.45 kWh/m^2/day. The selected area receives a significant quantity of solar radiation, making the use of a photovoltaic system an appealing power sourcing option. The performance of PV modules and air density are heavily influenced by the ambient temperature. As a result, collecting measured data on ambient temperature is especially important for this analysis. The annual average ambient temperature for the chosen locale is 26.3 °C while yearly temperature profile is depicted in Fig. 8.

3.3. Load profiles

For conducting the case studies, two different load profiles are made part of the evaluation. A residential home with peak load of 5 kW, annual average load of 1 kW and a load factor of 0.2 while a commercial market with peak load of 200 kW, annual average load of 50 kW and a load factor of 0.25 are considered. Figs. 9 and 10 depict the monthly residential and commercial load profiles.

3.4. System components

The core constituents of the grid-connected hybrid energy system are PV arrays, main grid, system converter, diesel generator and load. Commercial scale components are considered for commercial application accordingly. Cost of each component is taken according to the current market prices except grid. In case of grid, current applicable tariff with duties and taxes is considered that is available on Karachi Electric website in tariff structure section [50].

3.5. Hybrid power system configuration

During daytime, when PV output is capable enough to supply full or partial load demand, grid will be used as backup, supplying the remaining load demand which PV is unable to deliver. Whereas during nighttime, grid energy will be consumed primarily but for the case of power outages which are common in Karachi, generator will be utilized as grid backup. Grid and generator supply AC current whereas PV deliver DC current for which system converter is employed that convert DC current to alternating current, then supply it to the AC bus. Fig. 11 shows the schematic for PV/grid/generator hybrid energy system designed for conducting two case studies.

3.6. Mathematical representation

3.6.1. PV modelling

Photovoltaic panels (PV panels) turn sunlight into electricity which is fed into a DC line and converted to AC power by a system converter. The total PV installation cost vary depending on the size of project, type of PV being deployed, and the manufacturing company of PV panels. In this study, per kilowatt cost considered for the installation of PV panels is Rs. 120,000 whereas the considered operation and maintenance cost per kilowatt is Rs. 2800. The life of PV panels is considered as 25 years, same as the life of overall project. The derating factor is taken as 85% to account for the impact of dirt, temperature, and other losses. The HOMER calculates the output of photovoltaic arrays by using the given Eq. (1):

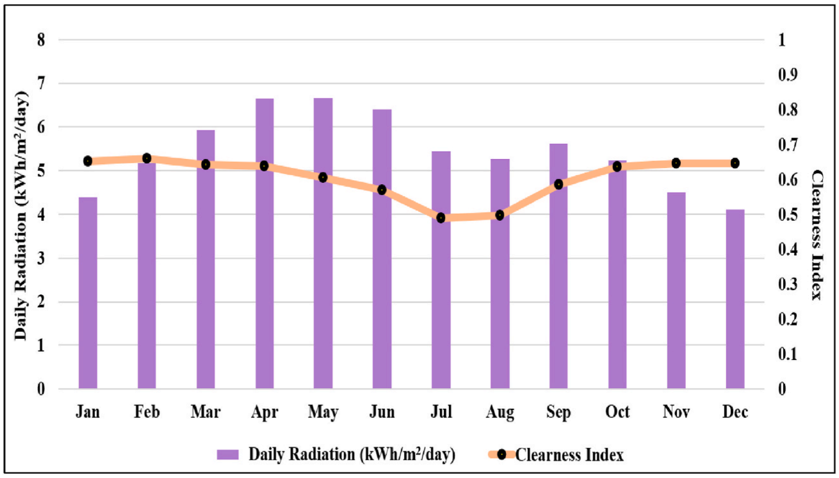


Fig. 7. Clearness index and solar irradiation, 2022.

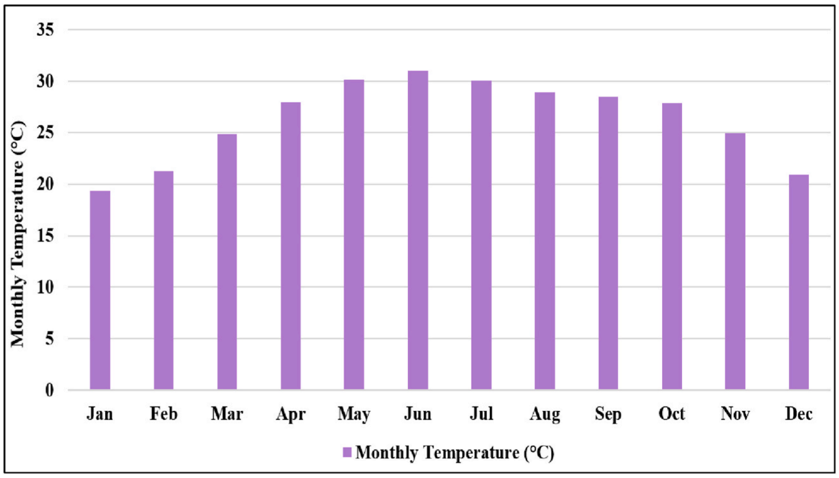


Fig. 8. Monthly temperature profile.

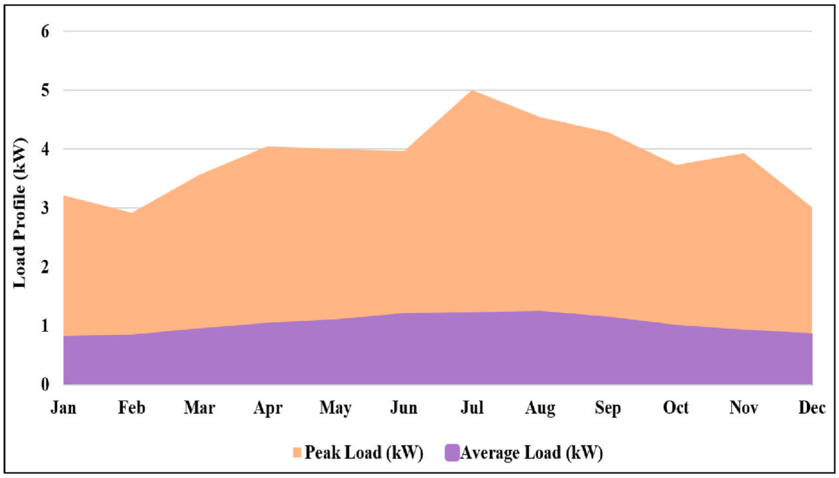


Fig. 9. Load profile for residential application.

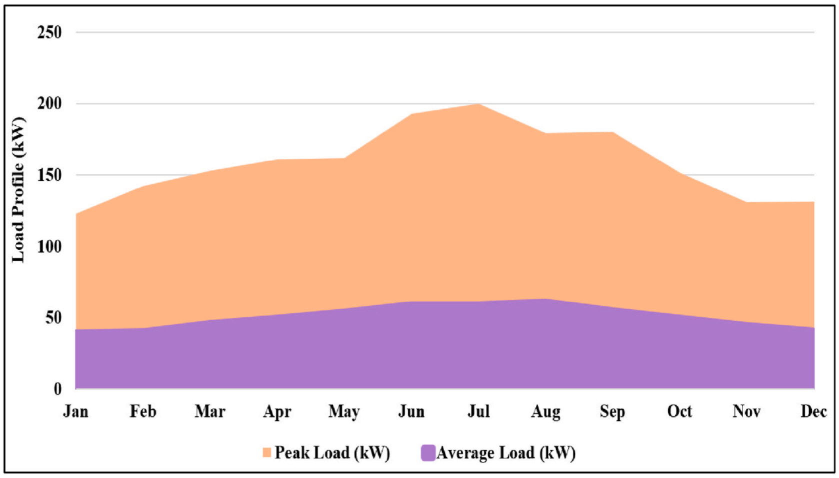


Fig. 10. Load profile for commercial application.

