" Optimal Design Strategies for Renewable-Powered Residential and Commercial Microgrids in India"

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ABSTRACT

Conventional Energy Sources (CESs) currently fulfill a significant portion of global energy demands; however, these resources are expected to face substantial depletion by the end of this decade. The generation of electricity from such sources is a major contributor to greenhouse gas emissions, leading to adverse environmental impacts and shifts in the planet's climate and energy patterns. In response to these challenges, there is a global shift toward energy decentralization, where microgrids play a crucial role.

The rapid adoption of renewable energy sources in microgrid systems can be attributed to their well-recognized benefits—being environmentally friendly, economically viable, and inexhaustible. India, despite possessing immense potential for renewable energy, still relies significantly on energy imports like coal, oil, and liquefied natural gas. Strategic planning and optimal microgrid design can substantially mitigate the ongoing energy crises, enhancing energy security, economic growth, and reducing carbon emissions across the country.

This study explores optimal component planning for grid-connected residential and commercial microgrids in India, focusing on five key objectives: minimizing energy costs, maximizing the share of renewables, reducing greenhouse gas emissions, enhancing power supply reliability, and ensuring long-term sustainability of electricity generation. Various solar photovoltaic (PV) capacities are analyzed against energy costs, renewable energy share, and greenhouse gas emissions to determine the optimal trade-offs.

The findings reveal that for residential applications, the cost of energy can be reduced by 92.47%, the renewable energy share can be increased to 85%, and CO2 emissions can be cut by 48% by integrating solar PV systems. In the case of commercial applications, energy costs can be reduced by 48.52%, the renewable share can rise to 71.1%, and CO2 emissions can be decreased by 61%. These results highlight the economic and environmental advantages of deploying renewable-powered microgrids in India, emphasizing the importance of strategic planning for sustainable energy solutions.

1. INTRODUCTION

With rapid technological advancements and accelerated industrialization, India has witnessed a substantial surge in energy demand. Traditionally, this demand has been predominantly met by conventional energy sources (CESs) such as coal, oil, and natural gas. But these resources are running out at a startling rate, which raises questions about sustainability and energy security. Projections indicate that, even with a modest annual growth rate of 1% in energy demand, these conventional sources may face critical shortages by the 2030s to 2040s. Additionally, a significant portion of India's population, particularly in rural areas, continues to live without reliable access to electricity due to the high initial investment required for grid expansion and the limited budget allocations for rural electrification. This situation underscores the urgent need to transition from centralized energy systems to decentralized solutions like microgrids.

A microgrid can be defined as a localized energy system that integrates distributed energy resources (DER)—such as solar photovoltaic (PV) systems, wind turbines, hydroelectric generators, batteries, and other storage technologies—to supply power either independently (in island mode) or in coordination with the main grid (grid-connected mode). The deployment of microgrids in urban areas of India, where grid access is available, is primarily motivated by the need to enhance energy reliability, reduce costs, and support environmental sustainability by minimizing greenhouse gas emissions. The global shift towards renewables is evident, with the installed renewable energy capacity surpassing 2839 GW in 2020 despite the economic challenges posed by the COVID-19 pandemic. This trend highlights the potential of renewables to transform India's energy landscape, particularly through the strategic deployment of microgrids.

Renewable energy sources—recognized for their sustainability, cost-effectiveness, and minimal environmental impact—are increasingly being integrated into microgrid systems worldwide. For India, leveraging its abundant solar and wind resources through optimal microgrid designs could significantly mitigate the challenges posed by conventional energy systems, including carbon emissions and environmental degradation. Microgrids equipped with advanced control systems can operate autonomously by disconnecting from the central grid when needed, thus enhancing energy security and resilience. Furthermore, they can act as grid-support mechanisms to ensure quick recovery during outages, reinforce grid stability, and optimize the integration of intermittent renewable energy sources.

The negative impacts of greenhouse gas emissions (GHGEs) from conventional power plants, particularly carbon dioxide, are well-documented, with India being one of the major emitters globally. Adopting renewable-powered microgrids could substantially reduce these emissions, aligning with the Paris Agreement 2015 targets to limit global temperature rise below 2°C. In this context, biomass-based energy systems can play a pivotal role by acting as carbon sinks, enabling negative emissions through effective carbon capture and storage mechanisms.

Given India's extensive renewable energy potential, a well-planned deployment of renewable-powered microgrids can address the current energy crisis, reduce reliance on imported fossil fuels, and contribute to economic growth. However, the effective integration of renewables into microgrids presents challenges due to their inherent variability and intermittency. Hybrid energy systems (HES), which combine conventional and renewable sources, offer a practical solution to this challenge by ensuring a stable and continuous power supply.

The primary objective of this research is to propose optimal design strategies for grid-connected microgrids catering to residential and commercial applications in India. This task involves minimizing energy costs, maximizing renewable energy penetration, reducing greenhouse gas emissions, and enhancing power supply reliability. The subsequent sections of this paper are organized as follows: Section 2 presents a comprehensive literature review, highlighting existing research on microgrid systems globally and in India, along with the identified research gaps. In Section 3, the suggested method for creating the best microgrid is talked about. This includes picking the right site, system parts, hybrid configurations, and mathematical modeling. In Section 4, the optimization results, the viability of the proposed designs, the sensitivity analysis, and the effects of following the latest energy trends are all looked at in great detail. Section 5 concludes with key findings and recommendations for future research.

This research aims to contribute significantly to India's energy transition by offering practical insights and optimal strategies for deploying renewable-powered microgrids at scale.

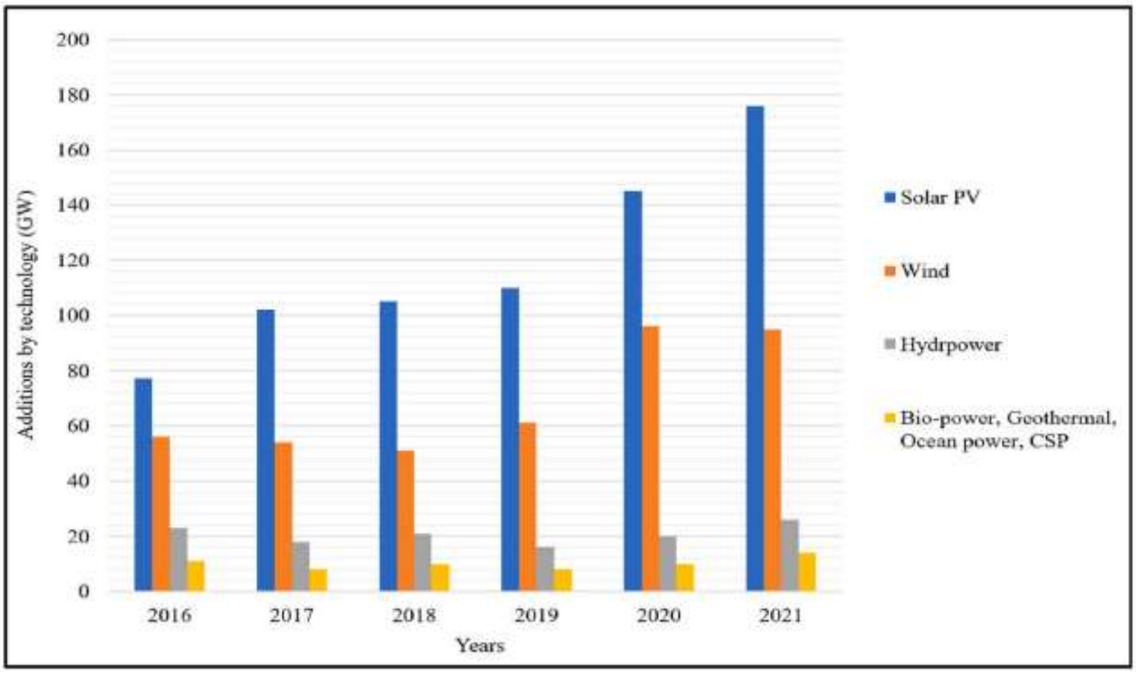


Figure 1: Annual Increments in Renewable Power Capacity by Technology, 2016–2021

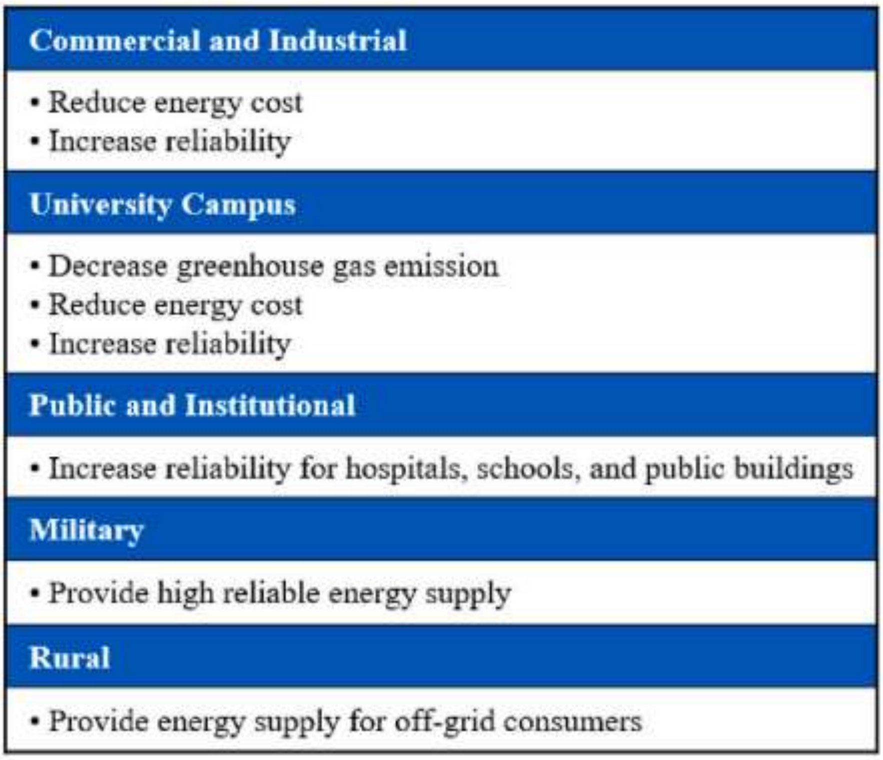


Figure 2: Various Types of Microgrids and Key Drivers for Their Deployment in Practical Applications

