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Techno-economic and sustainable energy solutions for the small industrial estate of Gujranwala, Pakistan-using hybrid microgrid

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ABSTRACT

This research comprises the energy solutions for small industrial estate in Gujranwala, Pakistan using HOMER pro simulation software and considering the best possible energy plan with maximum reliability, cost-effectiveness, efficiency, and availability. A small industrial estate is an industrial zone comprising small industrial units (ceramics, cutlery, sports goods, surgical instruments, tough tile, garments, etc.) organized by the provincial government of Punjab, Pakistan. In this research, we have proposed a microgrid framework to ensure continuity of supply for the small industrial estate of Gujranwala, Punjab, Pakistan. In this research work, we have collected the required data related to the availability of natural energy resources in the Gujranwala region like solar DNI (direct normal radiations), GHI (global horizontal irradiations) wind speed, and temperature from NREL's (National Renewable Energy Laboratory) official website. Then, we estimated the maximum power demand by collecting real-time one-year data from the existing 132kv Shaheen Abad grid, Punjab, Pakistan, which is feeding electric power to an existing small industrial state Gujranwala similar to a new industrial estate under construction. We have proposed a microgrid design by integrating that collected data into the HOMER Pro simulation application including electrical load profiles, solar irradiance data, regional temperature profile, diesel costs, PV module longevity, degradation rates, efficiency, costs of PV modules, national grid energy pricing and net metering with national grid. A comprehensive assessment of the proposed optimal system involves twenty-five years of technical and economic analysis for the small industrial estate of Gujranwala, Pakistan.

1. Introduction

The world economies are transforming from carbon to green economies due to consistent increases in fossil fuel demand and price [1-5]. Conventional fossil fuel-dependent energy sources contribute to greenhouse gas emissions and global climate change. [6-11]. It is a dire need of the hour to engage financial resources in developing green energy sources rather than investing money in conventional fossil fuel-dependent energy sources. The main objective of this research is to conduct a comprehensive, economic and technical analysis of small industrial estates in the province of Punjab Pakistan along with the electrical energy requirement. Which is under massive shifting from populated urban areas to a single industrial estate for the reduction of smog and air pollution in cities. The study proposes an economical and sustainable energy solution for small industrial estate dist. Gujranwala. The provincial government of Punjab has planned the massive shifting of scattered small industries to a single planned area with an investment of millions of dollars to meet energy demand using the old conventional power sources including deposit--Based erection of a 132kv air-insulated grid station connected with the national utility company [12].

A hybrid microgrid represents a compact AC/DC electrical system capable of generating, transmitting, and distributing energy effectively across a substantial area. This attribute endows microgrids with a remarkable level of flexibility that surpasses traditional electric power systems [13, 14]. In cases of power interruptions within a conventional grid, a grid-connected microgrid, equipped with meticulously engineered control mechanisms, can seamlessly operate as an independent entity—an "island"—while consistently supplying power to its designated loads. This functionality occurs without compromising the overall integrity of the primary grid. The involvement in microgrid initiatives encompasses a diverse array of stakeholders, including technology suppliers, consumers, power generation, transmission, and distribution providers, as well as policymakers. A visual representation of these stakeholders' engagement is depicted in Fig. 1.

