A DEVELOPMENT OF ECONOMICALLY EFFICIENT COMMUNITY MICROGRID SYSTEM WITH LOCAL POWER MARKET FOR ENHANCED POWER STABILITY AND ENERGY MANAGEMENT

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Abstract

This study investigates the capacity of incorporating renewable energy sources and backup generation into microgrid systems to reduce reliance on the main power grid and decrease carbon emissions. By employing demand side management, microgrid can effectively adjust consumption patterns in accordance with grid costs. The microgrid integrate many energy sources, including solar, wind, and diesel generators, to enable the sharing of energy and compensate for the variability of intermittent resources. This is accomplished by developing local energy market system that provide consumers with cheaper energy inside their specific microgrid, hence creating incentives for them. The analysis considers four distinct possibilities: a baseline scenario where the main grid is solely relied upon, and three progressive scenarios that integrate solar panels (PV), wind turbines, and diesel generators. This research study explores the vulnerabilities of a centralized electric power system, highlighting high costs and carbon emissions from conventional power generation. In the base scenario, daily power costs for a community of 50 houses reach approximately Rs. 45,540 for 1188 kWh with 567.864 kgs of CO2 emissions, underscoring the need for alternative energy sources. Case 1 shows that solar panel installations can cut energy costs by 52.13% (Rs. 23,740) and reduce carbon emissions by 257.78 kgs, paving the way for a sustainable energy future. Case 2 adds wind turbines to the mix, enhancing grid reliability and reducing grid import to 212.8 kWh at a cost of Rs. 8,895. However, high capital costs make this option financially unfeasible without subsidies, despite an 82.18% reduction in greenhouse gas emissions. Case 3 introduces a diesel generator alongside solar and wind, lowering grid-imported energy to 179.8 kWh for Rs. 7,527, and cutting CO2 emissions by 79.71%, though the high energy cost remains an issue. Case 4 demonstrates that demand-side management (DSM) can reduce grid dependence significantly, bringing grid reliance down to 72.23 kWh and resulting in a 93.7% reduction in energy bills and a 77.42% decrease in carbon emissions. Finally, Case 5 presents a Local Energy Management System (LEMS), The findings underscore the significant advantages of the LEMS method, which enhances energy self-sufficiency and reduces dependence on the grid. With only 12.8% of electricity costs attributed to capacity payments, the method achieves a remarkable 87.2% in savings. By enabling communities to trade energy within their own networks, energy savings reach 64.4%, and CO2 emissions are reduced by 70.72%.

Keywords: Local energy market system, Microgrid, Capacity payments, Demand side management, Energy management system, Feed-in tariff, , Pakistan, Renewable energy resources.

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List of Abbreviations

CP	Capacity Payments
CFR	Capital Recovery Factor
DSM	Demand Side Management
DERs	Distributed Energy Resources
DG	Distributed Generation
EMS	Energy Management System
FC	Fixed Cost
FIT	Feed in Tariff
LESM	Local Energy Market System
MG	Microgrid
PV	Photovoltaic
RER	Renewable Energy Resource
ROI	Return on Investment
VPP	Virtual Power Plant

Chapter 01: Introduction

1.1 Background

Energy accessibility contributes to improving living quality and relates to growing GDP. In the meantime, Pakistan is experiencing a serious energy crisis because of its inability to fulfill the rising demand brought on by its expanding population, developing businesses, and expanding agricultural sector [1]. According to world bank, in Pakistan 54% people still have no access to electricity [2]. Despite tremendous progress, tackling decentralized electrification remains a critical issue in Pakistan, particularly given the country's fast economic and demographic expansion. Traditional top-down electrification methods must be supplemented with more localized, bottom-up ones. While technology advancement has been rapid, potentially allowing every town and people to attain electricity self-sufficiency, persistent hurdles remain [3]. The addition of renewable energy (PVs, Wind) as distributed generations (DGs) to power distribution networks given birth to new market model selling and buying electricity from DGs, where consumers are connected to a micro-grid that can supply extra electricity to other nearby consumers, and export to public utility grid [4]. Electricity prices are defined as available generation (Thermal, Hydel, Nuclear, PVs, Wind etc.) end-user power price is more complex and consists of cost of generation, transmission and distribution other factors that are taxes, fuel prices adjustment and agreed upon capacity charges. In, Pakistan power sector is the only monopolized supplier of electricity all across the country, with an annual growth rate of 8%, total number of consumers are 31.5 million, where 48% consumers are domestic followed by the industrial consumers 28%, other including argi-commercial are 24% total demand is 31000MWs [5], **Figure 1.1** shows category wise power consumers of Pakistan.

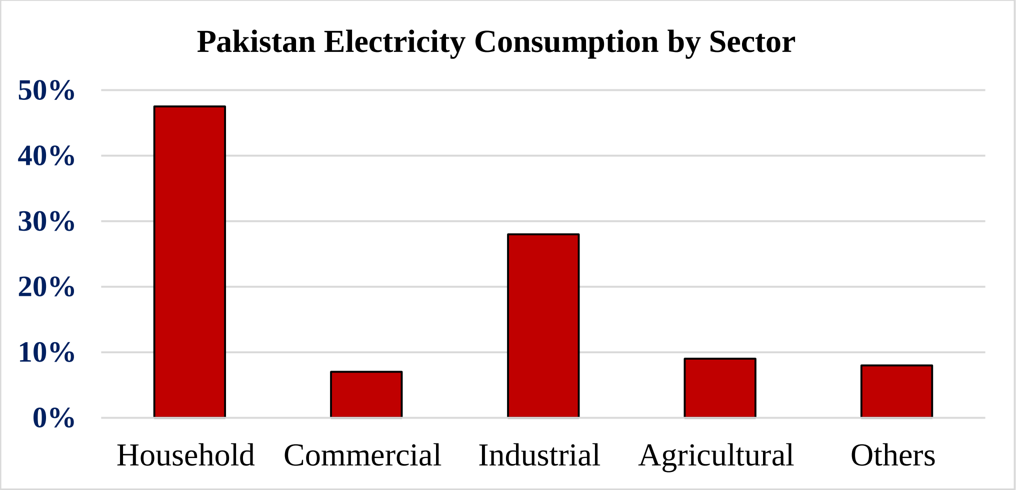

Figure 1-1: Category wise power consumers of Pakistan (2023).