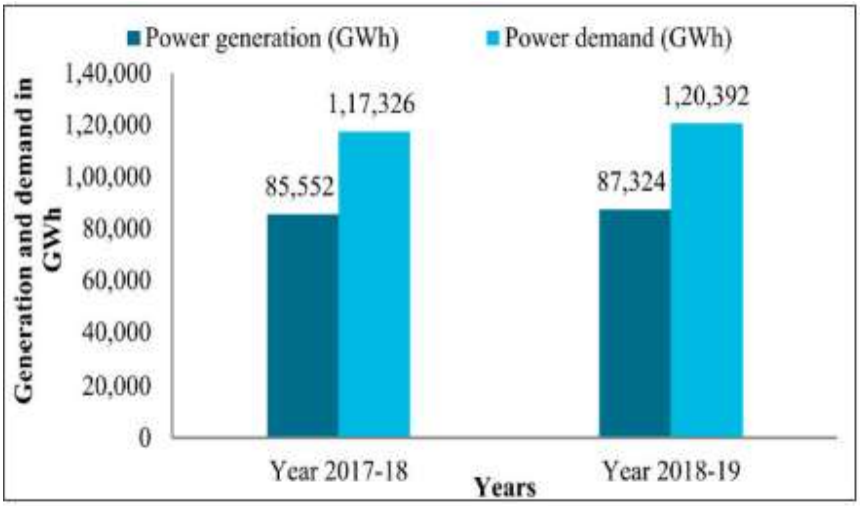


Figure 3: Power Generation and Demand Comparison

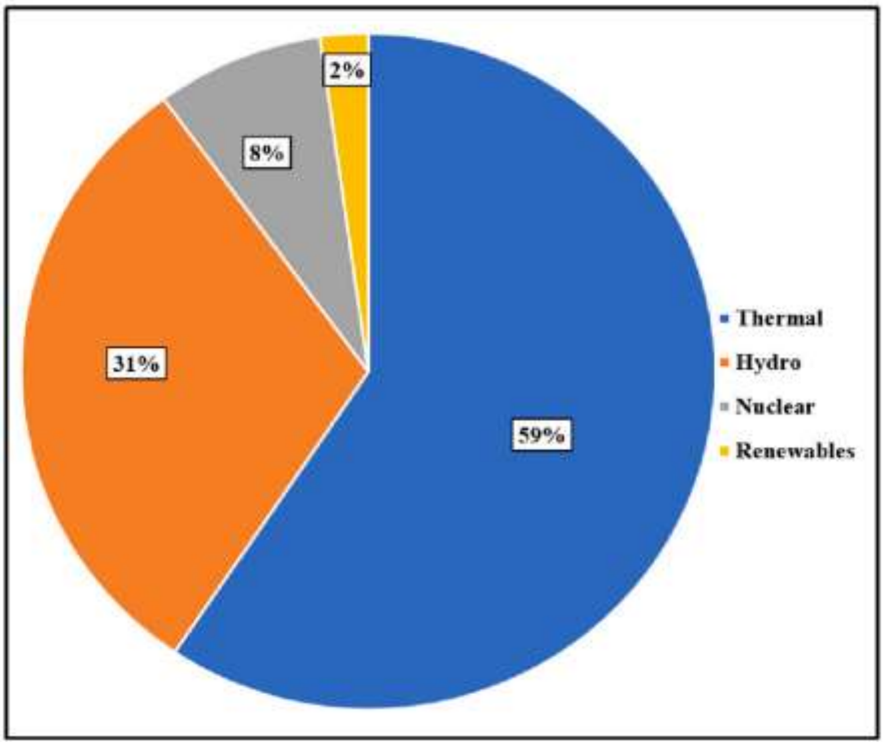


Figure 4: Share of Electricity Generation by Energy Source in 2021

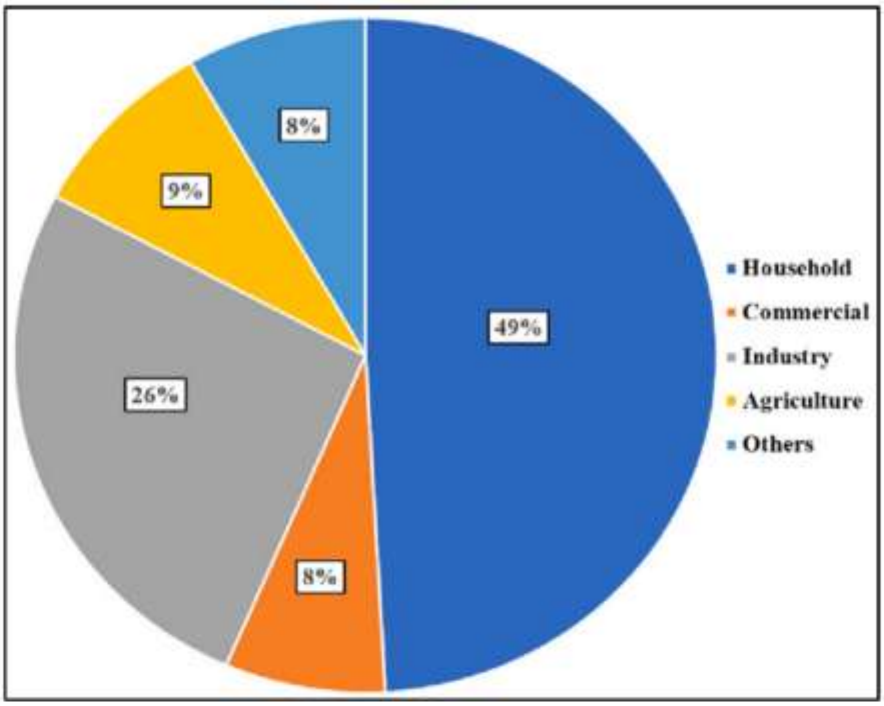


Figure 5: Sector-wise Distribution of Electricity Consumption in 2021

2. LITERATURE REVIEW

A thorough examination of the existing models and techniques in the literature has been conducted to address the challenges associated with operating renewable-powered residential and commercial microgrids in India.

2-A: Optimization Models for Microgrid Performance

This section provides a detailed evaluation of various models and approaches suggested by previous researchers for optimizing microgrid performance. The significance of these models lies in effectively managing energy production, distribution, and utilization within the context of a microgrid (Zahraoui et al., 2021). Methods such as cost-benefit analyses, energy management strategies, and optimization techniques play a crucial role in ensuring that microgrids in India are both economically feasible and sustainable (Khan et al., 2020). The primary objective is to identify methods that can effectively incorporate renewable energy sources, such as solar and wind, to decrease operational costs while improving energy reliability and profitability (AlHamrouni et al., 2019).

A hierarchical approach is utilized in India for the management of residential and commercial microgrids powered by renewable energy sources. This approach incorporates unit commitment, economic dispatch, and optimal power flow optimization (Ahmed et al., 2020). Many researchers have investigated different strategies to optimize unit commitment and economic dispatch for microgrids or Distributed Energy Systems (DESs), with the primary goal of minimizing energy costs during daily operations (Mekhilef et al., 2018). A mixed-integer linear model, for instance, was developed to reduce daily energy costs associated with grid power and natural gas for a microgrid while ensuring energy demand was met efficiently (Zahraoui et al., 2021).

2-B: Microgrid Design Strategies

This section discusses different design strategies for residential and commercial microgrids, focusing on component selection and sizing, including photovoltaic panels, inverters, energy storage systems, and control systems (Khan et al., 2020). The review explores trade-offs between fixed and variable capital costs and their implications on return on investment (ROI) for microgrid operators in India (AlHamrouni et al., 2019). Moreover, design strategies that enhance grid stability, reduce transmission losses, and optimize the balance between generation and consumption are extensively examined (Ahmed et al., 2020). Studies addressing challenges specific to India's regions, such as fluctuations in solar irradiance, regulatory frameworks, and financing options, are also reviewed (Mekhilef et al., 2018).

Choosing the right device types and sizes is a critical factor in microgrid design. Many mathematical models and optimization techniques have been developed to minimize costs, either in terms of total annual cost or lifetime cost (Zahraoui et al., 2021). Some studies incorporate uncertainties in renewable energy generation using Monte Carlo simulations (Khan et al., 2020), while others use mixed-integer linear programming (MILP) to optimize microgrid configurations under varying efficiency assumptions (AlHamrouni et al., 2019).

2-C: Advanced Optimization Algorithms and Real-Time Management

This section provides an overview of existing models addressing variability and unpredictability in renewable energy sources, emphasizing their relevance and implementation in the Indian context (Ahmed et al., 2020). Studies exploring consumer behavior, tariff mechanisms, and incentive-based adoption of microgrids are also reviewed (Mekhilef et al., 2018). By revisiting these works, this paper aims to identify gaps and areas for further research to enhance the economic feasibility of microgrids.

A Markovian method was utilized in our earlier work to tackle day-ahead unit commitment issues, avoiding the computational challenges of scenario-based approaches (Zahraoui et al., 2021). Unlike scenario-based methods, which are often computationally intensive, this method modeled wind generation as a Markov chain, enabling efficient data aggregation without scenario analysis (Khan et al., 2020). Moreover, a mixed-integer linear model was developed to enhance the performance of DESs without battery storage, significantly reducing operational costs (AlHamrouni et al., 2019).

To further optimize microgrid operation, researchers have explored multi-objective optimization methods considering factors beyond energy costs, such as carbon emissions (Ahmed et al., 2020). One study proposed a stochastic model minimizing both costs and emissions, utilizing a teaching-learning-based optimization algorithm to enhance efficiency (Mekhilef et al., 2018). Another study introduced a deterministic model aimed at minimizing power generation costs while extending battery lifespan using a genetic algorithm validated through real-world data (Zahraoui et al., 2021).

2-D: Future Research Directions

Given the operational and design challenges of DESs, this study integrates insights from both microgrid and DES literature to develop comprehensive strategies for optimizing renewable-powered microgrids in India (Khan et al., 2020). Further research should focus on addressing uncertainties in renewable energy generation to improve cost and efficiency predictions (AlHamrouni et al., 2019). The adoption of stochastic models and real-time optimization techniques may significantly enhance the economic feasibility and sustainability of microgrid solutions (Ahmed et al., 2020).

3. DESIGNED APPROACH

This research aims to achieve five key objectives: minimizing energy costs, increasing the share of renewable energy, reducing greenhouse gas emissions, enhancing the reliability of power supply, and ensuring long-term sustainability of energy generation in India. To accomplish these goals, an optimal planning framework for grid-connected microgrids has been developed.

The methodology proposed in Figure X provides a structured approach to realizing these objectives. Several tools for optimizing energy systems are available for microgrid design, including HOMER, TRNSYS, iHOGA, and RETScreen. Among these, HOMER has been widely recognized for its robust optimization capabilities and efficiency in designing cost-effective microgrid systems. Therefore, it has been chosen as the primary tool for this study.