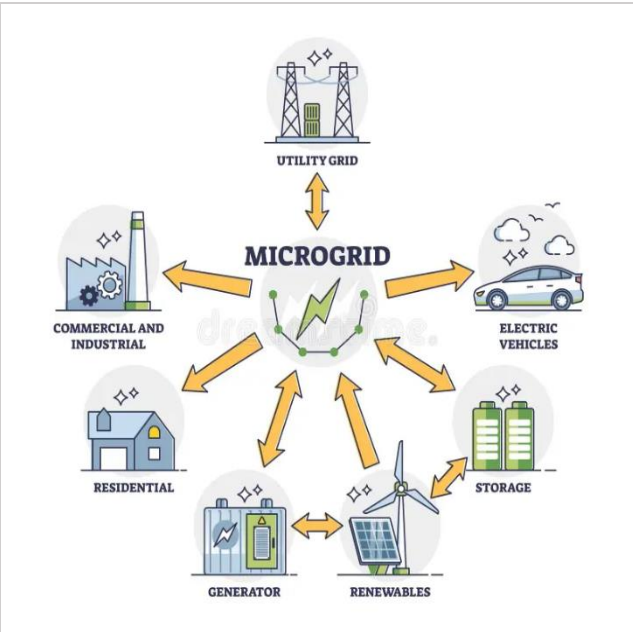

Fig. 1. Basic Concept of Microgrid

2. Literature Review

Progressive countries, like the USA, have been using microgrid technologies for decades, which is more than any other country in the world. A comprehensive study is conducted regarding microgrid systems in US energy infrastructure [15]. The economic aspects of the DC/AC hybrid microgrid are studied briefly. This review has been conducted by examining the most important constituents of both DC and AC MGs, accentuating their corresponding constraints and benefits. [16]. The main advantages and reasons for integrating AC/DC modern technology in a hybrid MG setting are briefly studied. [17]. In parallel to this, the review of standards in microgrids and modern communication technologies are studied, as well as the review of MGs energy management systems to enhance the efficiency of MGs, which is one of the main goals of the authors in this article. Also, in this research, the major trends of MGs in 2023 have been scrutinized to enhance the flexibility of system infrastructure. [18]. Necessary information is collected regarding industrial power loads on the efficiency of solar panels/diesel hybrid renewable power systems for rural areas' energy needs. [19]. A systematic and detailed study on industrial smart and MG modern systems is carried out. This research paper aims to give a comprehensive knowledge of the modern state of the art and the essential factors affecting the performance of modern MGs [20]. The study also highlights system optimization which is used to design optimum operation of MGs for electric energy exchange and trading between utility and microgrids. Renewable sources are also used to meet demands in microgrids with minimum operation cost and continuity of supply. [21]. Modern techniques and methods are studied to ensure long-term reliability and sustainability in interconnected microgrids through smart load management. [22]. A profitability grid optimization approach is deeply understood in virtual powerhouses comprised of industrial and residential microgrids for management demand-side applications. [23]. I thoroughly went through the economic and technical MG models needed for any DSM research. In addition, a detailed study of DSM technologies is conducted that helps MG operators keep reliability and costs within an acceptable range. [24]. A detailed study of MG applications and energy management systems in developed MGs is conducted. A comprehensive analysis of energy management systems, applications, and solution approaches has been examined. Optimizing MG system reliability, operation in microgrids and energy planning are also studies. [25]. The applications of Renewable sources are increasing due to the major drawback of increasing fuel prices. Not so many research works address microgrid implementation in industrial applications. This paper provides a detailed review of the modern art of industrial MGs based on renewable energies. [26]. The research covers the hybrid microgrids, designed by a combination of renewable sources, energy storage technologies, and interconnection with the grid can contribute to changing the economy of any country [27].

The application of HOMER pro simulation application is studied for modeling the best possible economical and sustainable energy plan [28]. Further advanced application of HOMER pro is reviewed. This paper explored a technique for optimum sizing of a hybrid energy management system for an industrial application and operation method of electric load using HOMER with modern topology. Technical analysis of feasibility and lifecycle costs of an MG for each hour of the complete year is determined by applying HOMER softwareb[29]. A new strategy for island power management has been presented and multiple simulations have been executed that, on a theoretical basis, such a methodology could be applied within the Microgrid concepts. Contingencies for modern communications and system failure have been studied and supply to top-priority electric loads has been managed wherever possible [30]. To accommodate the nature of increasing power demands, conventional power grids have been augmented with advanced network and communication technologies, such as advanced metering systems with sensors, demand responses, energy storage, and the integration of chargeable electric vehicles. To ensure localized energy management and reliability, Microgrids have been proposed [31]. MGs run at low or medium-voltage systems that operate with maximum efficiency, and resilience, and regulate the exchange of energy between the national grid [32]. A Comprehensive study is conducted on recent achievements and developments of MG capacity optimization and estimation for active distribution of power networks [33]. This research paper evaluates the economic benefits of modern microgrids with hybrid energy sources and energy storage devices. Different possible configurations of hybrid microgrid power systems are studied and a detailed comparative technical analysis is also studied. The operation cost, capital cost, fuel cost, cost of energy, and total cost are examined [34].