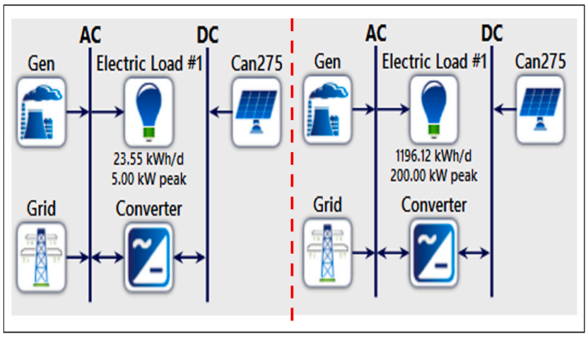


Fig. 11. Schematic for residential application and commercial applications respectively.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + a_P \left(T_C - T_{C,STC} \right) \right] \tag{1}$$

where, Y_{PV} is the rated capacity of the PV arrays, f_{PV} is the derating factor, $\overline{G}_T$ is the solar radiation incident on the PV array in the current time step [kW/m^2], $\overline{G}_{T,STC}$ is the incident radiation at standard test conditions [1 kW/m^2], α_p is the temperature coefficient of power [%/°C], T_c is the cell temperature in current time step [°C] and $T_{C,STC}$ is the PV cell temperature under standard test conditions [25 °C] [51].

3.6.2. Diesel generator modelling

Diesel generator is integrated into the hybrid microgrid system as an emergency backup power supply to ensure reliability of the system. In HOMER, the autosize generator, which automatically adjusts its capacity to accommodate the load, is chosen. The generator's capacity will be the smallest possible without causing a capacity shortfall. The initial capital and replacement cost per kW is taken Rs. 50,000 whereas the operational and maintenance cost per operating hour is taken as Rs. 120/op.hour for residential application while the initial capital and replacement cost per kW for commercial application is taken Rs. 70,000 whereas the operational and maintenance cost per operating hour is taken as Rs. 150/op.hour. The lifetime of diesel genset is taken as 15,000 h having a minimum load ratio of 25%. Furthermore, according to present market rates in Pakistan, fuel rate considered per liter is Rs. 264/L for the month of June 2022.

Over the course of a year, the average electrical efficiency of a generator is determined by dividing the electrical energy output by the fuel energy input, is calculated in HOMER as per Eq. (2):

$$\eta_{gen=} \frac{3.6 E_{gen}}{m_{fuel}\ LHV_{fuel}} \tag{2}$$

where, E_{gen} is the total annual electricity production of generator [kWh/yr], m_{fuel} is the total annual fuel consumption of generator [kg/yr] and LVH_{fuel} is the lower heating value of the fuel [MJ/kg].

In HOMER, the generator's lifetime is calculated in terms of operational hours. HOMER determines the number of years a generator will work as an output variable using the following Eq. (3):

$$R_{gen} = \frac{R_{gen,h}}{N_{gen}} \tag{3}$$

where, $R_{gen,h}$ is the generator lifetime in hours and N_{gen} is the number of hours the generator operates during one year [hr/yr] [52].

3.6.3. Emissions modelling

HOMER calculates the emissions of carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), particulate matter (PM), sulfur dioxide (SO_2) and nitrogen oxides (NO_X). Emissions are resulted from the production of electricity by generator and the consumption of grid electricity in the proposed designs. HOMER calculates the emissions factor that is the kilogram (s) of pollutant emitted per unit of fuel consumed by generator for each pollutant. The annual emission of that pollutant is calculated by multiplying the emission factor by the entire annual fuel use by generator.

When modelling a grid-connected microgrid system, the net grid purchases are computed by means of subtracting total grid sales from total grid purchases in HOMER, then the software multiplies the result (in kWh) with respective emission factor ((in g/kWh) of every single pollutant to find out emissions associated with them. It is possible to attain negative net grid-related emissions for each pollutant for the case when designed system can sell more electricity to the central grid as compared to the electrical units it is buying from the main grid over the year [52].

3.6.4. Net present cost

The net present cost of any component is the present value of all the costs that incurred during installation plus operating cost of the component over the life of the project, minus the present value of all the revenues that it earns over the project lifetime. HOMER determines the net present cost of each component in the system as well as NPC of the entire system [51].

3.6.5. Annualized cost

The cost of a component that, if it were to occur equally throughout the course of the project, would result in the same net present cost as the actual cash flow sequence associated with that component is known as its annualized cost.

After determining the net present cost, HOMER multiplies it by the capital recovery factor to determine annualized cost, as shown in Eq. (4):

$$C_{ann} = CRF\left(i, R_{proj}\right)\ .\ C_{NPC} \tag{4}$$

where, C_{NPC} is the net present cost, i is the annual real discount rate [%], R_{proj} is the project lifetime [yr] and CRF () is a function that returns the capital recovery factor calculated through Eq. (5) [51].

$$CRF\left(i, R_{proj}\right) = \frac{i\,(1+i)^{Rproj}}{(1+i)^{Rproj} - 1} \tag{5}$$

3.6.6. Cost of energy

It is the per unit cost of generated electrical energy from designed microgrid system over its lifetime. It is one of the economic factors to compare different system configuration. HOMER calculates the COE by dividing the yearly total cost of producing electricity by the total electric load served as per the following Eq. (6):

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{6}$$

where, $C_{ann,tot}$ is the total yearly cost of the system [Rs./yr] and E_{served} is the total electrical load served [kWh/yr] [52].

Total electrical load served is the sum of load served to the primary and deferable loads in addition to the grid sales over the entire year [51]. HOMER calculates the total electrical load served [kWh/yr] by using the following Eq. (7):

$$E_{served} = E_{served,prim} + E_{served,def} + E_{grid,sales} \tag{7}$$

3.6.7. Renewable share

The renewable share refers to the percentage of energy supplied to the load that is being generated from the renewable resources. The selected software calculates the renewable share as per the following Eq. (8):

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{served}} \tag{8}$$

where, E_{nonren} is the yearly electricity generation from non-renewable sources [kWh/yr] and E_{served} is the total electrical load served per year [52].

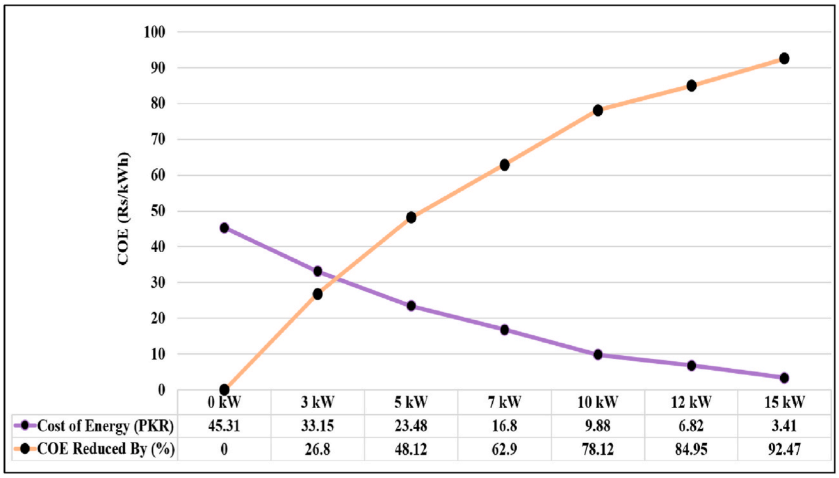


Fig. 12. Trade-off between cost of energy and different PV capacities for residential application.

4. Simulation outcomes and discussion

The HOMER software is used in this research as stated earlier to get the best sizing of energy sources in hybrid energy microgrid system to accomplish the five defined objectives of the study for residential and commercial applications. This research considers a project life of 25 years whereas discount rate of 9.75%, inflation rate of 13.8% and annual capacity shortage of 20% are considered keeping in view the current situation of the country.

4.1. Reduced cost of energy

The first objective of designing the proposed system is to decrease the electrical energy cost, however, the system is also intended to meet the objective of zero unmet load therefore the average per unit cost of electricity for residential sector in Pakistan with the provision of generator backup during power outages when no PV is included in the system is Rs. 45.31. Different capacities of PV are tested from 0 kW to 15 kW. It is possible to reduce per unit cost of electricity by 92.47% through deploying 15 kW solar panels. Fig. 12 depicts relation between the cost of energy for residential application and different PV capacities.