HOMER facilitates energy system simulations, provides optimized configurations based on economic feasibility, and performs sensitivity analyses. It evaluates multiple microgrid configurations by considering user-specified constraints and calculates both installation and operational costs over the project’s lifespan. The tool generates a ranked list of feasible system designs, sorted by Net Present Cost (NPC), allowing a comparative analysis from both technical and economic perspectives. For sensitivity analysis, HOMER iterates the optimization process while simulating different configurations across a range of sensitivity variables defined by the user.

All experiments and analyses conducted in this study adhere to ethical research guidelines and are supported by relevant academic and research institutions.

3.1. Details of the Selected Locations

For this study, India’s diverse geographical and climatic conditions have been considered to ensure comprehensive microgrid design strategies applicable across residential and commercial sectors. Major metropolitan cities, as well as semi-urban and rural regions, have been chosen for case studies to evaluate the feasibility of grid-connected microgrid implementations.

Delhi, Mumbai, Bangalore, and Chennai serve as prime urban centers with high electricity demand, commercial activity, and industrial loads. Meanwhile, semi-urban and rural locations across states such as Rajasthan, Gujarat, and Tamil Nadu have been included to assess microgrid viability in areas with high solar and wind energy potential. These places show a wide range of India's energy use patterns and grid infrastructure problems. This makes sure that the suggested microgrid design strategies can be used all over the country.

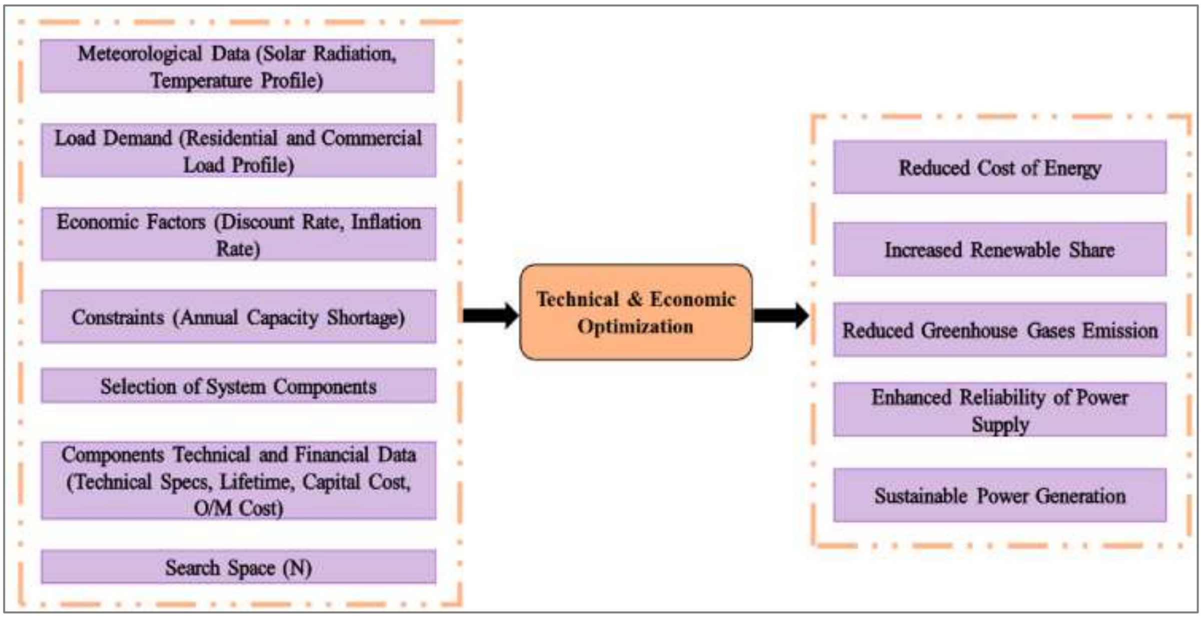


Figure 6: Approach To Designing Grid-Connected Microgrids Optimally

3.2. Solar Irradiation and Temperature Profile

The energy output of photovoltaic (PV) arrays is primarily influenced by solar irradiation and ambient temperature. In the context of designing renewable-powered microgrids, assessing the monthly average solar irradiation and temperature is crucial for accurate system modeling. This study uses data from NASA's Prediction of Worldwide Energy Resource (POWER) database for the year 2022 to analyze the solar radiation patterns of selected locations across India. Fig. 7 illustrates the clearance index and solar radiation data for the chosen sites. India receives an annual average solar irradiation of approximately 5.5 kWh/m²/day, making PV systems a highly viable energy source for microgrids.

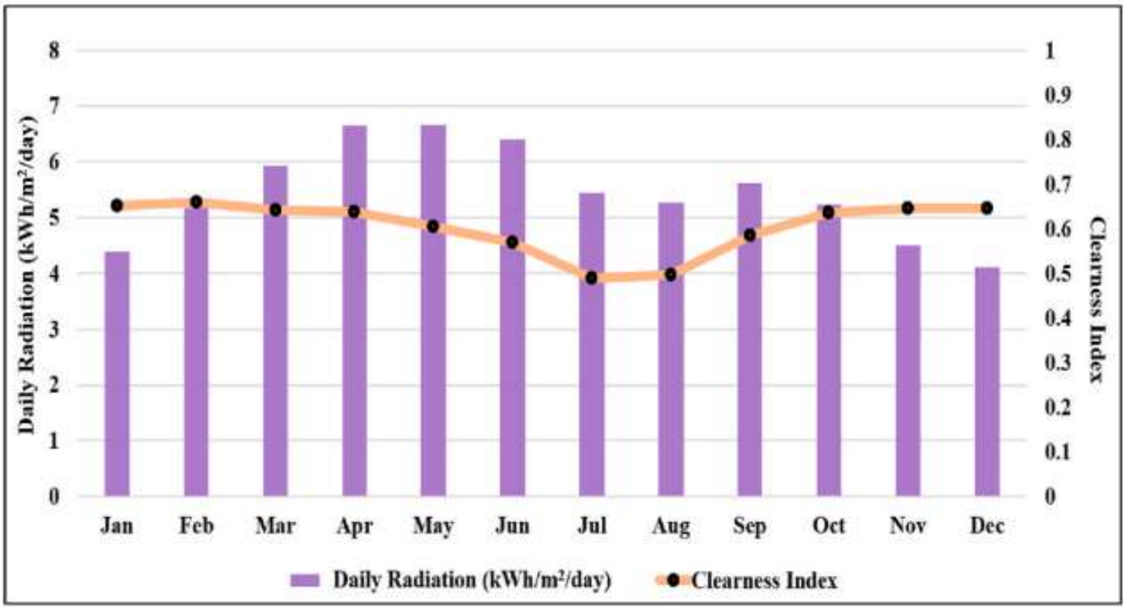


Figure 7: Solar Irradiation and Clarity Index for The Year 2022

The efficiency and output of PV modules are significantly affected by ambient temperature, influencing both power generation and system longevity. Hence, accurate temperature profiling is vital for optimizing microgrid performance. The selected locations exhibit an annual average ambient temperature of around 27°C, with seasonal variations depicted in Fig. 8. These variations need to be factored into system sizing and energy storage planning to enhance reliability and efficiency.

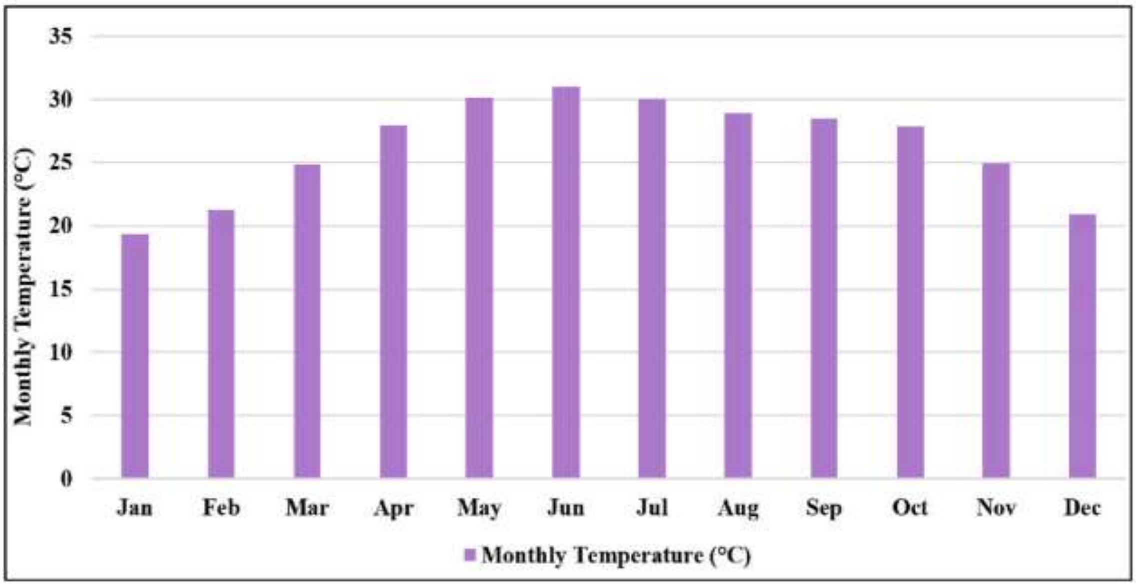


Figure 8: Temperature Profile for Each Month

3.3. Load Profiles

To evaluate the feasibility of microgrid configurations, two distinct load profiles have been considered—one representing a residential household and another representing a commercial establishment. The residential home has a peak load demand of 5 kW, an annual average load of 1 kW, and a load factor of 0.2. Conversely, the commercial setup exhibits a peak load demand of 200 kW, an annual average load of 50 kW, and a load factor of 0.25. Monthly variations in residential and commercial energy consumption patterns are illustrated in Figs. 9 and 10. Understanding these load profiles is critical for system design, ensuring optimal power generation, storage, and supply strategies tailored to residential and commercial needs in India.