3. Significance of the Proposed Design

The significance of this research lies in its multidimensional contributions to the energy sector, industrial development, renewable sources, environmental impacts, economic benefits, and academic discourse:

3.1 To Meet Energy Challenges

Given the increasing global emphasis on sustainable energy solutions and the challenges faced by the small industrial sector of Pakistan. This research aims to address critical energy issues. This proposed design can be implemented into other applications like domestic, agricultural, or commercial source load. Its significance lies in providing an innovative and practical solution to ensure an uninterrupted, cost-effective, and sustainable energy supply to the small industrial sector.

3.2 Integration of Renewables

Considering the integration of renewable energy resources such as Solar Photovoltaic (SPV), the research contributes significantly to the broader spectrum of reducing dependency on fossil fuels. It emphasizes the feasibility and effectiveness of harnessing renewable energy sources for consistent power generation.

3.3 Economic Benefits

This research emphasizes optimizing the hybrid microgrid configuration to minimize the Net Present Cost (NPC) holds substantial significance. It provides insights into cost-efficient energy solutions, demonstrating the economic viability of renewable energy integration and its potential to reduce long-term energy costs. It causes a sufficient reduction in global fuel transportation which ultimately results in economic growth.

3.4 Environmental Benefits

Green sources of energy are widely being added into global power systems due to their major advantage of minimum contribution to greenhouse gas emissions. Green energy also reduces air pollution and noise pollution to a reasonable level which is why considered an environmentally friendly energy source.

4. Proposed Methodology

To achieve my required objective, different types of data like the availability of natural sources, maximum power demand, selected site specifications, and sources of energy must be known first. Secondly, reference electric load is recorded from existing small industrial estates of similar capacity [35]. Thirdly, all collected data is inserted into HOMER Pro simulation software for final economics and optimized energy solutions for the next twenty-five years.

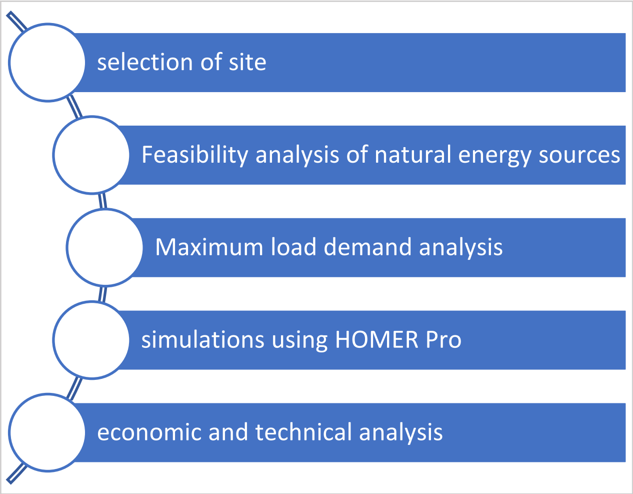

Fig. 2. Proposed Methodology

The proposed methodology is depicted in Fig.2. Thereafter, the main observation is conducted with and without renewable factors to conduct the cost-benefit analysis of the proposed design, In the end, the economic and technical comparison is elaborated to depict the worth of the proposed design.

5. Site Selection

The considered area is the small industrial estate, located in Gujranwala, Punjab, Pakistan. The latitude of the selected site is 32.018159, and the longitude is 74.225496. The land of a small industrial estate consists of 200 acres. The area required for the erection of the proposed 25000KW solar system requires approximately fifteen to twenty acres of land. [36].

Fig. 3. Location Of Small Industrial Estate Gujranwala

6. Required Data for Simulations

6.1 Solar Irradiations and Temperature

we collected the solar irradiation data sets: Direct normal irradiations and global horizontal irradiations (DNI and GHI) from NREL including 2001 to 2019 models [37]. The time series averaged daily irradiations and temperature are illustrated in the time series domain given in the figures: Fig.4, fig.5, and Fig. 6.