To cover the demand, the total current installed power capacity is around 41,500 MWs. **Figure 1.2** depicts the total power sources and their share in nation power. According to power regulator NEPRA (national electric power regulatory authority), the major generation source is thermal power (coal, oil and gas) contributes 63%, hydel power is 25% followed by nuclear 6.4%, the only input of renewable energy to national grid is 5.4% which is very small.

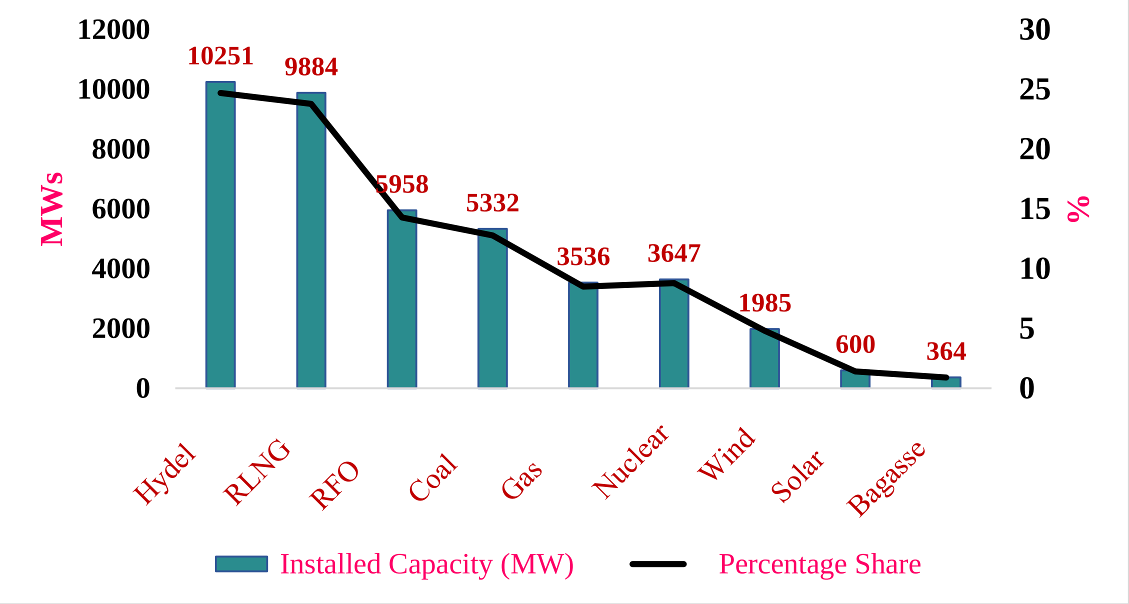

Figure 1-2: The total power sources and their share in nation power (2023).

In recent years, energy generating planning has prioritized costly and imported fossil fuels. Importing energy puts a load on the economy and has long-term adverse effects on the environment. Despite ranking eighth on the long-term global climate risk index, Pakistan's government remains uncertain about the country's clean and green future, relying on thermal fuels for inexpensive energy generation. The continues increase in cost of energy is a huge burden on consumers led to inflation, as power price varies slightly abnormal due to injection power by independent power producers (IPPs), the impact of high fuel (imported) prices makes additional tariff called fuel price adjustment, adding into it the capacity charges paid to IPPs is 65% of power tariff which is nearly 29.78 Rs/kWh and prices increase as power usage goes beyond 300kWh and 700kWh in Pakistan. Low per capita income of Pakistan [6][7]. The Pakistani government reports that the oil import bill climbed to US$17.03 billion in 2022, a 95.9% rise from 2020–2021. Imbalance in demand and supply 26,083MWs against 31,000MWs need to be covered immediately [8] as depicted in **Figure 1.3**.