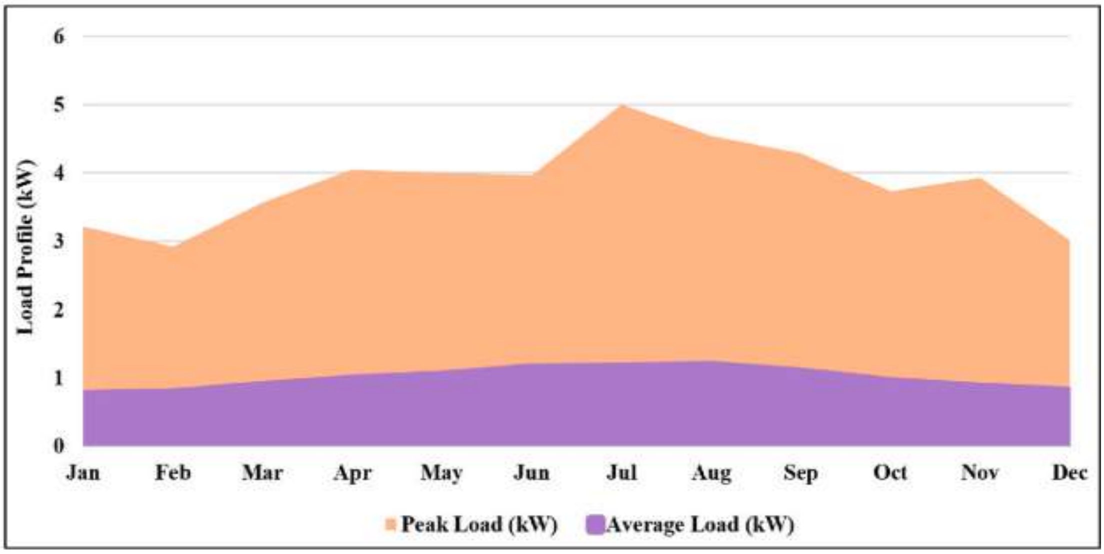


Figure 9: Residential Application Load Profile

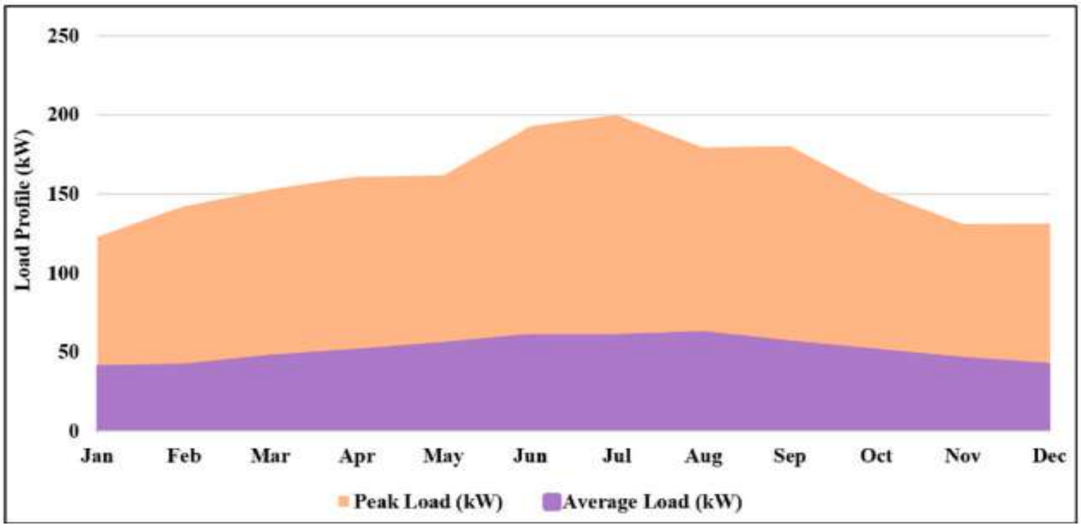


Figure 10: Commercial Load Profile

3.4. System Components

The core components of the hybrid renewable microgrid system include PV arrays, the main grid, energy storage systems (ESS), power converters, and backup generators. For commercial applications, system components are selected based on scalability and demand responsiveness. The prices of each part are based on how much they are selling for on the market right now. The grid electricity tariff, which includes any duties and taxes that apply, comes from the most up-to-date pricing information on the websites of India's electricity distribution companies.

3.5. Hybrid Power System Configuration

The proposed hybrid microgrid system integrates solar PV generation, grid connectivity, and backup power sources to ensure reliable energy supply. During daylight hours, PV output is prioritized to meet the load demand. The grid provides the extra power needed when solar generation isn't enough. At night, when solar generation ceases, grid energy is utilized as the primary source, with a backup generator available to compensate for power outages—a frequent occurrence in several Indian regions.

Both the grid and the backup generator supply alternating current (AC), while the PV system generates direct current (DC). A power converter is employed to convert DC output from the PV system into AC, ensuring seamless integration with the microgrid infrastructure. The schematic representation of the PV/grid/generator hybrid energy system, designed to accommodate the residential and commercial case studies, is illustrated in Fig. 11. This setup strikes the best balance between using renewable energy, being connected to the grid, and having backup power systems. This makes microgrid deployments in India more cost-effective and reliable.

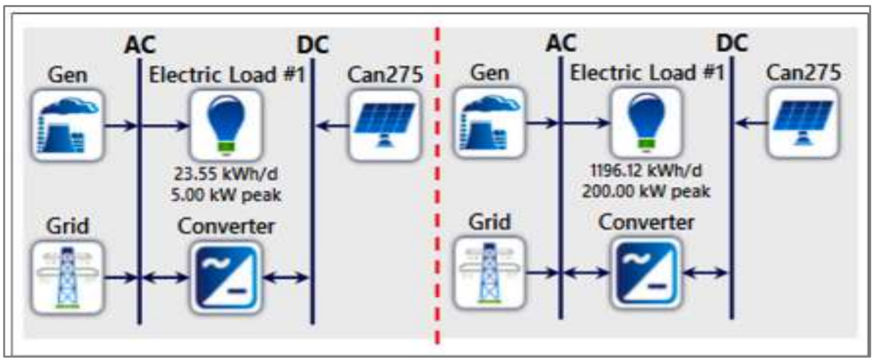


Figure 11: Residential And Commercial Application Schematics, Respectively

3.6. Mathematical Representation

3.6.1. Photovoltaic (PV) Modeling

Photovoltaic (PV) panels convert solar radiation into electrical energy, which is then transferred to a direct current (DC) line and subsequently transformed into alternating current (AC) power through an inverter. The total cost of PV installation is influenced by factors such as system size, PV panel type, and manufacturer specifications. In this study, the installation cost per kilowatt for PV panels is estimated at Rs. 120,000, with an operation and maintenance cost of Rs. 2,800 per kilowatt annually. The expected lifespan of PV panels, as well as the entire project, is assumed to be 25 years. A derating factor of 85% is applied to account for potential energy losses due to factors like dirt accumulation and temperature variations. The output power of PV arrays is calculated using the HOMER software, employing the following equation:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_P (T_C - T_{C,STC})]$$

where:

- Y_{PV} = Rated capacity of PV arrays,
- f_{PV} = Derating factor,
- G_T = Solar radiation on PV array at a given time step $[kW/m^2]$,
- $G_{T,STC}$ = Solar radiation under standard test conditions$[1kW/m^2]$,
- α_P = Temperature coefficient of power $[\%/^\circ C]$,
- T_C = PV cell temperature at a given time step $[^\circ C]$,
- $T_{C,STC}$ = PV cell temperature under standard test conditions $[25^\circ C]$.

3.6.2. Diesel Generator Modeling

A diesel generator is incorporated within the hybrid microgrid system as a backup power source to ensure system reliability. In HOMER, an auto-sized generator is selected, which dynamically adjusts its capacity to match the load requirements while minimizing capacity shortfalls. For residential applications, the initial capital and replacement cost per kilowatt is Rs. 50,000, with an operational and maintenance cost of Rs. 120 per operating hour. For commercial applications, the initial capital and replacement cost per kilowatt is Rs. 70,000, with an operational and maintenance cost of Rs. 150 per operating hour. The diesel generator has a lifespan of 15,000 operating hours, with a minimum load ratio of 25%. The cost of fuel, based on market rates in India as of June 2022, is considered Rs. 264 per liter. The generator's efficiency is determined using the following equation:

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

where:

- E_{gen} = Total annual electricity produced by the generator $[kWh/yr]$,
- m_{fuel} = Total annual fuel consumption $[kg/yr]$,
- LHV_{fuel} = Lower heating value of fuel $[MJ/kg]$.

The generator's lifespan in years is computed using:

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

where:

- $R_{gen,h}$ = Generator lifetime in hours,
- N_{gen} = Annual operating hours of the generator $[hr/yr]$.

3.6.3. Emissions Modeling

The HOMER software figures out how much carbon dioxide (CO2), carbon monoxide (CO), unburned hydrocarbons (UHC), particulate matter (PM), sulfur dioxide (SO2), and nitrogen oxides (NOX) are released when diesel generators and grid electricity are used. The emissions per pollutant are calculated by multiplying the emission factor (kg per unit of fuel consumed) by the annual fuel consumption. In grid-connected microgrids, the net grid energy purchased is computed by subtracting total grid sales from total grid purchases. The resulting value is then multiplied by the respective emission factor (g/kWh) to estimate emissions.

3.6.4. Net Present Cost (NPC)

The net present cost represents the present value of all expenses, including capital, operational, and maintenance costs, over the project's lifetime, minus any revenue generated. HOMER calculates the NPC for each component and the entire system.

3.6.5. Annualized Cost

The annualized cost represents the uniform cost distribution over the project's lifetime that equates to the net present cost. HOMER calculates it using:

$$C_{ann} = CRF(i, R_{proj}) \cdot C_{NPC}$$

where:

- C_{NPC} = Net present cost,
- i = Annual real discount rate $[\%]$,
- R_{proj} = Project lifetime $[yr]$,
- $CRF()$ = Capital recovery factor computed as:

$$CRF(i, R_{proj}) = \frac{i(1+i)^{R_{proj}}}{(1+i)^{R_{proj}} - 1}$$

3.6.6. Cost of Energy (COE)

The cost of energy represents the per-unit cost of electricity generated by the microgrid system. It is computed as:

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

where:

- $C_{ann,tot}$ = Total annualized cost $[Rs./yr]$,
- E_{served} = Total electrical load served $[kWh/yr]$.

The total electrical load served is calculated as:

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

3.6.7. Renewable Energy Share

The renewable energy share represents the fraction of energy demand met through renewable sources. HOMER calculates it as:

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

where:

- E_{nonren} = Annual electricity generation from non-renewable sources $[kWh/yr]$,
- E_{served} = Total annual electricity load served $[kWh/yr]$.

4. RESULTS AND ANALYSIS OF THE SIMULATION

The HOMER software has been employed in this research to determine the optimal sizing of energy sources in hybrid microgrid systems for both residential and commercial applications. This study considers a project lifespan of 25 years, with a discount rate of 9.75%, an inflation rate of 13.8%, and an annual capacity shortage of 20%, considering the prevailing economic conditions in India.