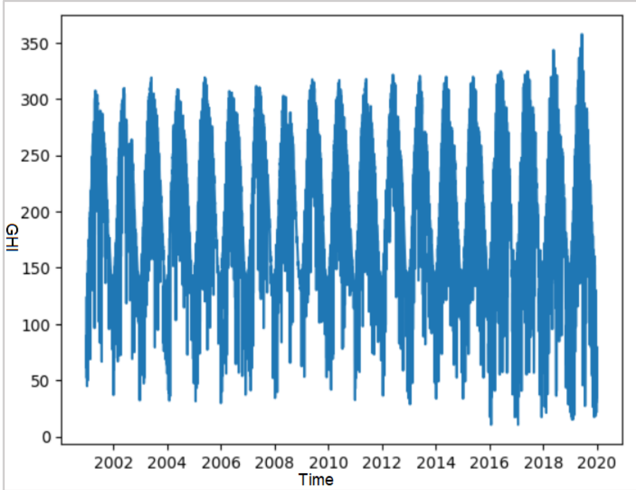

Fig. 4. NREL, Global Horizontal Irradiations Profile

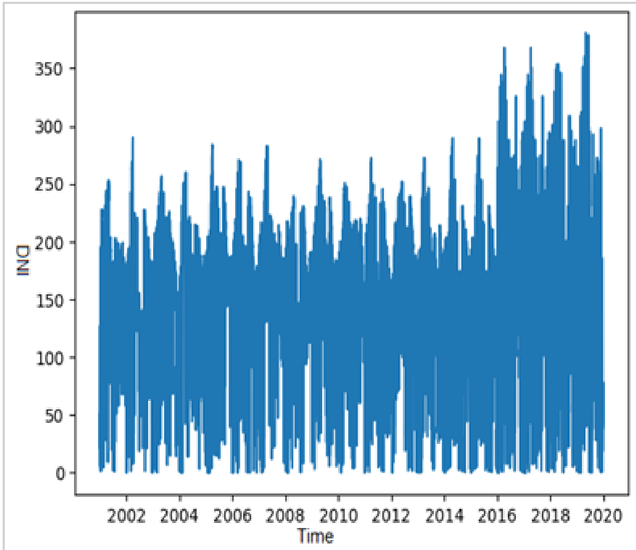

Fig.5. NREL, Direct Normal Irradiations Profile

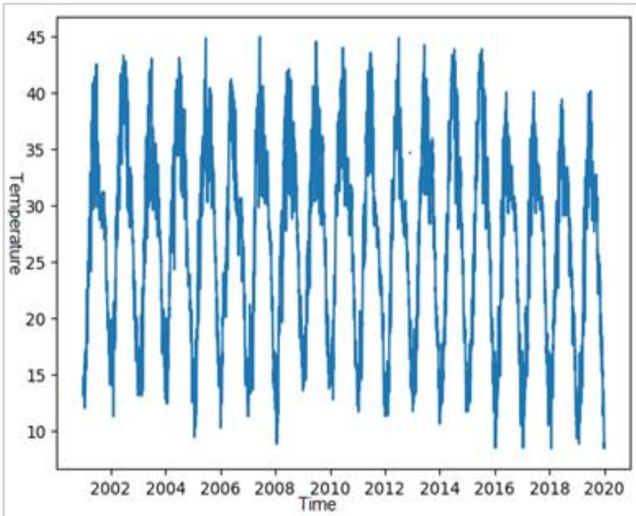

Fig.6. NREL, Temperature Profile

6.2 Determination of Maximum Demand

The PSIC (Punjab Small Industrial Estate Corporation) department, the government of Pakistan has launched the fourth project for small industrial development and economic growth by providing a sustainable and reliable energy source. One of three existing small industrial estates of similar capacity is taken as a reference model for the determination of estimated load, which is expected to be operated on newly small industrial estates under construction. The existing model is fed by a national grid of Pakistan with two 11kv feeders. The real-time one-year load collected data is illustrated in the following table. Its time series behavior is demonstrated in Fig. 7.