For commercial sector in Pakistan, per unit charges, including tariffs and taxes, are higher. As a result, incorporating renewable sources in the system to supply business load will be more beneficial than integrating renewable sources in the system to supply residential load. This can be proved by the fact that simple payback for residential application of 5 kW load with 15 kW of PV capacity is 6.8 years whereas for commercial application of 200 kW load with 250 kW installed PV capacity, payback period is 4 years. Fig. 13 shows the cost of energy for commercial application corresponding to different PV capacities.

4.2. Increased renewable share

The renewable share mentions the percentage of generated energy from renewable resources that is used to power the load. A larger renewable fraction indicates that renewable energy sources are used more frequently. Without significantly increasing the NPC, it is strongly suggested to maintain the renewable fraction as high as attainable, particularly due to environmental incentives [53]. In case of residential application, maximum renewable share of 85% can be attained with 15 kW PV capacity whereas in case of commercial load, maximum possible share with 250 kW of PV capacity is 71.1%. Figs. 14 and 15 show different values of renewable share corresponding to different PV capacities for residential and commercial applications respectively.

4.3. Reduced greenhouse gases emissions

Many pollutants like carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NOX), particulate matter are generated during the burning of fossil fuels for conversion of energy from one form to another. These emissions have a negative impact on our daily lives by creating air pollution, which harms the local environment. The ingestion of diesel is the only cause of emitted emissions in this investigation. The emissions from a diesel generator are proportionate to the amount of diesel consumed each year.

Fig. 16 shows a detailed analysis on greenhouse gases emissions from hybrid energy systems under different deployed PV capacities for residential application. It has been observed that emissions of all greenhouses gases are significantly reduced by introducing renewable to the system particularly emission of CO_2 is reduced by 2750 kg/yr for residential application. If simply one residence can reduce the emission of CO_2 by 48% from the base case by including the renewable source in the hybrid power system, then replication

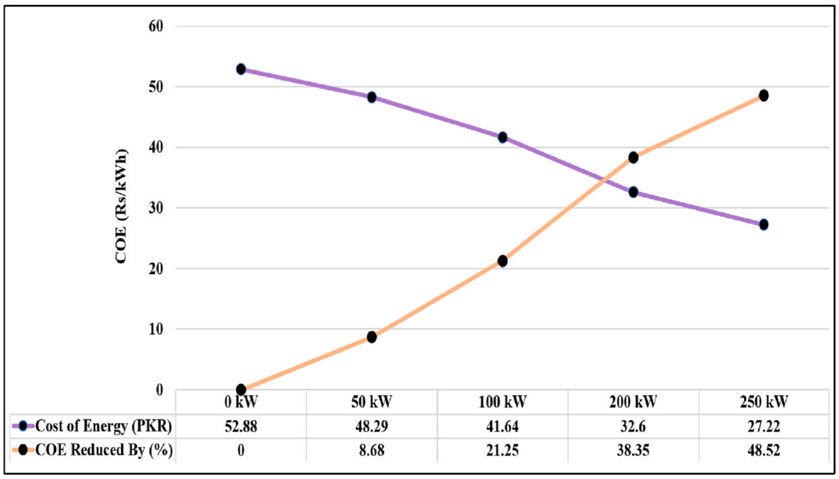
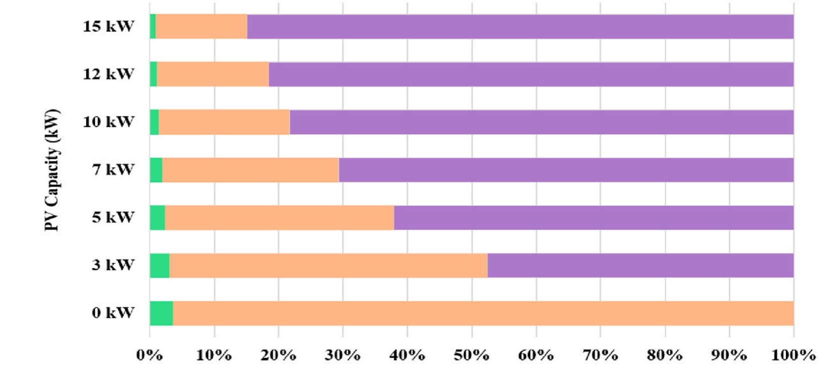
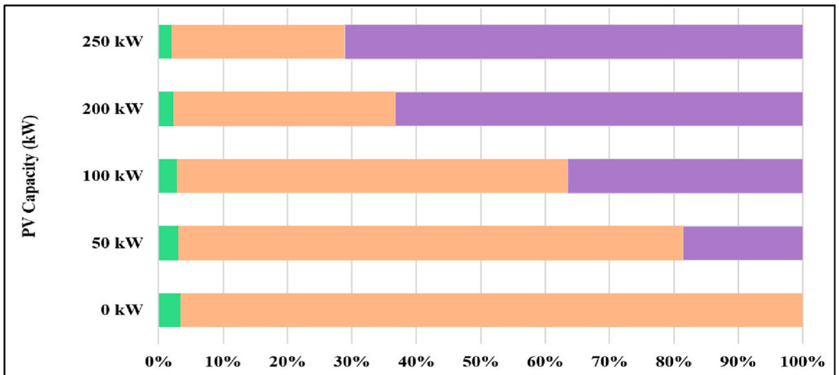


Fig. 13. Trade-off between cost of energy and different PV capacities for commercial application.



	0 kW	3 kW	5 kW	7 kW	10 kW	12 kW	15 kW
Generator (%)	3.65	3	2.34	1.86	1.34	1.12	0.862
Grid (%)	96.3	49.4	35.5	27.4	20.3	17.3	14.2
Renewable (%)	0	47.6	62.2	70.7	78.3	81.6	85

Fig. 14. Trade-off between renewable share (%) and different PV capacities for residential application.



	0 kW	50 kW	100 kW	200 kW	250 kW
Generator (%)	3.39	3.06	2.8	2.29	2.03
Grid (%)	96.6	78.3	60.7	34.5	26.9
Renewable (%)	0	18.6	36.5	63.2	71.1

Fig. 15. Trade-off between renewable share (%) and different PV capacities for commercial application.

of such hybrid power system for other households would significantly impact the environment of Pakistan where the air quality indexes of major cities have surged to hazardous levels [54,55].

Similarly, in case of commercial application, noticeable reduction in greenhouse gas emissions has been observed during the research. Emission of CO_2 is reduced by 171,895 kg/yr that is 61% less than the base case in which per year emission of CO_2 is 281,221 kg/yr as shown in Fig. 17.

Carbon intensity for energy production in Pakistan that is amount of CO_2 emitted per unit of energy production can be viewed from Fig. 18 [56]. Emissions of CO_2 per kWh of energy consumed in Pakistan is 0.615 kg CO_2/kWh [57].

4.4. Enhanced reliability of power supply

The total load served out of total load demand provides an indication about the reliability of the system. When demand for a service exceeds supply, it is known as unmet load. Proposed system is reliable with zero unmet load per year given that during grid power outages, PV is available during day while generator is on standby during night.

Furthermore, when base case that is grid/generator is considered for instance, if for any reason generator is not available, then Solar PV will be available for generating electricity in case of load shedding during daytime. Hence, enhanced reliability by introducing PV into power system by reducing unmet load per year for the two proposed optimized designs of residential and commercial applications is quantified in Table 1.