4.1. Cost Reduction in Energy Consumption

The primary objective of designing the proposed system is to reduce the cost of electricity while ensuring zero unmet load. The cost of electricity is significantly high for residential users in India when they rely solely on grid power. By integrating solar PV systems, different capacities, ranging from 0 kW to 15 kW, were tested. The results indicate that the cost per unit of electricity can be reduced by approximately 92.47% with the deployment of 15 kW solar panels. Similarly, incorporating renewable sources proves even more beneficial for commercial establishments, where per-unit charges are higher due to tariff structures. The simple payback period for a 5 kW residential load with 15 kW PV capacity is estimated at 6.8 years, whereas a commercial setup with a 200 kW load and 250 kW PV capacity achieves payback within four years.

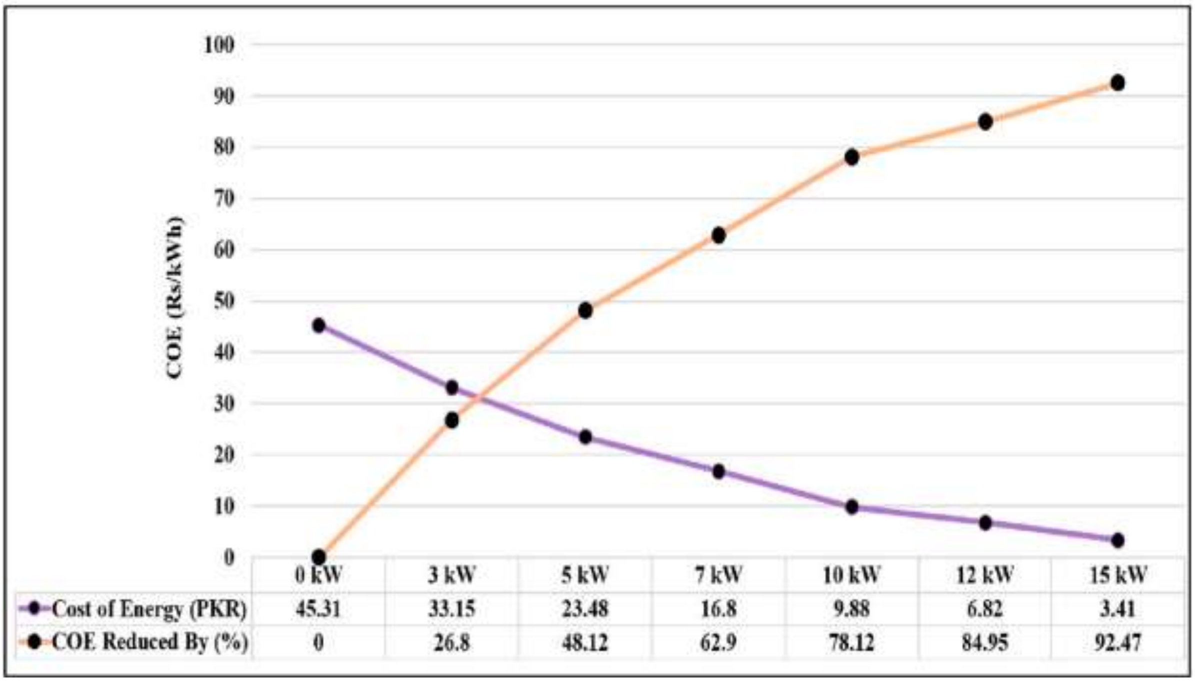


Figure 12: Energy Cost Trade-Off Versus Various Pv Capacities for Home Use

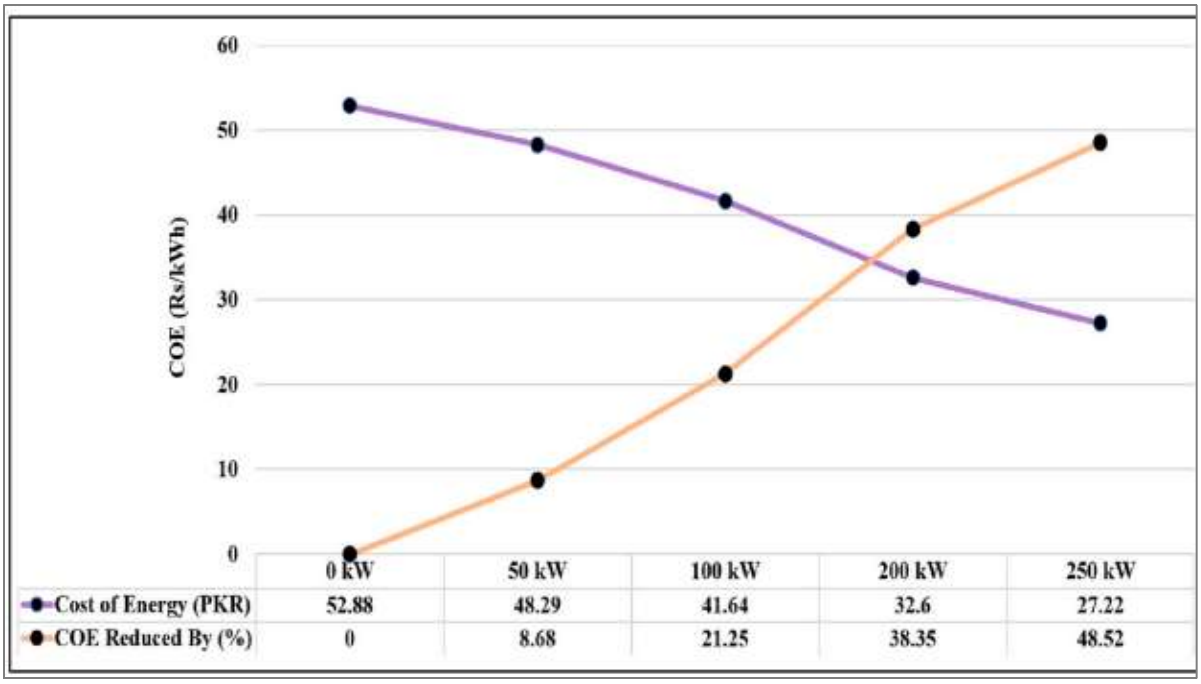


Figure 13: Commercial Application Trade-Off Between Energy Cost and Various Pv Capacities

4.2. Increased Renewable Energy Share

A higher renewable fraction signifies greater reliance on clean energy sources. For residential applications, the maximum renewable share achievable with a 15 kW PV capacity is 85%, whereas commercial setups with a 250 kW PV system attain a renewable share of 71.1%. Maintaining a high renewable fraction without significantly increasing the net present cost (NPC) is crucial for achieving long-term energy sustainability.

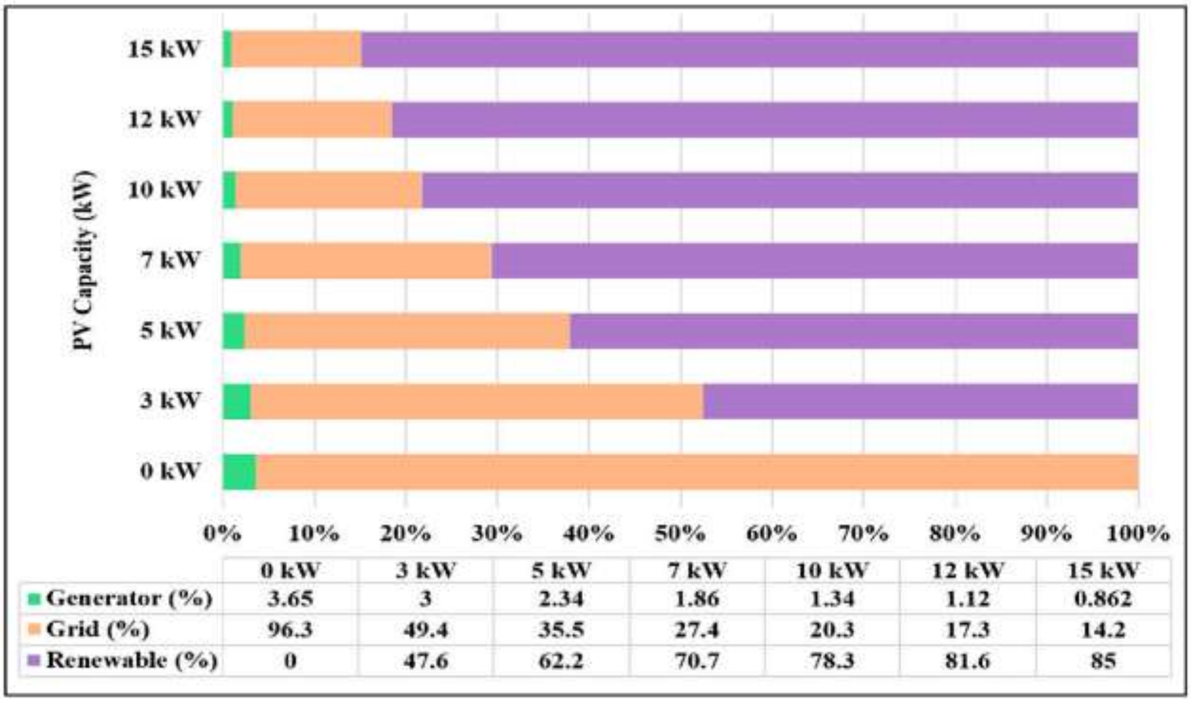
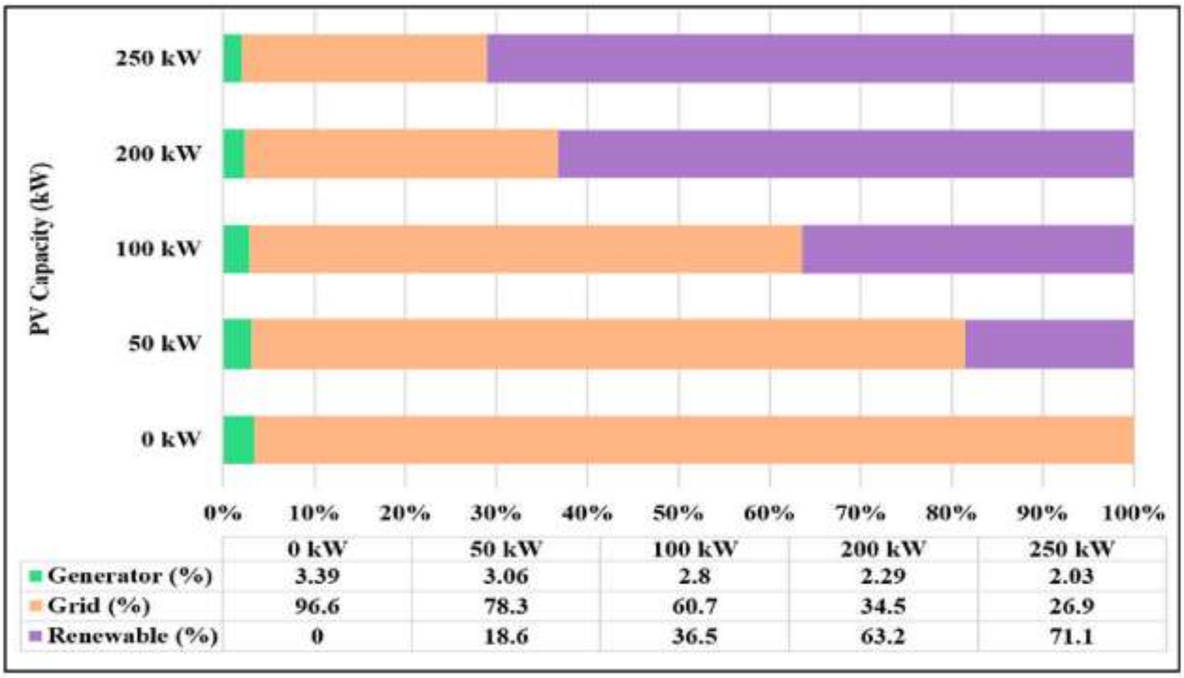