Table 1

Monthly load profile of existing small industrial estate

MWH consumption of existing SIE model			
MONTH	11kv SIE feeder 01 MWH	11kv SIE feeder 02 MWH	Total MWH
JAN	1023.66	1230.637	1023.66
FEB	993.201	1151.836	993.201
MAR	1082.689	1356.666	1082.689
APR	780.18	1297.519	780.18
MAY	1041.7	1675.407	1041.7
JUN	1075.588	1801.797	1075.588
JUL	1002.248	1679.091	1002.248
AUG	1282.324	1883.576	1282.324
SEP	1167.16	1694.925	1167.16
OCT	1049.44	1362.872	1049.44
NOV	949	1284.035	949
DEC	933.55	1256.398	933.55

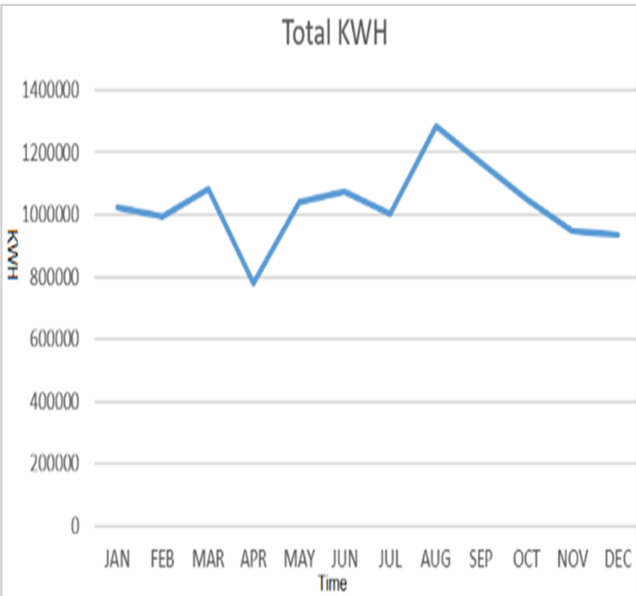

Fig. 7. Load Profile Of Existing Small Industrial Estate

6.3 HOMER Pro as a Tool

HOMER Pro software is a product of the National Renewable Energy Laboratory (NREL), which is located in Colorado, USA, and stands as an advanced tool dedicated to formulating optimal hybrid designs, ensuring uninterrupted and cost-effective electricity for both grid-connected and off-grid applications. This sophisticated and dedicated software application employs intricate decision variables, meticulously analyzing diverse resource combinations to derive the most efficient hybrid configuration. Renowned for its precision and impartiality, it integrates meteorological data sourced from the National Aeronautics and Space Administration (NASA) to assess available renewable resources at specific locations. The software operates through three distinct phases: initial project inputs, encompassing site-specific resources, load profiles, and system components; simulation and optimization, involving sensitive variables; and ultimately, presenting detailed outcomes covering financial metrics, performance, and system sizing.

6.4 Electric Load Profile

The load is estimated from the existing SIE model of similar capacity. The design of the microgrid for any specific site purely depends on the scenario of energy consumption, for which the sources need to be integrated and fulfill the demand. The purpose is to provide uninterrupted and quality power to the industrial consumer. The first step for the project is to measure the load of existing SIE Gujranwala, Pakistan. The hourly and monthly load profile for the site is presented in Fig.8 and Fig. 9 respectively.

6.5 Diesel Generator

Table 2

A diesel generator with the following particulars is used in simulations as an emergency power supply to critical loads

Diesel Generator	Description of Parameters	
Manufacturer	Generac	
Capacity	1000	kw
Capital Cost	186700	$
Replacement Cost	186700	$
Fuel curve intercept	14	L/h
Minimum load ratio	25.00	%
Lifetime	15000	Hours

6.6 Bidirectional Power Converter

Table 3

The converter with the following particulars is used as a coupler between the AC and DC bus bar.