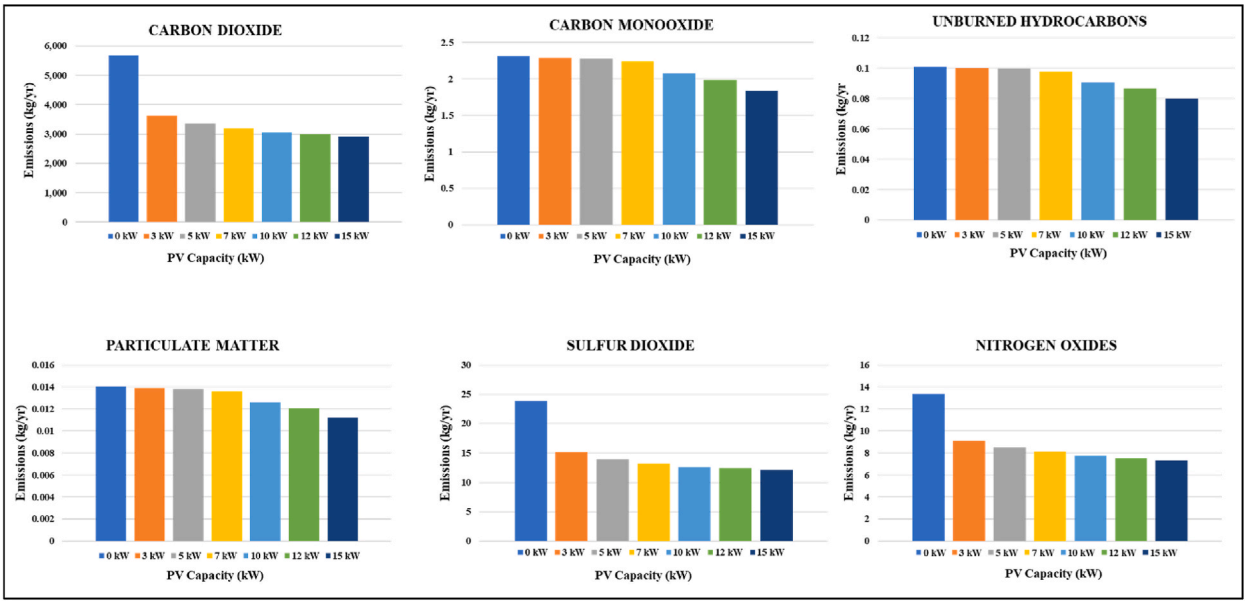


Fig. 16. Greenhouse gases emissions (kg/yr) against different PV capacities (kW) from residential application.

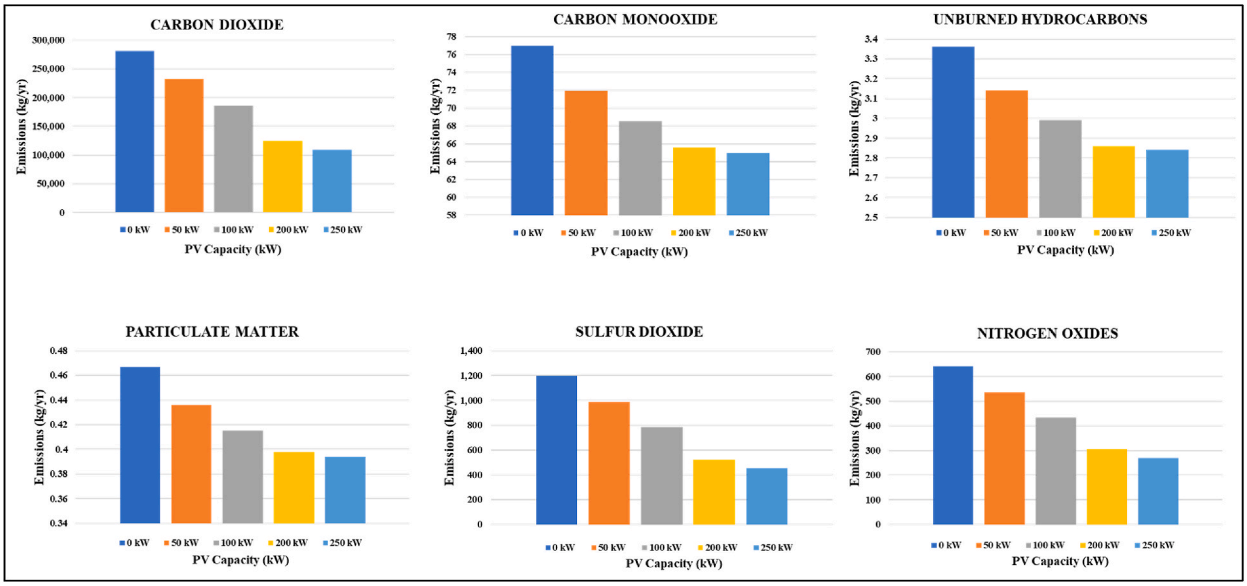


Fig. 17. Greenhouse gases emissions (kg/yr) against different PV capacities (kW) from commercial application.

4.5. Sustainable power generation

Electricity produced from renewable is the main reason behind the global energy shift towards sustainability. It sets out a route for the world to back off itself from existing fossil-fuel-based energy system and move towards a more affordable, clean, efficient, sustainable, and secure energy future [58]. Pakistan spends a generous portion of its budget on energy imports of coal, oil, and liquefied natural gas [16]. Though, the country holds the enormous potential of renewable energy sources and with properly planned utilization of these sources, prevailing energy crises may be eradicated or at least reduced to a greater extent that will eventually ensure energy security, economic growth and reduced GHGs emissions within the country [17]. Furthermore, increasing renewable energy penetration will assure the sustainability of electrical energy in the long run for the country, which is currently reliant on imported conventional energy sources.

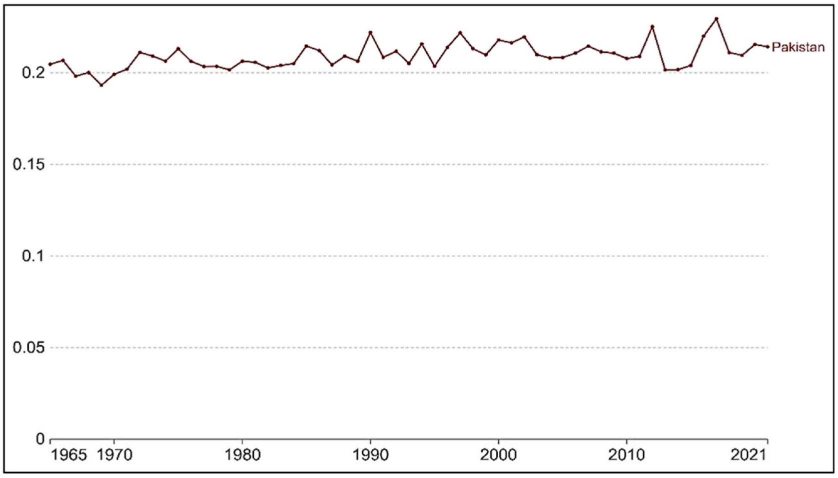


Fig. 18. Carbon intensity of energy production in Pakistan [kg CO_2/kWh] [56].

Table 1
Unmet electric load.

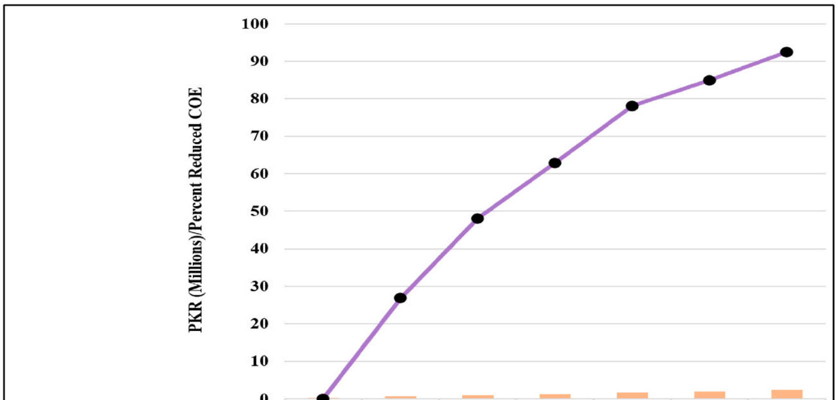
5 kW Residential Application		200 kW Commercial Application	
With PV (Grid/PV)	113 kWh/yr	With PV (Grid/PV)	4394 kWh/yr
Without PV (Grid)	214 kWh/yr	Without PV (Grid)	10,945 kWh/yr
Reduced by	101 kWh/yr	Reduced by	6551 kWh/yr
% Decrease	47.20%	% Decrease	59.85%

4.6. Limitations

The limitations in the practical implementation of proposed systems are initial capital cost and land requirements. The goal of the proposed solutions is to achieve zero unmet load, therefore capital cost of generator is also included in the initial capital cost requirement along with cost of solar PV and other system components. Initial capital cost has a substantial impact on cost of energy as can be observed from Fig. 19 where through investing Rs. 2.46 M PKR, cost of energy will drop by 92.27%.