Figure 14: The Trade-Off Between Various PV Capacities and The Percentage of Renewable Energy Used in Residential Applications



	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

Figure 15: Trade-Off Between Renewable Share and Different Pv Capacities for Commercial Application

4.3. Reduction in Greenhouse Gas Emissions

Conventional fossil fuel-based power generation results in emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter, contributing to environmental degradation. In this study, the emissions from a diesel generator were analyzed, showing a proportional relationship with annual fuel consumption. The findings indicate that introducing renewable energy sources into the system significantly reduces emissions. In residential applications, CO_2 emissions decrease by 2,750 kg per year, reducing total emissions by 48% compared to the base case. For commercial applications, the reduction is even more substantial, with a 61% decrease in CO_2 emissions, amounting to 171,895 kg per year.

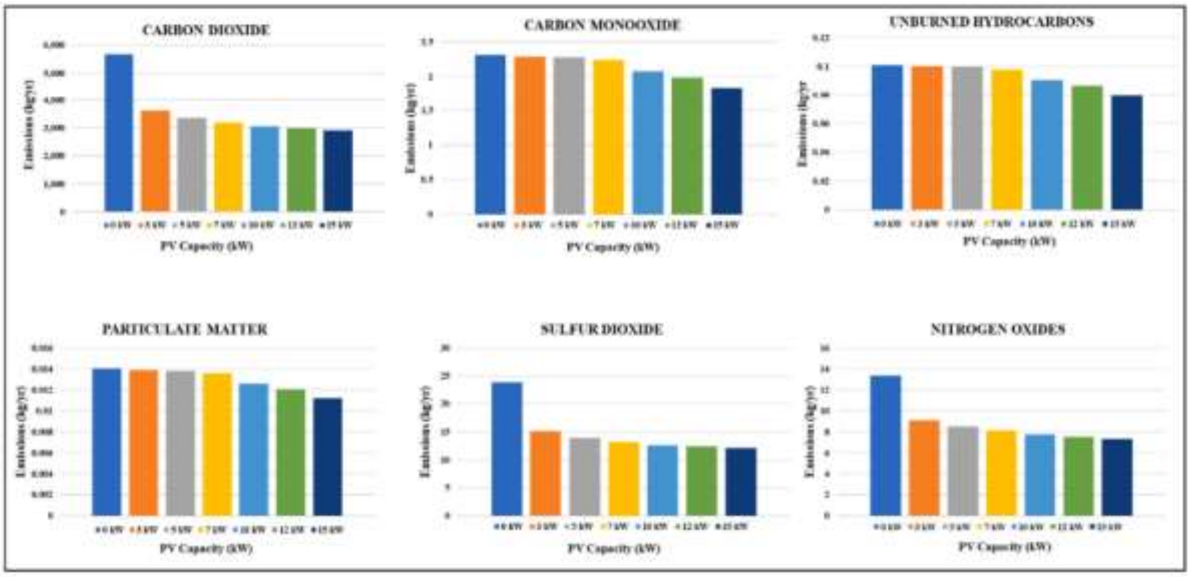


Figure 16: Emissions of Greenhouse Gases (kg/yr) As A Function of Residential PV Capacity (kW)

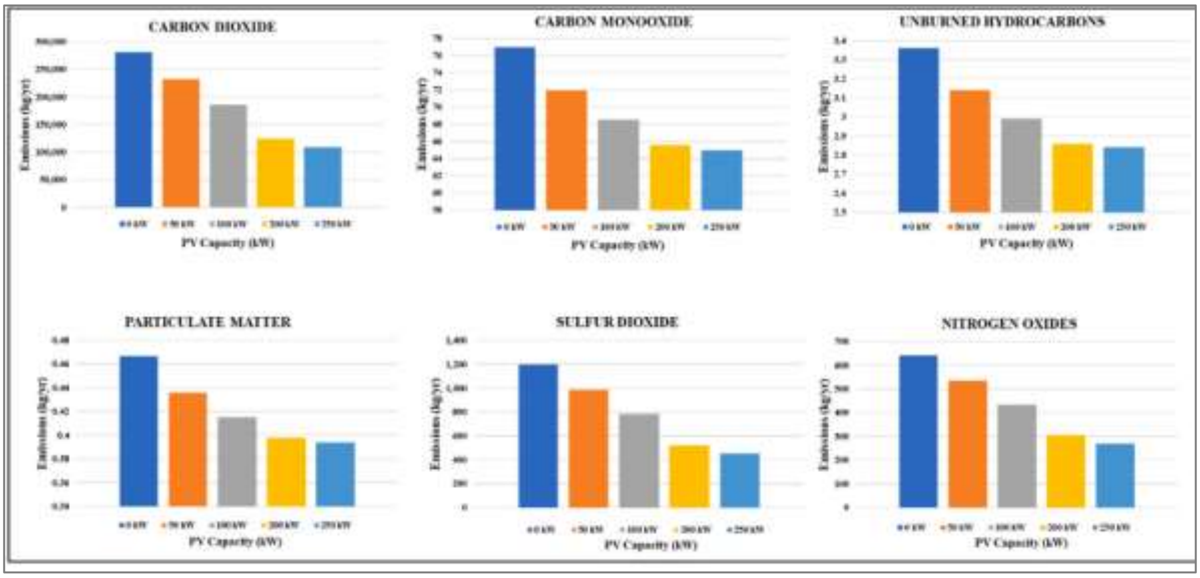


Figure 17. Commercially Applicable Greenhouse Gas Emissions (kg/yr) Versus Various PV Capacities (kW)

4.4. Enhanced Reliability of Power Supply

System reliability is evaluated by assessing the total load served compared to the total demand. The proposed microgrid system ensures zero unmet load annually. During grid outages, PV generation supplements power supply during the daytime, while backup generators ensure nighttime reliability. This enhanced reliability is particularly crucial for commercial establishments where power disruptions can lead to financial losses.

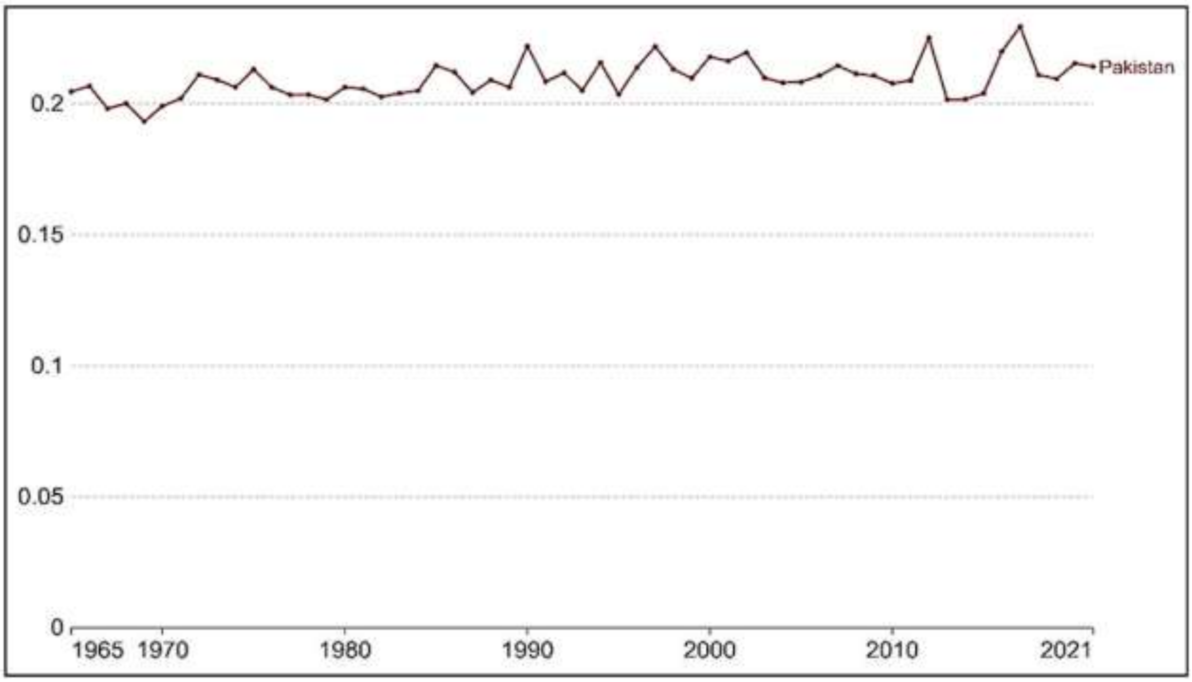


Figure 18: Emissions Per Kilowatt-Hour of Carbon Dioxide Produced in India

4.5. Sustainable Power Generation

Renewable energy plays a pivotal role in the transition to a sustainable energy future. India, like many developing nations, is striving to reduce its dependence on imported fossil fuels by harnessing its vast renewable energy potential. A properly designed microgrid system enhances energy security, fosters economic growth, and contributes to reduced greenhouse gas emissions. Increased penetration of renewable energy into India's power sector will ensure long-term sustainability and resilience.