Bidirectional Converter	Description of Parameters	
Manufacturer	Generic	
Capital Cost	10000$	1000-kW
Replacement Cost	10000$	1000-kW
O and M	100	($/year)
Lifetime	15	Years
Efficiency (inverter input)	95	%

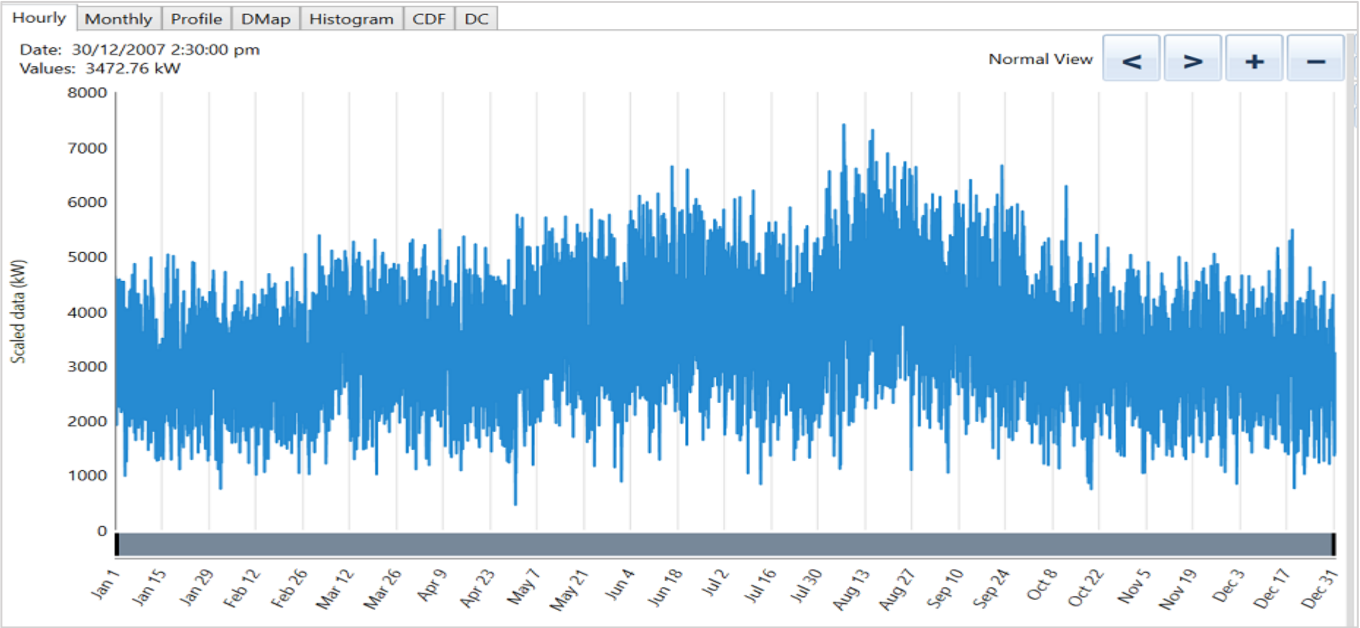

Fig. 8. Hourly Averaged Load Profile

Fig. 9. Monthly Averaged Load Profile

6.7 Solar Photovoltaic

In the proposed microgrid design, the solar PV system parameters are as follows:

Flat plate-type solar PV panels from Peimar Inc. with a rated capacity of 24.0 MW, were selected to align with the energy consumption of SIE Gujranwala. Monocrystalline photovoltaic cells, chosen for their commendable efficiency of 27.00%, are employed in the HOMER simulation. The nominal operating temperature is set at 27°C, with a default temperature coefficient of -0.400, representing the effect of temperature on the power output of the photovoltaic system.

Table 4

Solar PV contribution

Quantity	Value	Units
Rated Capacity	24	MW
Mean Output	3.03	MW
Mean Output	72.735	MWh/d
Capacity Factor	12.6	%
Total Production	26,548.2	MWh/yr
Minimum Output	0	kW
Maximum Output	16.376	MW
PV Penetration	88.9	%
Hours of Operation	4,385	hrs/yr
Levelized Cost	0.0057	Rs/kWh

7. Mathematical Modelling

7.1 PV Output Power

"HOMER uses the following Eq. to calculate the output of the PV array.[38]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right]$$

PV = the rated capacity of the PV array, meaning its power output under standard test conditions [kW]