For commercial application, a major initial capital cost is required owing to the huge load demand of 200 kW but cost of energy can be reduced drastically by 48.52% with promising payback period of only 4 years, however, emissions of greenhouse gases have reduced significantly. There always exist a compromise between the capital cost required initially and percent reduced cost of energy as can be viewed from Fig. 20.

One of the most important aspects of designing microgrids for metropolitan settings is determining the required space for deploying



	0 kW	3 kW	5 kW	7 kW	10 kW	12 kW	15 kW
Initial Capital Cost in Rs (M)	0.28	0.716667	1.01	1.3	1.74	2.03	2.46
COE Reduced By (%)	0	26.8	48.12	62.9	78.12	84.95	92.47

Fig. 19. Interrelation b/w initial capital cost, % reduced cost of energy, and different PV capacities for residential application.

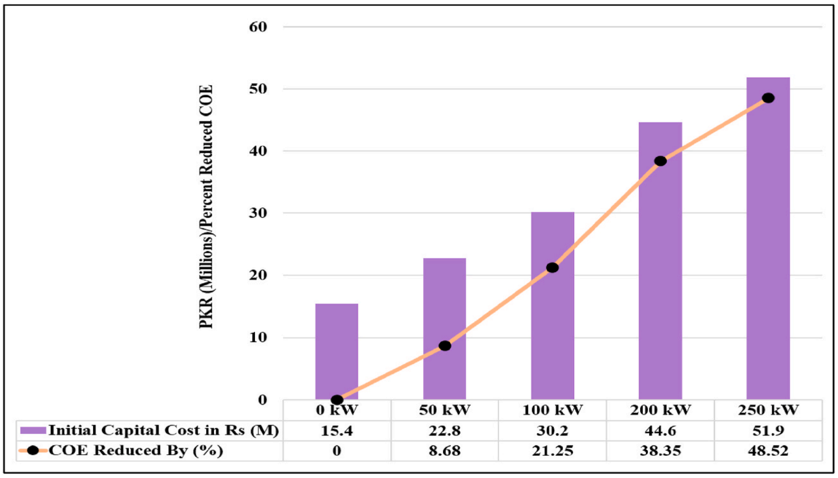


Fig. 20. Interrelation b/w initial capital cost, % reduced cost of energy, and different PV capacities for commercial application.

renewable resources. The major zone for putting the components is usually the roof region of a building. 1 kW of solar panels requires around 100 sq ft of space when utilized on rooftops and in modest ground-mounted installations [59]. Therefore, for deploying 15 kW PV panels, 1500 sq ft land will be required in case of residential application (5 kW peak load) in order to reduce the cost of energy by 92.47% for the user whereas to reduce the energy cost by 48.52% in case of commercial application (200 kW peak load), the amount of land required for deploying 250 kW solar PV would be 25,000 sq ft accordingly.

4.7. Grid-connected microgrid design with energy storage systems

Energy storage systems can be added in the designs of grid-connected microgrids for residential and commercial applications. Tables 2 and 3 presents comparison between different configurations for both residential and commercial cases from where trade-offs can be observed clearly. Since one of the objectives of the study is to ensure reliability of power supply, therefore, PV-Battery-Grid configuration is impotent to fulfill the purpose. PV-Battery-DG-Grid configuration has zero unmet load but at the cost of increased capital cost specially for the case of commercial application. Moreover, since systems are designed for urban areas, availability of space to place batteries with proper protection is a major area of concern, specifically for commercial case a plenty of batteries are required to be accommodated with suitable protection.

4.8. Sensitivity analysis

Sensitivity analysis has been performed considering the impact of variable fuel price and solar radiation. Figs. 21 and 22 depict the effect of changing fuel prices on NPC and COE of the designed systems for residential and commercial application respectively. It can be observed that if fuel price is increased by 14%, net present cost is increased by 4.2% while cost of energy is increased by 4.4% for residential case however for the commercial case, NPC is increased by 0.998% while COE is increased by 0.936%. Fuel price variation has a significant impact on residential application as compared to commercial application.

Figs. 23 and 24 present the impact of varying average solar radiation on net present cost and cost of energy respectively. Owing to the changing climatic conditions, if average solar radiation is reduced by 27%, NPC will increase drastically by 121% while COE will increase exorbitantly by 187% for residential case. In case of commercial application, NPC and COE will increase by 15% and 31% respectively for the same variation of −27% in average solar radiation of the selected location. Likewise observed in fuel price variation, changing average solar radiation has notable effect on residential application as compared to commercial application.

4.9. Elimination of energy crisis in Pakistan by adopting latest energy trends of the world

Strategically and geographically, Pakistan holds a pivotal position in the South Asian region being one of the most populous

Table 2
Comparison of different grid-connected microgrid designs for residential application.

Factors	PV-Battery-Grid	PV-DG-Grid	PV-Battery-DG-Grid
NPC (M PKR)	−1.390	3.800	1.610
COE (PKR)	−1.260	3.410	1.450
CAPEX (M PKR)	2.210	2.460	2.640
Unmet Electric Load (kWh/year)	88.500	0.000	0.000

Table 3
Comparison of different grid-connected microgrid designs for commercial application.

Factors	PV-Battery-Grid	PV-DG-Grid	PV-Battery-DG-Grid
NPC (M PKR)	300.000	601.000	484.000
COE (PKR)	13.420	26.710	21.530
CAPEX (M PKR)	36.700	51.9	61.9
Unmet Electric Load (kWh/year)	3380.000	0.000	0.000

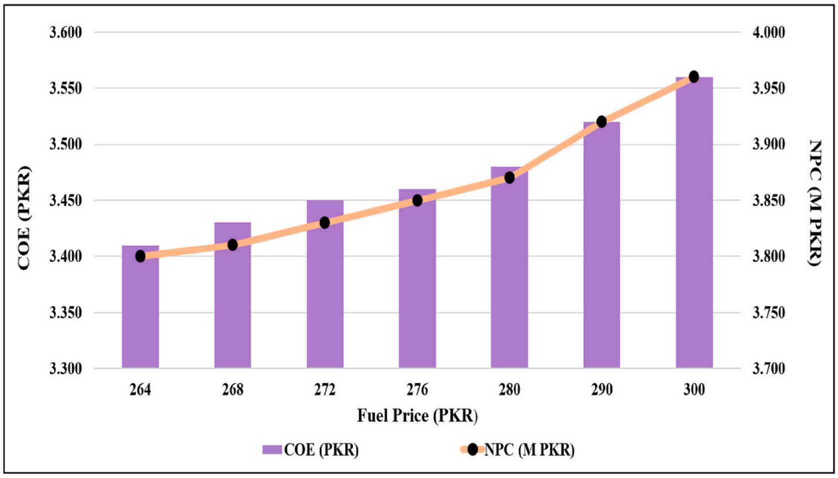


Fig. 21. Effect of changing fuel price on NPC and COE for residential application.