Table 1: Unused Electrical Demand

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. Challenges and Constraints

Despite the advantages, certain challenges hinder widespread implementation. The major limitations include high initial capital costs and land requirements for PV deployment. Achieving zero unmet load necessitates additional investment in backup generators and energy storage systems. For instance, to achieve a 92.47% reduction in energy costs, an investment of INR 2.46 million is required for a 15 kW residential PV system. Similarly, for commercial applications, a 250 kW solar PV system necessitates significant capital investment but ensures a promising payback period of four years. Another critical challenge is land availability, particularly in urban settings, where rooftop space constraints may limit large-scale solar deployment.

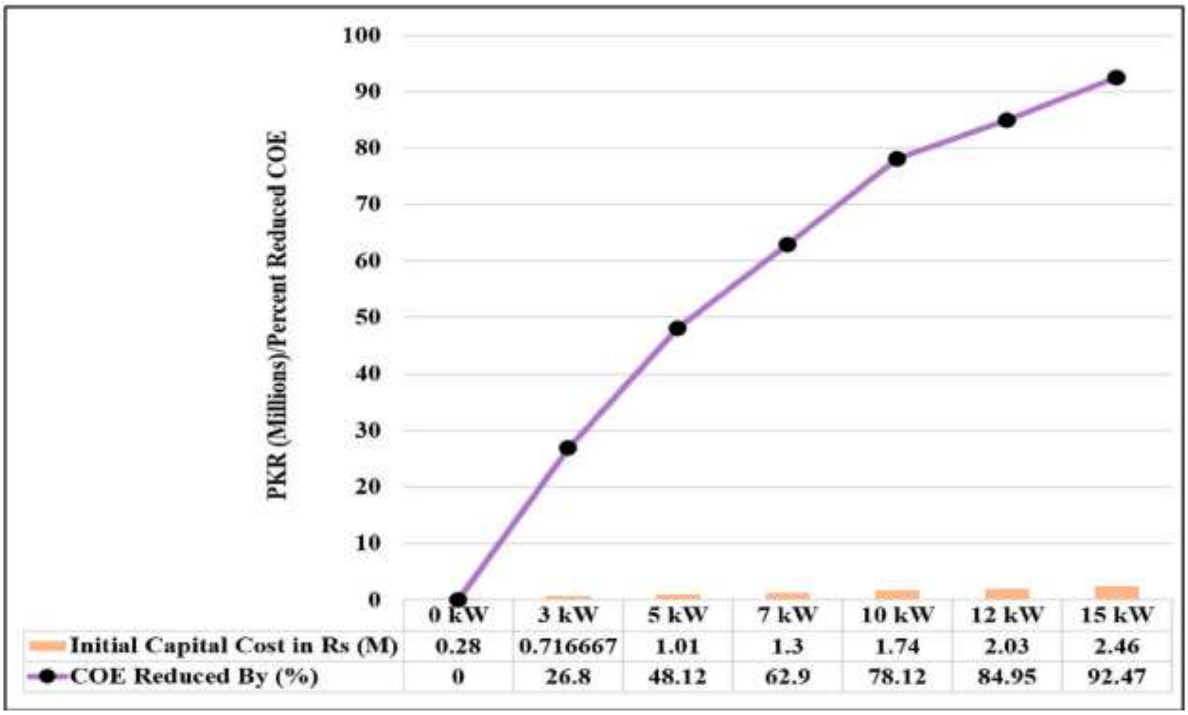


Figure 19: Relationship Between Different PV Capacities for Residential Applications, Initial Capital Cost, And Percentage Reduced Energy Costs

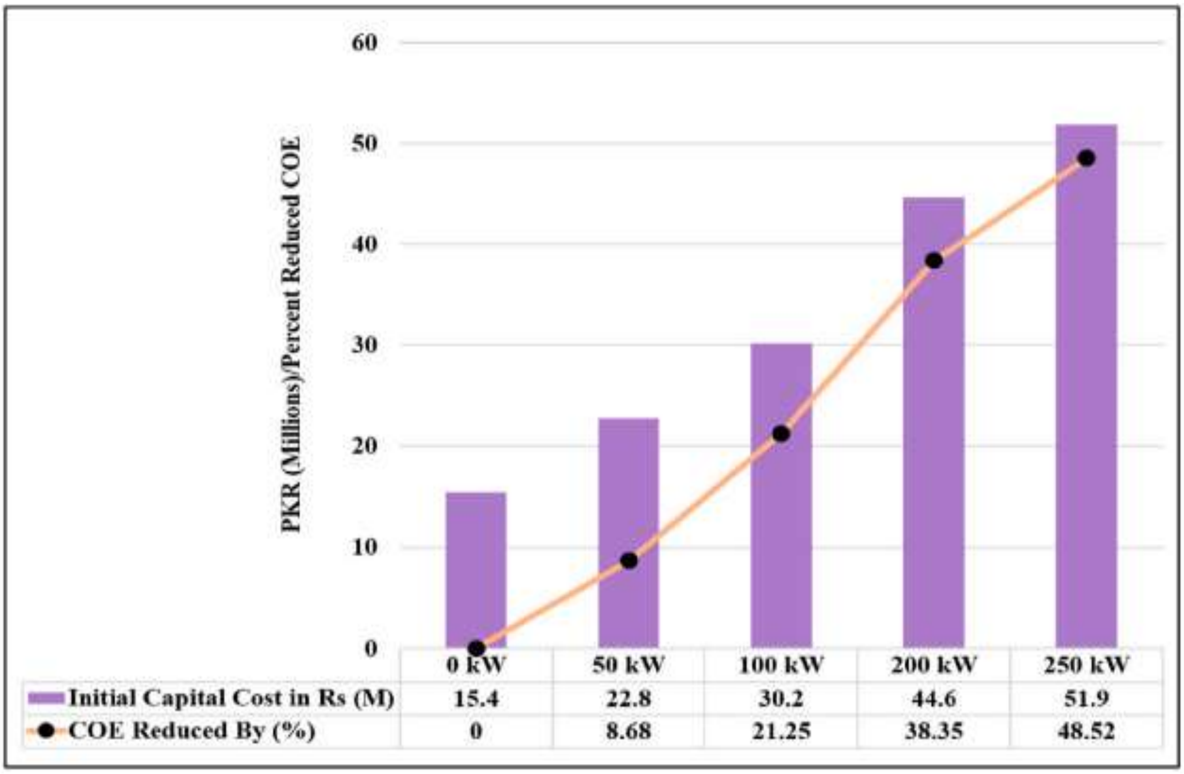


Figure 20: Relationship Between Different PV Capacities for Commercial Applications, Initial Capital Cost, And Percentage Reduced Energy Costs

4.7. Integration of Energy Storage in Grid-Connected Microgrids

Energy storage systems further enhance reliability by ensuring an uninterrupted power supply during low solar radiation periods. A comparative analysis of different microgrid configurations highlights the trade-offs between reliability and capital cost. The PV-Battery-Grid system offers high reliability, while the PV-Battery-DG-Grid configuration eliminates unmet load but increases capital costs. Space constraints for battery storage also pose challenges, particularly for commercial setups requiring substantial energy storage capacity.

Table 2: Evaluation Of Various Home Microgrid Designs for Grid Connection

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

Table 3: Assessment Of Various Commercially Applicable Grid-Connected Microgrid Designs

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

4.8. Sensitivity Analysis

The sensitivity of microgrid economics to fluctuating fuel prices and solar radiation levels is analyzed. A 14% increase in fuel prices leads to a 4.2% rise in NPC and a 4.4% increase in the cost of electricity for residential users, while commercial users experience a marginal increase of 0.998% and 0.936%, respectively. In the same way, a 27% drop in average solar radiation causes NPC to rise by 121% and energy costs to rise by 187% for residential users. For commercial users, these numbers rise by 15% and 31%, respectively.

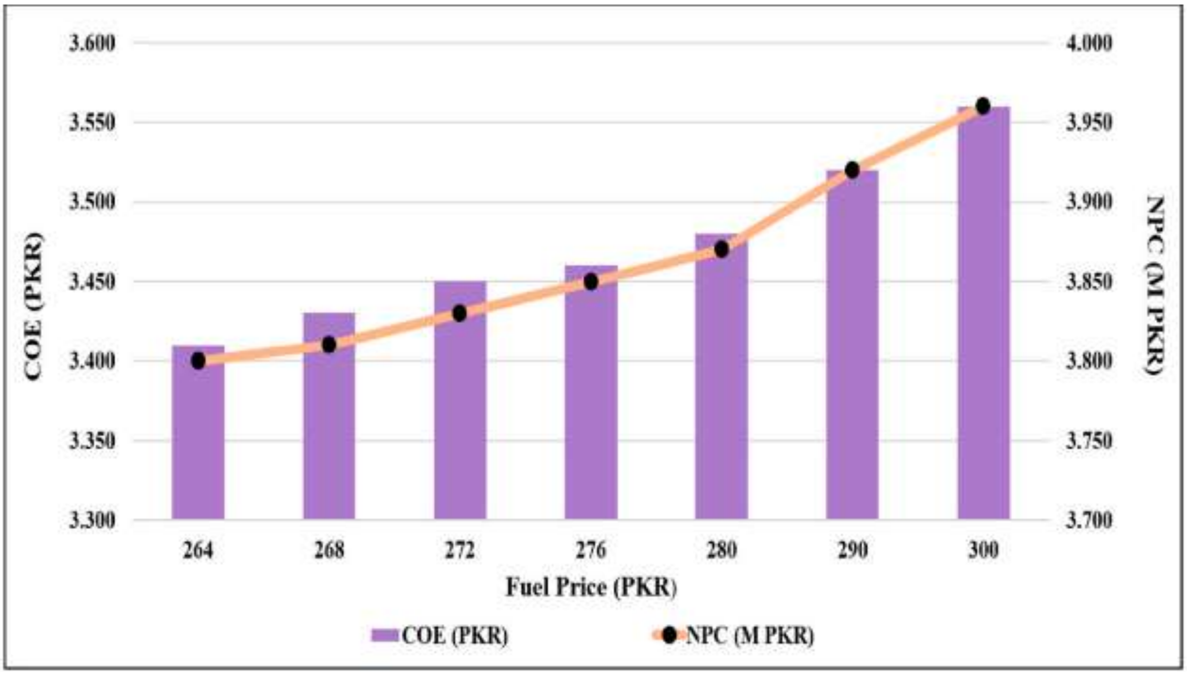


Figure 21: The Impact of Fluctuating Fuel Prices on Residential Application's NPC and COE