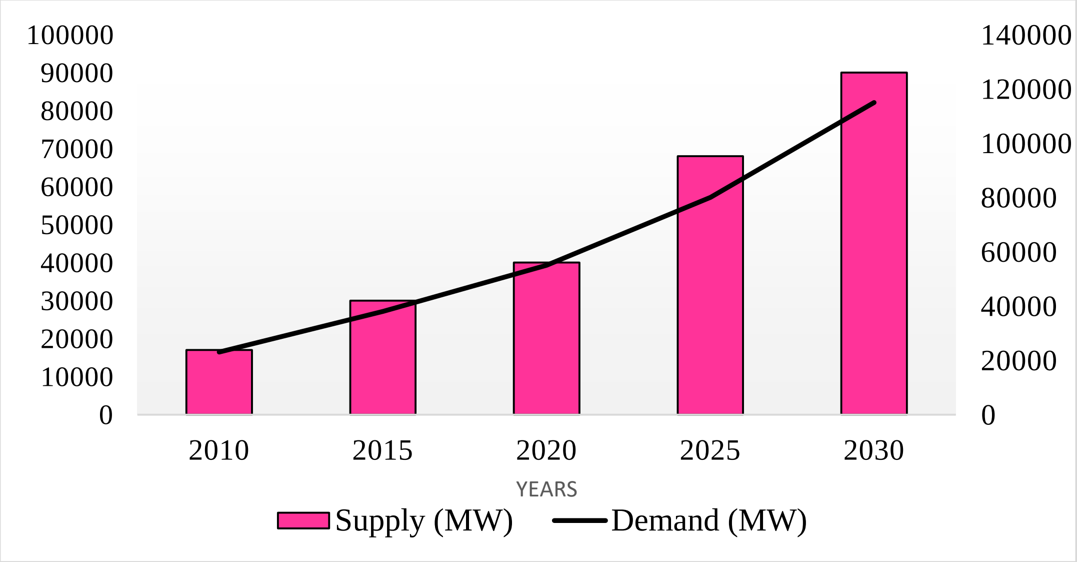

Figure 1-3: The supply and demand of electricity dynamics from 2010 to 2030

Pakistan's power distribution infrastructure is a critical component of its energy sector, responsible for delivering electricity from generation sources to end users. Primarily managed by state-owned Distribution Companies (DISCOs), this infrastructure faces significant challenges and inefficiencies. Among the primary issues are high transmission and distribution losses, overburdened networks, financial difficulties, and widespread electricity theft.

Technical and non-technical losses, which range from 18% to 30%, are mainly due to outdated network infrastructure, inadequate maintenance, and pervasive theft. Overloading of the distribution network frequently leads to voltage fluctuations and unscheduled power outages, exacerbated by insufficient funding for infrastructure repairs. The Ministry of Energy's Power Division recently reported that circular debt increased by Rs. 84 billion in January 2024, reaching Rs. 2.64 trillion, up from Rs. 2.55 trillion at the end of December 2023. The sector is further burdened by high-capacity fees and a reliance on expensive oil imports [9].

Two decades ago, reforms were implemented in the energy sector, leading several countries to adopt centralization or divide the market into competitive and non-competitive segments for vertically integrated utilities. Power generation, transmission, and distribution are now viewed as separate entities. To optimize each part of the power supply chain, participants such as Generation Companies (GENCOs), the National Transmission and Despatch Company (NTDC), and DISCOs engage in the buying and selling of services and power. Market exchanges or facilitators operate the power market, while the National Electric Power

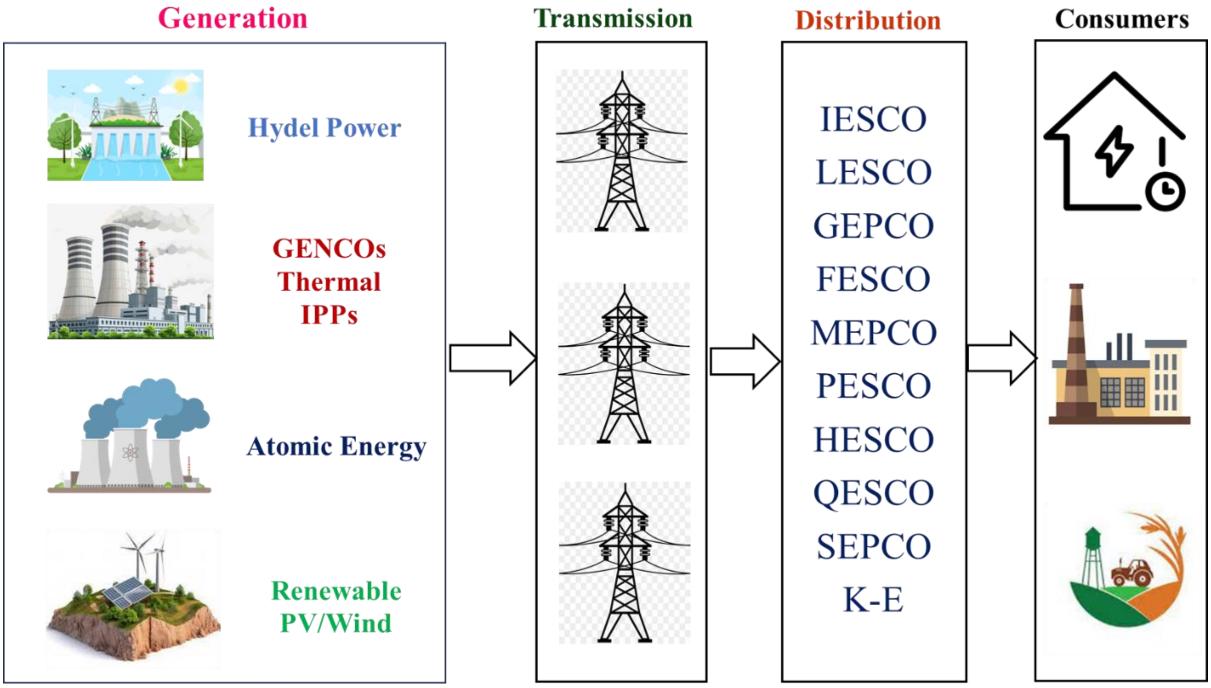

Figure 1-4: The current power infrastructure of Pakistan

Regulatory Authority (NEPRA) and the Central Power Purchasing Agency (CPPA) act as regulators and market operators. Figure 1.4 shows the current power infrastructure of Pakistan.