PV = the PV derating factor [%]

$\bar{G}_T$ = the solar radiation incident on the PV array in the current time step [kW/m2]

$\bar{G}_{T,STC}$ = the incident radiation at standard test conditions [1 kW/m2]

αP = the temperature coefficient of power [%/°C]

Tc = the PV cell temperature in the current time step [°C]

STC = the PV cell temperature under standard test conditions [25°C]"

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right)$$

7.2 Levelized Cost of Energy

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}}$$

Where

$C_{ann,\ tot}$ = system's annualized cost ($/yr)

C_{boiler} = boiler's marginal cost ($/kWh)

H_{served} = served thermal load (kWh/yr)

E_{served} = handled electrical load (kWh/yr)

7.3 Renewable Fraction

$$f_{ren} = 1 - \frac{E_{nonren} - H_{nonren}}{E_{served} + H_{served}}$$

Where

E_{nonren} = non-renewable energy production (kWh/yr)

$E_{grid,\ sales}$ = energy sold to the grid (kWh/yr)

H_{nonren} = thermal production from non-renewables (kWh/yr)

E_{served} = handled electrical load (kWh/yr)

H_{served} = Served thermal load (kWh/yr)

7.4 Operating Cost

$$C_{operating} = C_{ann,tot} - C_{ann,cap}$$

"Where $C_{operating}$ is the total annualized cost of the system ($/yr), $C_{ann,\ the\ cap}$ is the total annualized capital cost ($/yr)."

8. Proposed HOMER Pro Hybrid Microgrid Design

The proposed hybrid microgrid simulation design for the SIE, Gujranwala site Punjab, Pakistan encompasses a diverse array of all components like energy sources, estimated load, maximum demand, solar irradiations, generator, converter, and national grid aimed at optimizing energy production shown in fig. 10.

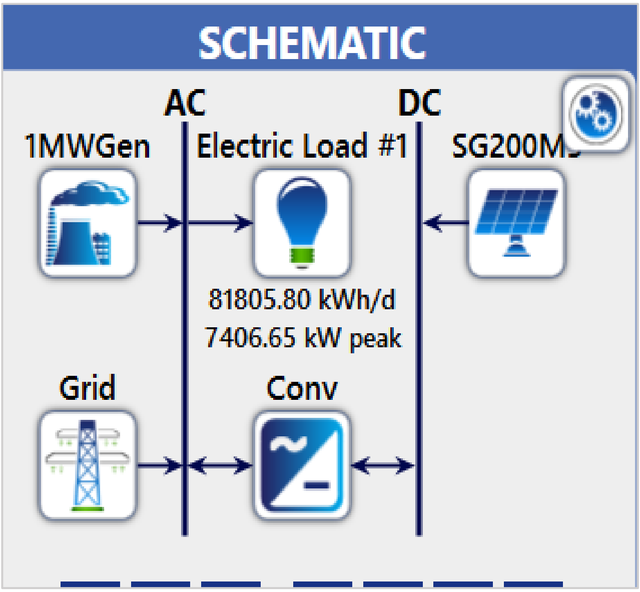

Fig.10 The Proposed Hybrid Microgrid Simulation

9. Optimization Of Proposed Design And Discussion

9.1 Cost analysis

To get the optimal results the setting upper and lower limits for each energy source is left for the HOMER by choosing the option of "Optimization". The optimized design of the microgrid is out of six hundred simulations, which is presented in the following table. The two optimized designs of microgrid for the SIE Gujranwala, have been proposed based on the five performing criteria including net operating cost, cost of energy, operating cost, capital cost, and renewable fraction. I have considered the first one, which is most efficient and economical. The source's contribution is described in the Fig. 11.