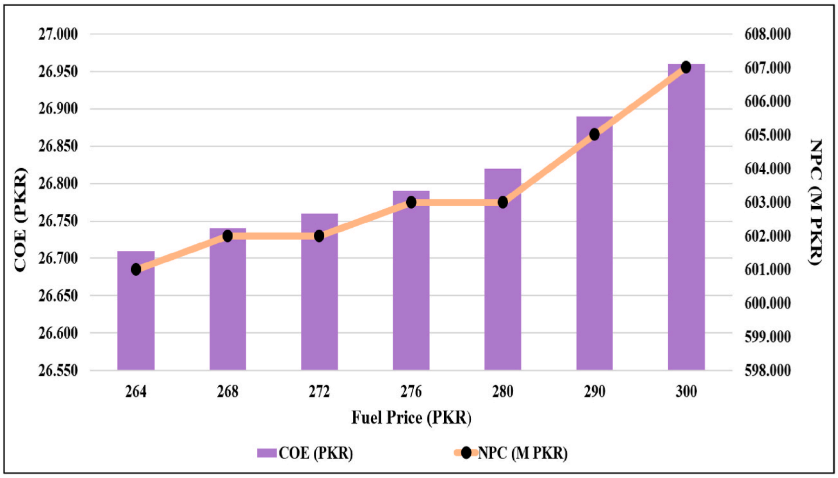


Fig. 22. Effect of changing fuel price on NPC and COE for commercial application.

countries in the world. Unfortunately, due to political adversity and misconduct of the energy sector, generation of electricity through oil and natural gas ensuring their availability is getting more challenging with time. The nation is currently suffering from energy crisis that is indirectly diverting the attention from societal concerns. People are tired of the gas load shedding and electrical shortages. Their commercial endeavors are not expanding effectively. The energy crisis has contributed to unemployment and poverty as well. Moreover, shortage of electricity is severely impacting industrial, agricultural, educational and health sectors of the country. Pakistan has abundant natural gas, coal, and renewable energy resources, but because of poor management and governance, it is now reliant on imported fossil fuels. This reliance has negatively impacted the national treasure.

Most of the developed nations have acknowledged, embraced, and set goals for shifting their energy generation from conventional sources to RE sources. But Pakistan still heavily relies on traditional energy sources despite experiencing an energy crisis in the form electricity shortfall and high production costs incurred during energy production through conventional energy sources.

An increase in electricity generation by renewables in recent years signals a strong commitment towards reducing carbon emissions

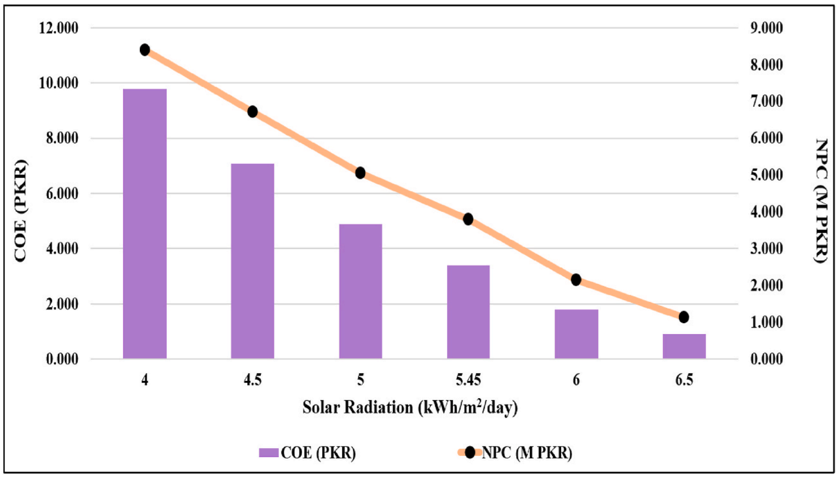


Fig. 23. Effect of variable average solar radiation on NPC and COE for residential application.

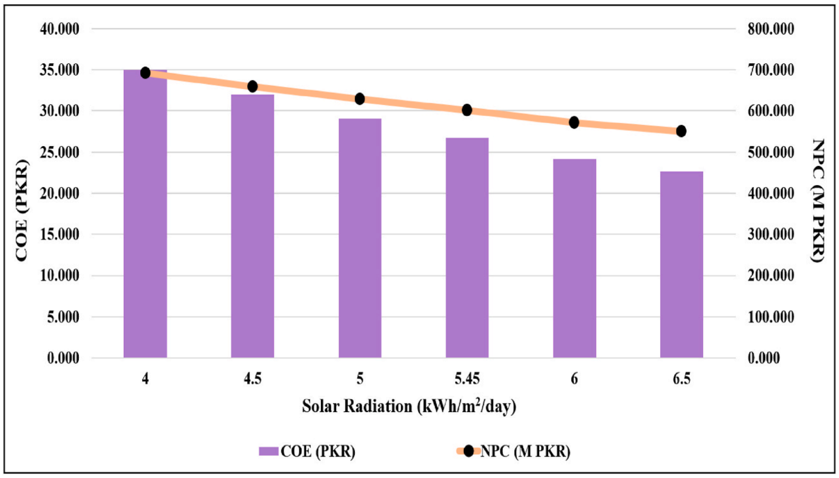


Fig. 24. Effect of variable average solar radiation on NPC and COE for commercial application.

and addressing climatic changes. The number of installed new solar power projects is more than the net additions by gas, coal, and nuclear plants combined.

Solar energy is the most accessible and abundant source of all RE. The estimated potential of solar PV power in Pakistan is around 1600 GW [60], however, the currently installed capacity is only 530 MW [61]. Therefore, Pakistan should move towards hybrid energy systems following the trend of the world majorly incorporating Solar energy into the current power system.

5. Conclusion

Technical and Economic Optimization for Grid-Connected Microgrid Systems for Residential and Commercial Applications is performed as reference case studies for the practical implementation of the same in the urban areas of Pakistan. All five objectives are achieved at the end of each case study which are reduced cost of energy, increased renewable share, reduced greenhouse emissions, reliable power supply and long-term sustainable generation of electricity. In order to achieve the trade-off, different solar PV capacities are tested against energy cost, renewable share and emission of greenhouse gases.

The two limitations that may hinder the actual implementation of offered solutions in Pakistani cities with enough solar radiation to create an efficient hybrid energy system are initial capital expenditures and land requirements. However, through deployment of 15 kW solar PV with a payback period of 6.8 years for residential application of 5 kW load, cost of energy can be minimized to Rs. 3.41 that is 92.47% lower than the base case energy cost, renewable share can rise to 85%, and CO_2 emissions can be decreased by 48% compared to the base scenario with no renewables. Whereas, in case of commercial application, cost of energy can be reduced to Rs. 27.22 that is 48.52% less from the base case cost of energy, renewable energy share can increase up to 71.1% while CO_2 emissions can be reduced by 171,895 kg per year that is 61% less than the base case, by means of installing solar PV capacity of 250 kW for 200 kW of commercial load.

Different grid-connected microgrid configurations have been evaluated and discussed for both residential and commercial cases. System economics (NPC, COE, CAPEX) and reliability are compared. Moreover, the need for shifting towards hybrid energy systems following the current trends of the world is discussed to overcome social and economic issues associated with electrical energy.

This study can be extended in various directions. For instance, technical and financial benefits of integrating several microgrids into a grid-connected centralized smart grid for a particular residential area can be investigated. Furthermore, advanced net metering technology can be integrated in the designed system to manage economics of the electricity for selected area with multiple residential peak loads. Impact on cost of energy and carbon emissions can be evaluated after incorporating smart grid and advanced net metering technology in centralized smart grid designed for residential locale.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contribution statement

Syeda Sakina Zaidi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Syed Sajjad Haider Zaidi; Bilal Muhammad Khan; Lubna Moin: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

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.