The current power market comprises the generation, transmission, and distribution of electricity to domestic, commercial, industrial, and agricultural consumers. This is managed through various power distribution companies (such as IESCO and QESCO) that control different regions, as illustrated in Figure 1.4. Historically, these companies held monopolies in their respective areas, overseeing both production and retail of electricity. Consequently, pricing is regulated solely by the National Electric Power Regulatory Authority (NEPRA) and the Central Power Purchasing Agency (CPPA), resulting in a completely monopolized market [10].

1.2 Energy Price Structure

The National Electric Power Regulatory Authority (NEPRA) regulates the supply of energy in Pakistan and is responsible for setting power rates and tariffs. The tariff structure is complex, consisting of a base tariff, fuel adjustment charges, taxes, and other components. The base tariff is a fixed rate designed to cover the operating expenses of utility companies, as well as the costs associated with generation, transmission, and distribution.

Fuel adjustment charges are added to the base tariff and fluctuate monthly based on the prices of fuels such as coal, oil, gas, and hydropower used in electricity generation. Since a significant portion of Pakistan's energy production relies on imported fossil fuels, these charges adjust to reflect changes in international fuel prices. Figures 1.5 illustrate the domestic energy tariff for different categories [11].

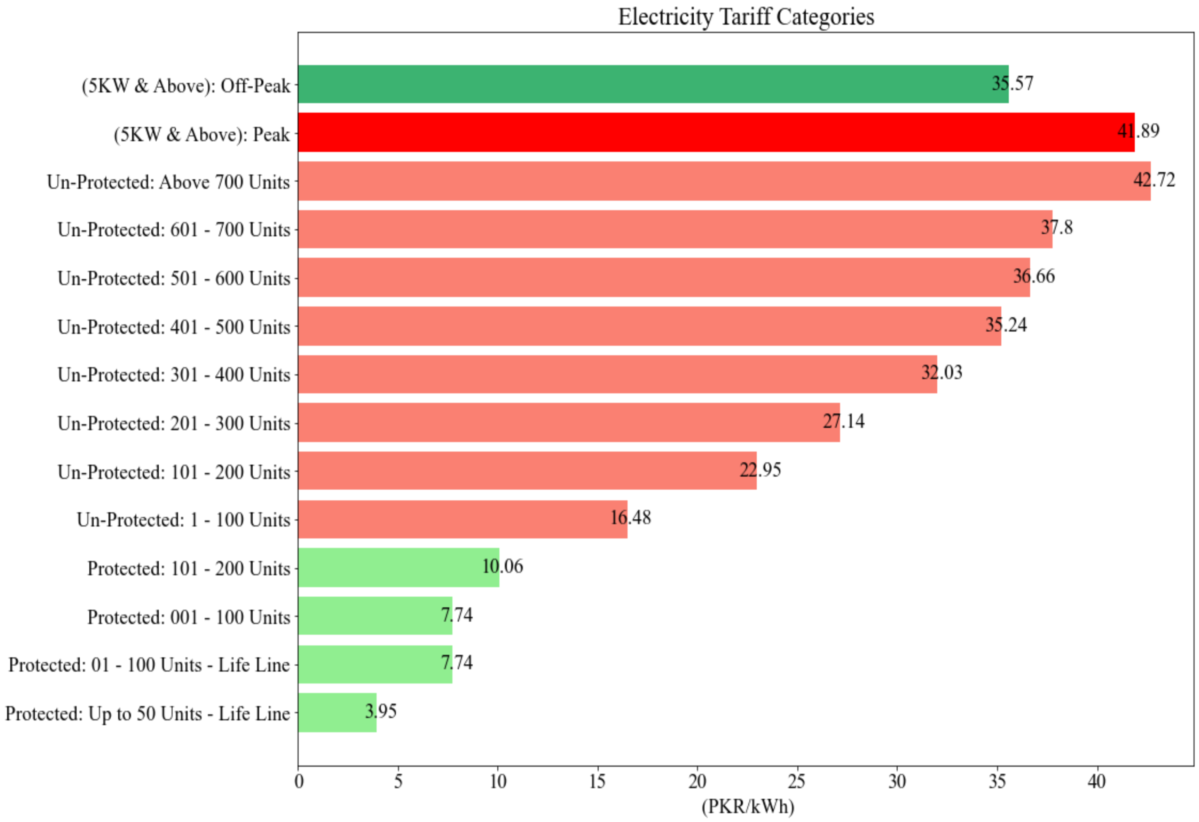

Figure 1-5 Current domestic energy tariff

The energy prices vary with consumption for domestic consumers divided into protected and unprotected categories. If consumption goes beyond certain limits the price of energy along with tax increased these categories were designed to reduce the power usage, however power users having load 5kW or above falls under peak and off-peak energy prices as listed in figure 1.5. These power prices are very high as compared to Asian energy market like India, Bangladesh, Sri Lanka and Afghanistan. The effect of power price hike in Pakistan is mainly due to thermal power supply by independent power producers (IPPs), who taking a huge amount of capacity charges as per their power purchase agreement (PPA). So, these capacity payments give a sky rocking effect to per kWh prices [12]. Adding into it the high transmission and distribution losses, less recoveries and uncontrolled electricity theft contributing more. Govt and policy makers are trying to cut the power prices by implementing different strategies by introducing the distributed energy systems and net-metering [13][14].

The net-metering implementation allows any consumer to install renewable energy sources (PV, Wind, Biomass) and sell extra energy to national grid by feed in tariff (FIT) which is Rs.

19.78 per kWh. However, grid price is higher than FIT, Unit exported to grid is equal to unit imported from grid so, power prices variation again made.