COE	NPC	operating cost	initial capital	Renewable Fraction
Rs7.29	Rs33.90	Rs0.30	Rs1.66	58.80%

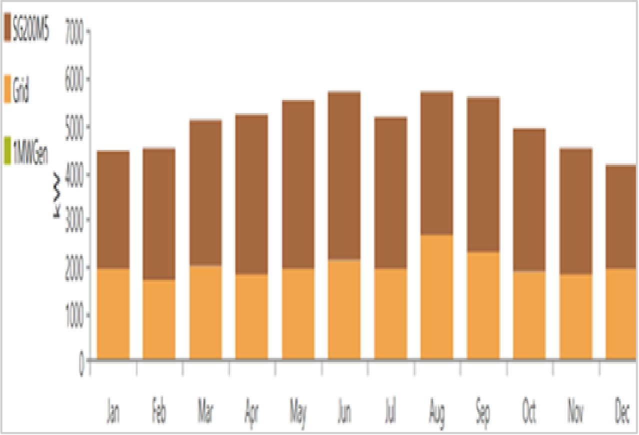

Fig. 11. The Source's Contribution

9.2 Net Metering With National Grid

Irrespective of energy user type either domestic, commercial, or industrial, everyone is planning to arrange independent and cost-efficient renewable energy sources due to rising electricity prices. The optimized system will exchange the electricity to the national grid as per the NEPRA net metering policy [39]. In the optimal design of the microgrid proposed by the HOMER, for SIE Gujranwala, Pakistan, the power purchased from the grid is 17696.2 MWh, and power sold to the grid is 13.06 MWH.

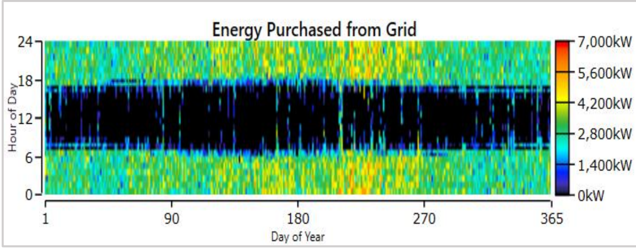

Fig. 12. Energy Purchased From Grid

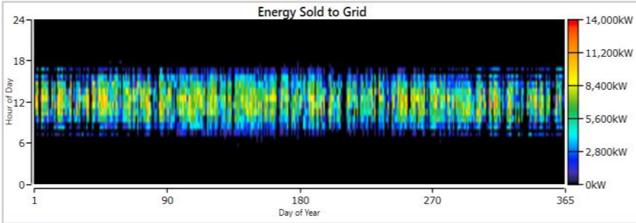

Fig. 13. Energy Sold To The Grid

9.3 Economic Benefits

Economic benefits for an estimated period of twenty-five years are described in Table 5.

After a detailed economic analysis of an optimized system for the term of twenty-five years, we reached the gist that the system would save 37 billion Pakistani rupees using the proposed hybrid microgrid energy system.

Table 5

Economic comparison of with and without renewable and savings in the next 25 years (billion rupees)

	COE	NPC	Operating cost	Initial capital	Renewable Fraction
Without Renewable	59.85	193	1.79	0.05	0%
With Renewable	7.29	33.9	0.3	1.66	58.80%
Annual difference	52.56	159.1	1.49	-1.61	
25 years savings			37.3		

10. Conclusion

In this research, an optimized hybrid microgrid system consisting of solar energy with a converter, a diesel generator, and a national grid is designed to supply uninterrupted, cheap, and quality power to SIE Gujranwala. However, the optimal operation and the sizing of this power system are carefully designed to avail all the benefits. To get the correct and reliable results, real-time load data is collected from similar capacity existing small industrial estates. Solar irradiation data sets are fetched from the NREL (National Renewable Energy Laboratory) official website. The design, simulations, and optimization of the proposed hybrid microgrid are briefly examined. The program has found the optimum size of each component based on the available data. It also provides an economic analysis of the system for 25 years. Simulation has been performed on the estimated yearly power consumption of existing SIE Gujranwala. In conclusion, the integration of a 25000KW PV system, 1000 kW diesel generator, and a national grid with net metering is found to be the optimum design of microgrid to perform efficiently and economically for the selected load profile, which can save up to 37.3 billion Pakistani rupees in 25 years. The effects of PV degradation, energy outages, costs, demand increase, and multiple other factors have been advocated in the proposed hybrid microgrid. The proposed design of the microgrid is feasible and fulfills the performance targets.

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