References

[1] Y.A. Ul'yanin, V.V. Kharitonov, D.Y. Yurshina, Forecasting the dynamics of the depletion of conventional energy resources, Stud. Russ. Econ. Dev. 29 (2) (2018) 153–160, https://doi.org/10.1134/S1075700718020156.
[2] International Energy Agency, World Energy Outlook 2016, International Energy Agency, Paris, France, 2016.
[3] T. Urmee, D. Harries, A. Schlapfer, Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific, Renew. Energy 34 (2) (2009) 354–357, https://doi.org/10.1016/j.renene.2008.05.004.
[4] C. Marnay, S. Chatzivasileiadis, C. Abbey, R. Iravani, G. Joos, P. Lombardi, J. Von Appen, Microgrid evolution roadmap, in: 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), IEEE, 2015, September, pp. 139–144, https://doi.org/10.1109/SEDST.2015.7315197.
[5] A. Hirsch, Y. Parag, J. Guerrero, Microgrids: a review of technologies, key drivers, and outstanding issues, Renew. Sustain. Energy Rev. 90 (2018) 402–411, https://doi.org/10.1016/j.rser.2018.03.040.
[6] H.E. Murdock, D. Gibb, T. André, J.L. Sawin, A. Brown, L. Ranalder, L. Brumer, Renewables 2022-Global Status Report, 2022.
[7] G. Strbac, N. Hatziargyriou, J.P. Lopes, C. Moreira, A. Dimeas, D. Papadaskalopoulos, Microgrids: enhancing the resilience of the European megagrid, IEEE Power Energy Mag. 13 (3) (2015) 35–43, https://doi.org/10.1109/MPE.2015.2397336.
[8] U. Akram, M. Khalid, S. Shafiq, Optimal sizing of a wind/solar/battery hybrid grid-connected microgrid system, IET Renew. Power Gener. 12 (1) (2018) 72–80, https://doi.org/10.1049/iet-rpg.2017.0010.
[9] M.A. Ramli, A. Hiendro, S. Twaha, Economic analysis of PV/diesel hybrid system with flywheel energy storage, Renew. Energy 78 (2015) 398–405, https://doi.org/10.1016/j.renene.2015.01.026.
[10] L. Berga, The role of hydropower in climate change mitigation and adaptation: a review, Engineering 2 (3) (2016) 313–318, https://doi.org/10.1016/J.ENG.2016.03.004.
[11] Hannah Ritchie, Max Roser, Pablo Rosado, CO_2 and greenhouse gas emissions, in: Our World in Data, 2020.
[12] C. Kennedy, I.D. Stewart, M.I. Westphal, A. Facchini, R. Mele, Keeping global climate change within 1.5 C through net negative electric cities, Curr. Opin. Environ. Sustain. 30 (2018) 18–25, https://doi.org/10.1016/j.cosust.2018.02.009.
[13] V. Johansson, M. Lehtveer, L. Göransson, Biomass in the electricity system: a complement to variable renewables or a source of negative emissions? Energy 168 (2019) 532–541, https://doi.org/10.1016/j.energy.2018.11.112.
[14] T. Castillo-Calzadilla, A.M. Macarulla, O. Kamara-Esteban, C.E. Borges, A case study comparison between photovoltaic and fossil generation based on direct current hybrid microgrids to power a service building, J. Clean. Prod. 244 (2020), 118870, https://doi.org/10.1016/j.jclepro.2019.118870.
[15] Y. Wang, L. Xu, Y.A. Solangi, Strategic renewable energy resources selection for Pakistan: based on SWOT-Fuzzy AHP approach, Sustain. Cities Soc. 52 (2020), 101861, https://doi.org/10.1016/j.scs.2019.101861.
[16] S. Malik, M. Qasim, H. Saeed, Y. Chang, F. Taghizadeh-Hesary, Energy security in Pakistan: perspectives and policy implications from a quantitative analysis, Energy Pol. 144 (2020), 111552, https://doi.org/10.1016/j.enpol.2020.111552.
[17] Y.A. Solangi, Q. Tan, N.H. Mirjat, S. Ali, Evaluating the strategies for sustainable energy planning in Pakistan: an integrated SWOT-AHP and Fuzzy-TOPSIS approach, J. Clean. Prod. 236 (2019), 117655, https://doi.org/10.1016/j.jclepro.2019.117655.
[18] M.A. Raza, K.L. Khatri, A. Israr, M.I.U. Haque, M. Ahmed, K. Rafique, A.S. Saand, Energy demand and production forecasting in Pakistan, Energy Strategy Rev. 39 (2022), 100788, https://doi.org/10.1016/j.esr.2021.100788.
[19] Pakistan Economic Survey 2020-21, Ministry of Finance, Government of Pakistan, 2021. Available online (assessed on 20 May 2023): https://www.finance.gov.pk/survey/chapters_21/PES_2020_21.pdf.
[20] A.S. Aziz, M.F.N. Tajuddin, M.R. Adzman, A. Azmi, M.A. Ramli, Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: a case study of Iraq, Renew. Energy 138 (2019) 775–792, https://doi.org/10.1016/j.renene.2019.02.004.
[21] P. Iemsomboon, T. Pati, K. Bhumkittipich, Performance study of micro hydro turbine and PV for electricity generator, case study: bunnasopit school, Nan Province, Thailand, Energy Proc. 34 (2013) 235–242, https://doi.org/10.1016/j.egypro.2013.06.752.