1.3 PV Energy buyer model using net-metering

Pakistan's net metering policy serves as an incentive for installing renewable energy sources like solar panels. This policy allows customers to earn credits on their electricity bills by feeding excess power back into the national grid. Around 113,000 residential units, or 0.3% of households, have rooftop solar with net metering connections. These "distributed generators" typically have over five kilowatts of capacity, placing them among the more privileged, high-consumption segments of society. Utilizing a bi-directional meter, it tracks both the energy supplied to the grid and the energy consumed from it, as depicted in Figure 04, with a feed-in tariff set at Rs.19.78/kWh by NEPRA. These feed-in tariffs make investments in solar, wind, and other renewable energy sources highly attractive by offering long-term contracts with guaranteed purchase prices for the generated energy. For the latest pricing and regulations, stakeholders are advised to consult NEPRA directly [15]. Despite the rapid installation of net metering, the government faces the burden of paying capacity charges to producers, which are subsequently passed on to consumers. This issue is compounded by the heavy reliance on thermal generation, leading to escalating energy prices. To address this, a new concept of a local energy market is proposed. This approach aims to reduce wheeling charges and other related taxes that currently contribute to high electricity costs.

The current electricity pricing system tends to benefit wealthier households that generate their own solar power, while placing a greater financial burden on those who rely on the grid for their electricity needs. The existing feed in tariff is about Rs.19.78 per kilowatt-hour, which is significantly higher than the average fuel cost of around Rs.9/kWh [16][17]. A counterargument is that households generating electricity through rooftop solar also rely on the grid when solar production drops, such as at night. These households incur capacity costs since the grid acts as their backup power source. Therefore, they should pay a fair price for maintaining access to this essential backup.

Given Pakistan's current energy challenges, developing a strong electricity market is essential. Recent studies on local electricity markets show that they can improve efficiency, attract investment, and ensure fair pricing. A well-designed electricity market would help balance supply and demand, alleviate power shortages, and support sustainable energy practices, benefiting everyone fairly. A local energy market is a specific framework often linked to distributed energy resources like small-scale solar and energy storage systems. These markets allow transactions between local producers and consumers, facilitating power exchange within a specific area, such as a neighbourhood, community, or small grid sector. The objectives of local energy markets include maximizing local energy use, promoting renewable energy adoption, maintaining grid stability, reducing transmission losses, and potentially enabling peer-to-peer energy trading within the community.

1.4 Capacity Payments

Capacity payments to net metering consumers incentivize installing renewable energy systems, easing the national grid's load, and promoting sustainability. Regulatory authorities like NEPRA set tariffs based on generation costs, energy type, and system capacity. Through net metering, consumers offset their electricity use with their own generation, earning credits or payments for any surplus fed back into the grid. These payments compensate for the system's potential to generate power and support the grid. The regulatory framework ensures fair compensation and covers installation, metering, and maintenance. This system offers financial returns, boosts grid stability by promoting distributed generation, and encourages clean energy use, reducing carbon emissions and environmental impact. [17]. Cost energy supplied by the grid have approximately Rs.18/kWh capacity payments which is very high resulting in huge burden of govt as well power consumers. Mean while net-metering tariff also includes capacity charges having FIT rate Rs. 19.78/kWh. Currently, consumers are recovering their investment in just 18 months at the existing payback rate. However, with the government planning to cut this rate to Rs 11 per unit, to reduce the financial burden [17]. So, a possible solution is trading energy locally without involving grid.

1.5 Meeting the essential criteria: Objectives of power distribution utilities.

The main objective of power distribution utilities is to meet three essential criteria: providing the necessary amount of electricity at the exact time it is required, while also guaranteeing a reliable and consistent service. However, achieving effective communication between energy providers and customers is still a challenging endeavour, especially in developing regions. The maintenance of different energy demands, such as residential and industrial, in the face of escalating global energy requirements relies heavily on economic growth and the development of sustainable energy solutions.

1.6 Challenges and factors that contribute to energy crises

The energy crises witnessed in multiple nations arise from several sources, with the primary cause being the lack of strong government policies that can effectively respond to increasing energy needs and alleviate electricity shortages. The situation becomes worse by factors such as Greenhouse Gas (GHG) emissions, widespread power theft, and transmission line losses caused by over dependence on traditional energy sources. Furthermore, the traditional system in which all power generating facilities are centralised and remotely controlled by a grid which is far away from the consumption centre adversely enhances these challenges because of the limitation of the efficient power distribution and transmission networks.

1.7 Enhancing energy solutions by utilising microgrid

An optimal approach would involve implementing a cluster arrangement of energy sources within a microgrid, comprising a combination of renewable energy sources such as wind and solar, with traditional alternatives like a diesel generator. This design does not necessitate a transmission network, such as those used in main grid network. While it remains challenging to adapt usage patterns to the optimal period considering possible fluctuations in grid energy supply, it has been demonstrated that real-time monitoring of consumption patterns and efficient load management may be successfully implemented. Besides, making the grid stable by optimizing the output from all the available sources is a difficult task in the conventional energy management system.

1.8 Problems in the integration of renewable energy sources

The application of Renewable Energy Sources (RESs) together with distributed generation (DG) in the process of electrical system modernisation presents numerous challenges. The use of Renewable Energy Sources (RESs) by utilities has caused the power system to become more complex and unstable [18]. Besides, RESs (Renewable Energy Sources) and DG (Distributed Generation) are intentionally planned to have the transmission grid capacity to be reduced and thus, the system operation is more stable. This suggests the necessity for a significant alteration in the arrangement of the grid.

1.9 Cutting costs and managing peak-to-average demand ratios

The lowering of the consumption costs and PAR critically depend on the accessibility of RTP information [19]. Real-time, intra-day, and day-ahead changes are very important for maintaining the balance between generation and load in a very short period of time. Thus, the co-ordination of energy management is vital for the matching of power generation and consumption activities [20].