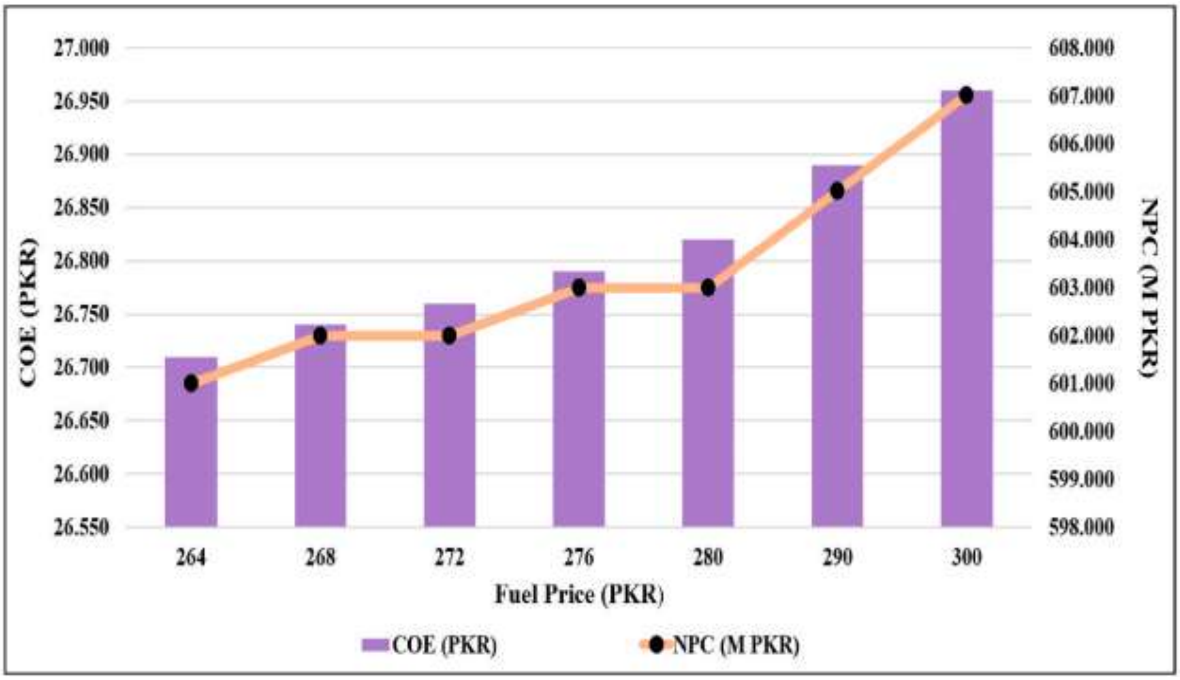


Figure 22: The Impact of Fluctuating Fuel Prices on NPC and COE In a Business Setting

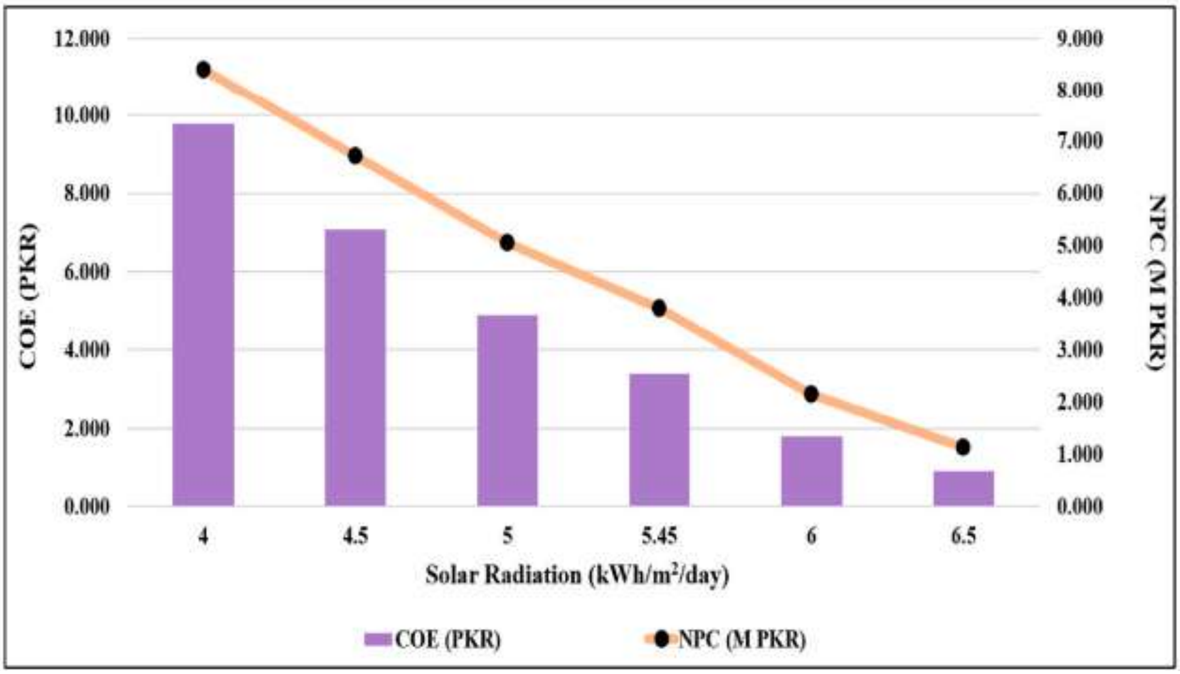


Figure 23: Relative Impacts of Fluctuating Average Solar Radiation on Home NPC and COE

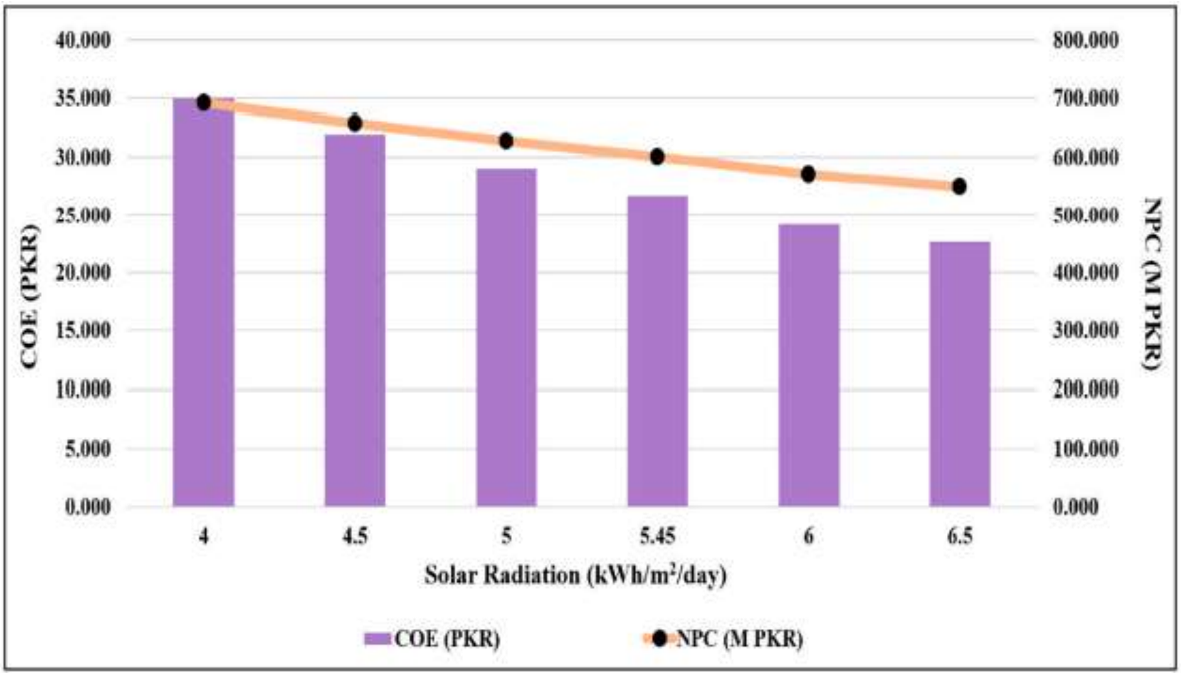


Figure 24: Effect Of Variable Average Solar Radiation on NPC and COE For Commercial Applications

4.9. Addressing India's Energy Crisis Through Global Best Practices

India, with its growing energy demand, faces challenges similar to other developing nations in ensuring stable electricity supply. Political and economic constraints, coupled with an over-reliance on conventional energy sources, contribute to periodic power shortages and high production costs. However, the global trend toward renewable energy adoption provides a viable solution. Many developed nations have successfully transitioned to renewables, reducing carbon footprints and ensuring long-term energy security. India, with an estimated solar PV potential exceeding 750 GW, has made significant progress but still relies heavily on conventional sources. Transitioning toward hybrid energy systems, particularly those incorporating solar PV, will significantly improve the country's energy resilience and environmental sustainability.

5. CONCLUSION

The study explores the technical and economic optimization of grid-connected microgrid systems for residential and commercial applications in India. This study successfully meets its main goals by looking at various setups of microgrids that are powered by renewable energy. These goals include lowering costs, increasing the share of renewable energy, lowering greenhouse gas emissions, improving power reliability, and ensuring long-term sustainability.

To find the best balance between system efficiency and economic viability, different solar photovoltaic (PV) capacities are weighed against factors like carbon footprint, energy cost, and the amount of renewable energy used. A primary challenge in implementing such microgrids in urban India is the high initial capital investment and land constraints. However, findings indicate that a 15 kW solar PV system for a 5 kW residential load can significantly lower the cost of electricity (COE) to ₹3.41/kWh, reflecting a 92.47% reduction from conventional energy sources. Additionally, the renewable share increases to 85%, while CO_2 emissions drop by 48% compared to a non-renewable base case.

For commercial applications, an optimized 250 kW solar PV system for a 200 kW load results in a 48.52% decrease in energy costs, reducing it to ₹27.22/kWh, while the renewable share rises to 71.1%. Furthermore, CO_2 emissions are reduced by 171,895 kg annually, which is 61% lower than the baseline scenario. The study looks at different grid-connected microgrid configurations and rates their Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Capital Expenditure (CAPEX), and dependability to find the best design strategies for India.

Additionally, the research underscores the urgent need to transition toward hybrid energy systems to mitigate the social and economic challenges associated with conventional electricity dependency. Future work can explore integrating multiple microgrids into a centralized smart grid, leveraging advanced net metering technologies to optimize financial returns and energy management. More research may also be done to see how integrating smart grids affects saving money and lowering carbon emissions, which would ensure long-term energy solutions for India's homes and businesses.

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