[22] M. Haratian, P. Tabibi, M. Sadeghi, B. Vaseghi, A. Poustdouz, A renewable energy solution for stand-alone power generation: a case study of KhshU Site-Iran, Renew. Energy 125 (2018) 926–935, https://doi.org/10.1016/j.renene.2018.02.078.
[23] B. Zhao, X. Zhang, P. Li, K. Wang, M. Xue, C. Wang, Optimal sizing, operating strategy and operational experience of a stand-alone microgrid on Dongfushan Island, Appl. Energy 113 (2014) 1656–1666, https://doi.org/10.1016/j.apenergy.2013.09.015.
[24] A. Aziz, Techno-economic analysis using different types of hybrid energy generation for desert safari camps in UAE, Turk. J. Electr. Eng. Comput. Sci. 25 (3) (2017) 2122–2135, https://doi.org/10.3906/elk-1602-159.
[25] A.K. Nag, S. Sarkar, Modeling of hybrid energy system for futuristic energy demand of an Indian rural area and their optimal and sensitivity analysis, Renew. Energy 118 (2018) 477–488, https://doi.org/10.1016/j.renene.2017.11.047.
[26] D.I. Papaioannou, C.N. Papadimitriou, A.L. Dimeas, E.I. Zountouridou, G.C. Kiokes, N.D. Hatziargyriou, Optimization & sensitivity analysis of microgrids using homer software-a case study, in: MedPower 2014, IET, 2014, pp. 1–7, https://doi.org/10.1049/cp.2014.1668.
[27] M.R. Memar, M. Moazzami, H. Shahinzadeh, D. Fadaei, Techno-economic and environmental analysis of a grid-connected photovoltaic energy system, in: 2017 Conference on Electrical Power Distribution Networks Conference (EPDC), IEEE, 2017, pp. 124–130, https://doi.org/10.1109/EPDC.2017.8012752.
[28] H. Shahinzadeh, M. Moazzami, S.H. Fathi, G.B. Gharehpetian, Optimal sizing and energy management of a grid-connected microgrid using HOMER software, in: 2016 Smart Grids Conference (SGC), IEEE, 2016, pp. 1–6, https://doi.org/10.1109/SGC.2016.7882945.
[29] N. Shirzadi, F. Nasiri, U. Eicker, Optimal configuration and sizing of an integrated renewable energy system for isolated and grid-connected microgrids: the case of an Urban University Campus, Energies 13 (14) (2020) 3527, https://doi.org/10.3390/en13143527.
[30] M.A. Khan, M.S. Aziz, A. Khan, K. Zeb, W. Uddin, M. Ishfaq, July). An optimized off-gird renewable AC/DC microgrid for remote communities of Pakistan, in: 2019 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), IEEE, 2019, pp. 1–6, https://doi.org/10.1109/ICECCE47252.2019.8940636.
[31] M.J.A. Baig, M.T. Iqbal, M. Jamil, J. Khan, Design and analysis of an isolated DC-microgrid for a remote community in Pakistan, in: 2021 IEEE 12th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), IEEE, 2021, pp. 712–716, https://doi.org/10.1109/UEMCON53757.2021.9666665.
[32] M. Ahmad, A. Khan, M.A. Raza, M.A. Khan, M.A. Rehman, Study, design and analysis of an optimized off-gird renewable AC/DC microgrid for a rural school in swabi, Pakistan, in: 2019 22nd International Multitopic Conference (INMIC), IEEE, 2019, pp. 1–6, https://doi.org/10.1109/INMIC48123.2019.9022780.
[33] R. Khan, A. Khan, A. Zahra, Cost optimization of hybrid microgrid for rural electrification along western alignment of China-Pakistan economic corridor (CPEC) in Pakistan, in: 2019 IEEE Global Humanitarian Technology Conference (GHTC), IEEE, 2019, pp. 1–6, https://doi.org/10.1109/GHTC46095.2019.9033039.
[34] M.S. Aziz, M.A. Khan, A. Khan, F. Nawaz, M. Imran, A. Siddique, Rural electrification through an optimized off-grid microgrid based on biogas, solar, and hydro power, in: 2020 International Conference on Engineering and Emerging Technologies (ICEET), IEEE, 2020, pp. 1–5, https://doi.org/10.1109/ICEET48479.2020.9048222.
[35] R. Khan, A. Khan, Cost optimization of hybrid microgrid across China-Pakistan economic corridor (CPEC) eastern route for rural electrification in Pakistan, in: 2019 3rd International Conference on Energy Conservation and Efficiency (ICECE), IEEE, 2019, pp. 1–7, https://doi.org/10.1109/ECE.2019.8920948.
[36] Zaidi, S. A. N., & Jamil, M. Design and Analysis of a Small Scale Micro-grid for a Rural Settlement in Pakistan.
[37] M.U. Khan, M. Hassan, M.H. Nawaz, M. Ali, R. Wazir, Techno-economic Analysis of PV/wind/biomass/biogas hybrid system for remote area electrification of Southern Punjab (Multan), Pakistan using HOMER Pro, in: 2018 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET), IEEE, 2018, pp. 1–6, https://doi.org/10.1109/PGSRET.2018.8686032.
[38] S. Tahir, M.A. Khan, M. Rasool, N. Naseer, An optimized off-grid renewable micro-grid design and feasibility analysis for remote industries of gadoon swabi (Pakistan), in: 2021 International Conference on Artificial Intelligence and Mechatronics Systems (AIMS), IEEE, 2021, pp. 1–6, https://doi.org/10.1109/AIMS52415.2021.9466023.
[39] A. Khan, R. Khan, Cost optimization of hybrid microgrid using solar PV, fuel cell and diesel generator in HOMER, in: 2018 2nd International Conference on Energy Conservation and Efficiency (ICECE), IEEE, 2018, pp. 14–18, https://doi.org/10.1109/ECE.2018.8554974.
[40] M. Rasool, M.A. Khan, S. Tahir, Optimal on-grid hybrid AC/DC microgrid for a small village in Muzaffargarh District, Pakistan, in: 2021 International Conference on Emerging Power Technologies (ICEPT), IEEE, 2021, pp. 1–8, https://doi.org/10.1109/ICEPT51706.2021.9435501.
[41] J.A. Shaikh, Techno-economic sizing and optimization of microgrid; a case study of a higher education institution, Int. J. Elec. Eng. Emerg. Technol. 4 (2) (2021) 37–40.
[42] O.A. Memon, A.M. Soomro, M. Kumar, M. Farhan, Implementation of microgrid with integration of hybrid renewable sources using different backup techniques, Indian J. Sci. Technol. 13 (33) (2020) 3457–3466, https://doi.org/10.17485/IJST/v13i33.763.
[43] M.R. Elkadeem, S. Wang, A.M. Azmy, E.G. Atiya, Z. Ullah, S.W. Sharshir, A systematic decision-making approach for planning and assessment of hybrid renewable energy-based microgrid with techno-economic optimization: a case study on an urban community in Egypt, Sustain. Cities Soc. 54 (2020), 102013, https://doi.org/10.1016/j.scs.2019.102013.
[44] O. Boqtob, H. El Moussaoui, H. El Markhi, T. Lamhamdi, Optimal sizing of grid connected microgrid in Morocco using Homer Pro, in: 2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS), IEEE, 2019, pp. 1–6, https://doi.org/10.1109/WITS.2019.8723790.
[45] F. Antonio Barrozo Budes, G. Valencia Ochoa, L.G. Obregon, A. Arango-Manrique, J. Ricardo Núñez Álvarez, Energy, economic, and environmental evaluation of a proposed solar-wind power on-grid system using HOMER Pro®: a case study in Colombia, Energies 13 (7) (2020) 1662, https://doi.org/10.3390/en13071662.
[46] M.S. Saleem, N. Abas, A.R. Kalair, S. Rauf, A. Haider, M.S. Tahir, M. Sagir, Design and optimization of hybrid solar-hydrogen generation system using TRNSYS, Int. J. Hydrogen Energy 45 (32) (2020) 15814–15830, https://doi.org/10.1016/j.ijhydene.2019.05.188.
[47] G. Zubi, R. Dufo-López, G. Pasaoglu, N. Pardo, Techno-economic assessment of an off-grid PV system for developing regions to provide electricity for basic domestic needs: a 2020–2040 scenario, Appl. Energy 176 (2016) 309–319, https://doi.org/10.1016/j.apenergy.2016.05.022.
[48] Y. Pan, L. Liu, T. Zhu, T. Zhang, J. Zhang, Feasibility analysis on distributed energy system of Chongming County based on RETScreen software, Energy 130 (2017) 298–306, https://doi.org/10.1016/j.energy.2017.04.082.
[49] S. Bahramara, M.P. Moghaddam, M.R. Haghifam, Optimal planning of hybrid renewable energy systems using HOMER: a review, Renew. Sustain. Energy Rev. 62 (2016) 609–620, https://doi.org/10.1016/j.rser.2016.05.039.
[50] Karachi Electric Tariff Structure. Available Online (assessed on 10 June 2022):: https://www.ke.com.pk/customer-services/tariff-structure/.
[51] HOMER Pro 3.14 User Manual, released August 10, 2020. Available Online (assessed on 13 June 2022): https://www.homerenergy.com/products/pro/docs/index.html.
[52] HOMER Energy, Homer Pro Version 3.7 User Manual vol. 7, HOMER Energy, Boulder, CO, USA, 2016.
[53] F. Belaïd, M.H. Zrelli, Renewable and non-renewable electricity consumption, environmental degradation and economic development: evidence from Mediterranean countries, Energy Pol. 133 (2019), 110929, https://doi.org/10.1016/j.enpol.2019.110929.
[54] A. Shareef, D.R. Hashmi, Impacts of COVID-19 pandemic on air quality index (AQI) during partial lockdown in Karachi Pakistan, J. Health Environ. Res. 6 (3) (2020) 93–97.
[55] M.S. Anjum, S.M. Ali, M.A. Subhani, M.N. Anwar, A.S. Nizami, U. Ashraf, M.F. Khokhar, An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan; a critical review, J. Hazard Mater. 402 (2021), 123943, https://doi.org/10.1016/j.jhazmat.2020.123943.
[56] Hannah Ritchie, Max Roser, Pablo Rosado, Energy, Published online at OurWorldInData.org. Retrieved from:, 2022 https://ourworldindata.org/energy.
[57] M. Brander, A. Sood, C. Wylie, A. Haughton, J. Lovell, Technical Paper| Electricity-specific Emission Factors for Grid Electricity, Ecometrica, Emissionfactors.com, 2011.
[58] D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A.S. Oyewo, M. Child, C. Breyer, Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, Energy 227 (2021), 120467, https://doi.org/10.1016/j.energy.2021.120467.

[59] Area Required for Solar PV Power Plants-Suncyclopedia. Available online (assessed on 10 June 2022): http://www.suncyclopedia.com/en/area-required-for-solar-pv-power-plants/.
[60] A. Ashfaq, A. Ianakiev, Features of fully integrated renewable energy atlas for Pakistan; wind, solar and cooling, Renew. Sustain. Energy Rev. 97 (2018) 14–27.
[61] State of Industry Report 2021, National Electric and Power Regulatory Authority (NEPRA), Government of Pakistan, 2021. Available Online (assessed on 11 April 2023): https://www.nepra.org.pk/publications/State%20of%20Industry%20Reports/State%20of%20Industry%20Report%202021.pdf.