1.10 Ensuring the stability of integrating solar and wind power.

The performance of solar energy systems is determined by factors such as sun irradiation and temperature variations, which have a direct impact on their efficiency [21]. Nevertheless, the variability of solar electricity requires the use of strategies to regulate the output of power. In case solar electricity will not be enough to meet the energy demand, other power sources like the diesel generators must quickly boost their production to fill the gap [22]. The exact amount of power produced by the solar system changes in relation to the weather conditions. On the contrary, the changing wind speed relationship of the wind energy conversion system is a source of additional complexity. The fluctuations in power levels are a problem in terms of power quality and grid interoperability, as they might potentially affect the stability and interoperability of the system due to the deviations from the expected power levels. Tackling these problems is the key to the flawless integration of solar and wind energy into the grid[23].

1.11 The benefits of microgrid in upgraded power system

In the modern power system, Microgrid has a lot of advantages over the conventional grid system. The benefits include self-monitoring, strong grid structure, self-healing, adaptability, intelligence, and resilience among others that enable the microgrid to manage the load demand. The microgrids are also characterized by the aspects whereby they combine adaptive electricity use and production due to the electricity constraints [24]. This aspect involves improved balance between power consumption and power generation that makes the system more reliable and reduces the cost.

The inherent unpredictability of the renewable energy sources is the main obstacle to the stability of the main electricity grid. Nevertheless, the well-managed and strategically placed microgrid systems offer a feasible way of solving such issues [25]. Microgrid systems are the key to the grid stability due to the fact that they are able to handle the unpredictability that comes from the changing output of the renewable energy sources. The microgrids and the unpredictable nature of the renewable energy sources can be solved and used to mind the present power grid. The microgrids should be managed and controlled by an autonomous agent. These robots are autonomous information processing systems that operate independently to realize the objective set to them. The Multi-Agent System method used to control energy management systems, enhances the effectiveness of and Energy management system [26] and

[28]. Each agent in this paradigm has the proactive, reactive, and social capabilities [27]. A key advantage of the MAS technique is its solid and reliable character, as well as its flexibility and dedication to environmental sustainability [29]. The combination of MAS improves the overall performance and creates a self-governing network to ensure the effective production control.

1.12 The economic influence of a local energy market system

The advanced pricing system in the market enable the precise distribution of energy resources in the local energy market system. By doing this, the stakeholders can plan and allocate energy resources in the best way to react to the changing circumstances, and thus, achieve the best efficiency and cost-effectiveness [30]. Also, the market system stimulates the competition among suppliers, hence, the innovation is boosted and finally, they get the service reliability and customer satisfaction.

1.13 Enhancing the efficiency of resources distribution.

The most important characteristic of the local electricity market is the ability to plan energy resources efficiently by using the dynamic pricing signals. Through the synchronization of energy generation and usage with market prices, stakeholders may be able to make well-informed decisions to maximize profitability while ensuring the stability and reliability of the power system. The fact that it is possible to use the existing resources more efficiently leads to a more efficient operation and a reduction in the costs, making it a more affordable option.

1.14 Improving Dependability and Preserving Customer Privacy

Microgrids not only reduce the costs but they also have a great deal in ensuring the reliability and the protection of client privacy [31]. By the decentralization of energy generation and transmission, and the reduction of the dependence on the centralized system, microgrids are the main factors in the improvement of the grid reliability and stability. On the other hand, microgrids systems are also equipped with the latest privacy-preserving technology that guarantees confidentially of client data. Thus, the regulatory requirements are met, and a trustworthy customer base is established in this case.

1.15 Reduction of operational costs

Cost-saving is another attractive characteristic of microgrid operation achievable through the local electricity market. Operating costs for microgrid operators can be reduced, while the service provided remains reliable by using dynamic pricing signals and resource allocation optimization. This approach allows microgrid to consume the available sources of energy as needed ensuring that the energy used is effective, low cost of energy, and economical stable of the system. The local electricity market is essential for operational improvement for energy resource management, greater reliability, consumer privacy protection, and cost reduction. On this basis, it is evident that the market penetration would be necessary to enhance the promotion of the grid system sustainability and resiliency [32] .

Demand response programs are vital in today’s energy management as the programs allow the consumers to have the control of their own electric patterns [33]. The department of energy explains demand response programs as programs which help customers to use electricity based on their willingness to match the need of dependable energy grid. This is the source of the grid stability and the power system relief and, finally, the energy cost reduction for the utilities and for the customers. The foundation of the concept is the dynamic pricing, meaning that the power prices will be changed based on the supply and demand conditions existing in the market currently. In case the demand is increasing, or the supply is decreasing, for example, during the extremely hot summer days or the unannounced power outages, these power prices can increase rapidly. Customers will be offered the possibility to use demand response programs and modify their behaviour in terms of energy based on these prices. Moreover, these demand response programs usually provide people with financial incentives or credits for the fact that they reduced their energy consumption during the peak hours. Finally, even these incentives work as a driving force for the customers to choose energy-efficient solutions and technologies, and the energy system becomes more sustainable.

Besides cost reducing and financial reasons, demand response programmes do play a great role in enhancing grid reliability and strength. By the application of the coordinated demand response programs, utilities can reduce the stress on the grid infrastructure, lower the probability of power outages or voltage reductions, and increase the overall system efficiency. Demand response initiatives also enable the integration of renewable energy resources by giving capacity to effectively handle the balance between supply and demand in real-time which consequently contribute to the adoption of a greener and cleaner energy future.

1.16 Objectives

1. To minimize electricity production costs by reducing capacity payments through the generation and distribution from the renewable resources.
2. Reducing reliance on the main grid by local production of power and exporting excess PV energy back to the grid through the local energy market system (LEMS).
3. To improve the grid reliability using DSM in the local energy distribution network

4. To analysis the impact of capacity charges on energy prices within community
5. To reduce the carbon emission for promoting clean environment by the integration renewable resources.

1.17 Research Gap

In this research study unlike other research works that have primarily focused on energy trading inside local market reducing the cost of energy, capacity payments effect of consumer tariff considering the Pakistan current power prices structure, this study addresses the gap by optimization of PV energy prices inside community to provide a more comprehensive understanding of distribution of power with and without capacity charges.

1.18 Thesis Organization

The paper is organised into multiple distinct sections to provide a thorough comprehension of the findings. The following sections are outlined as follows.

1. Introduction (Chapter 1) provides an overview of the study's goals and its context.
2. The Literature Review (Chapter 2) examines and evaluates the existing literature and research. This process develops the fundamental basis for the study's framework and methodologies.
3. Proposed Research Methodology (Chapter 3) presents and provides detailed explanations of the methodology, delineating the subsequent steps and procedures employed in carrying out the study. Illustrates the proposed methodology through a flow chart, clarifying the step-by-step processes involved. It specifically highlights how photovoltaic (PV) sources, diesel generators, and wind sources are integrated into the system framework.
4. Results (Chapter 4) presents a thorough analysis and interpretation of the obtained results. This includes the use of relevant figures and detailed explanations to enhance understanding and provide valuable insights into the findings.
5. Discussion and Conclusion (Chapter 5) provides a clear summary of the main results of the study and suggests prospective directions for further research and advancement.

Chapter 02: Literature Review

Localised energy distribution to local consumers through microgrids, usually connected to the main grid, may operate under electricity rates regulated as tariffs. However, it is no longer essential to set power tariffs for energy transactions within given communities [34]. According to Lezama et al. (2019) [35], microgrids and local energy communities are poised to play a pivotal role in balancing local energy production and usage through time. These entities operate as catalysts in promoting local energy markets, empowering smaller stakeholders, and advancing towards fully transactive energy systems. The emergence of distributed generation technologies, such as solar photovoltaic, has empowered consumers to actively engage in the production of energy at a local level. The advent of smart grids introduces a new paradigm marked by peer-to-peer electricity trading [36] [37].

In [38], the author acquired technological and economic benefits by utilising a hybrid energy management strategy that combines Mixed-Integer Linear Programming (MILP) and multi-objective optimisation approaches. The author suggested employing JAYA, Teacher Learning-Based Optimisation (TLBO), and Rao1 techniques in [39] for comparison analysis to validate the findings. It is suggested in [40] that Microgrids (MGs) should be encouraged to take part in incentive-based pricing systems organised by Distribution Network Operators (DNOs) using MILP techniques to identify equilibrium points. In reference [41], the author utilised the MILP methodology to tackle energy consumption scheduling issues, aiming to minimise power expenses. Energy trading among adjacent Microgrids (MGs) and efficient storage resource management are strategies proposed in the literature [42] to alleviate grid dependence.

Within the framework of multi-microgrid systems, the management of energy is made easier by the cooperation of interconnected microgrids within a decentralised structure, as stated in reference [43]. The strategy proposed in [44] aimed to guarantee the dependability of microgrids while minimizing operational expenses through the utilization of demand response techniques. However, concerns about client privacy prompted the author of [45] suggested an efficient energy management strategy. Meanwhile, the work presented in [46] proposed the proposed incorporating a multi-agent system to optimally allocate distributed resources across microgrids in a decentralized manner. Additionally, the preference for decentralized, bottom-up approaches to centralized energy management was emphasized in [47]. This proposed strategy drew from the Multi-Agent System concept, seeking to both improve system dependability and respect user privacy through the balanced and collaborative control of local energy assets.

In [48] the author has proposed a meta-heuristic method to optimise the resource allocation under energy market framework. In [49] based on the methodological scheme for the developments, the paper proposed a method exploiting the awareness of the customer to encourage the participation in demand response programs and allow energy exchange between micro grids using energy management through the agent-based. In [50] the paper presented an Energy Management System that uses agent-based technology developed to enact demand response legislation. The author in [51] presented a plan that utilises Feed-in Tariff (FIT) and Time-of-Use (TOU) pricing to reduce peak prices.

In [52], a suggested multi-agent control system aims to enhance the efficiency of information flow among numerous microgrids operating within the energy market framework. This system focuses on various elements, including the changes in pricing, fluctuations in load demand, and uncertainties associated with renewable resources, specifically during the day-ahead stage. As proposed in [53], energy arbitrage-related services are regulated during the real-time phase by executing an optimal schedule for power storage.

In addition, a virtual power plant has reportedly implemented an innovative approach with the goal of improving its overall economic influence, as described in reference [54]. This strategy focuses on economic scheduling and utilises the Ng-Jordan-Weiss spectral clustering algorithm, employing a multi-time-scale approach. The main priority of the virtual power plant (VPP) is to increase financial performance through active wholesale market participation. Thus, the economic activity of the VPP should be carefully monitored and improved to achieve maximum benefit. There have been studies devoted to the collaborative approach to promote energy exchange between prosumers, specifically cases where one has an energy surplus and the other needs additional energy [55]. Multiple researchers have suggested multiple approaches to encourage energy trading between nearby prosumers [56]. Moreover, there have been numerous efforts to analyse the benefits of the supportive collaborative model without rigid trade rules. Such efforts attempt to minimize the overall batteries consumption while promoting a fair surplus-trade opportunity. In other words, both parties get equal benefits from the agreement [57]. The combination of Genetic Algorithm (GA) with other evolutionary algorithms has proven to be a viable optimisation technique that utilises computational intelligence. This combination enables the most efficient arrangement of equipment, resulting in lower electricity expenses and reduced stress on the power grid during periods of high usage [58]. Research efforts in the field of Home Energy Management Systems (HEMS) generally concentrate on minimising energy costs. Furthermore, important goals consist of improving the comfort of consumers [59], reducing the peak to average ratio (PAR) [60], and minimising emissions [61]. The HEMS literature thoroughly explores these many objectives. In this study [62], the author presented to develop a MATLAB/Simulink-based energy management for optimizing renewable energy deployment into the power system. The study in [63] introduces a genetic algorithm (GA) to reduce the cost associated with maintenance cost of the system, limit the land required for installing the DG and PV system, and minimize the overall annual cost of the system. This paper [64] suggested the framework targets to optimize social welfare by equitably distributing resources, enhancing the reserve capacity of the main grid, and reducing peak power demand to improve the reliability of the system. While the standard model focuses solely on profits, the author proposed in [65] a complementary approach inspired by shared resource systems. This framework envisions small electricity collectives forming a distributed grid where neighbours directly exchange locally generated power. In the literature [66], author has suggested that, in order to improve energy efficiency, strategies enabling energy suppliers and policymakers to set grounds to stimulate energy consumer behaviour should be developed. The literature study highlights notable efforts in the field of managing distributed energy resources (DERs).

The DERs policies in Pakistan are designed to tackle energy shortages and encourage distributed generation, particularly through rooftop solar systems, Maaz et al., 2023 and Waqas et al., 2017 [67][68]. These policies provide economic benefits to homeowners and help alleviate demand-supply gaps. However, their implementation faces hurdles such as a complex application process, financial constraints, and low awareness among potential users[69]. According to Saleh & Sara, 2020, the adoption of net metering has been largely limited to major cities, revealing an uneven distribution across the country [70] . Additionally, Pakistan has introduced other measures like the Energy Wheeling Policy and Energy Import Policy to manage electricity demand more effectively Abbas et al., 2022 [71]. The adoption of smart grid technologies and advanced metering infrastructure could further enhance the efficiency of distribution companies and tackle issues such as electricity theft and load management Maaz et al., 2023 [68].

S. Bjarghov et al., 2021 and R. Faia et al., 2024 suggested that local electricity markets (LEMs) are emerging as a promising approach to tackle challenges in power systems, such as integrating distributed renewable generation and increasing consumer involvement[72] [73]. Despite their potential benefits, several obstacles remain in moving from research to large-scale implementation. These include the need for a well-defined market framework, fair handling of deviations, and concerns about data privacy. In a review paper by Doumen et al., 2022 suggested that by implementing LEMs requires careful consideration of various stakeholders' needs and the intricacies of power systems [74]. According to Zulfiqar, A et al., 2022, in developing countries like Pakistan, reforms such as the Competitive Trading Bilateral Contracts Market (CTBCM) aim to improve sector performance and offer more cost-effective power [76]. However, successful implementation of these reforms demands thorough design analysis, stakeholder engagement, and learning from international experiences. Future research should address these barriers and investigate the effects of widespread LEM adoption.

Recently, Moradi et al. (2023) and Moret & Pinson (2018) examined how the integration of distributed energy resources (DERs) into power systems has presented both opportunities and challenges. As a result, local energy markets have been developed to maximise local energy consumption and trading [77]. Prosumers can engage in energy trading through LEMs, such as Community-Based Markets (CBMs) and Peer-to-Peer (P2P) markets. CBMs are run by community managers to simplify regulations and interaction between systems. According to research by Ye et al. (2017) and Khorasany et al. (2018), competitive energy trading in community-based microgrids (CBMs) might result in large economic advantages, improve social welfare, and lower energy costs by managing risk and allocating resources fairly [78]. In addition, CBMs offer ancillary services that are essential to grid dependability, such as voltage support, peak shaving, and reserve provision. Studies demonstrate how CBMs may be scaled up and down to accommodate large numbers of users while optimising energy distribution. Communities working together to trade energy further boosts earnings and lowers risks, which makes CBMs a viable option for future energy markets [79] [80][81].

Table 2-1 Overview of related research work

Region	Year	Research Contribution/ Highlights	Ref
Pakistan	2022	This article designed an energy management system for industrial consumers was developed, allowing power producers and customers to communicate in both directions. To increase total profit and decrease expenditures and the peak-to-average ratio (PAR), the cuckoo search algorithm (CSA) was used.	[82]
Pakistan	2022	This paper proposes an off-grid solar–biogas microgrid for rural communities. HOMER was used to simulate the hybrid power system. The optimal system features a 30-	[83]

		kW PV, a 37-kW biomass hybrid system, and a 20-kW inverter. This setup, generating 515 kWh of electricity and 338.5 m³ of biogas daily, effectively meets the cooking and power needs of 900 people in 100 homes.	
Russia	2021	This study focused on reinforcement framework for learning using bilevel programming is used to optimise energy management of community microgrids with local power markets, improving power stability and lowering LCOE by up to 24%.	[84]
Italy	2023	The model uses dispatch algorithms to balance variable loads and optimize power output based on the lowest Levelized Cost of Energy (LCOE) and Net Present Cost (NPC). It also incorporates demand-side load control for better energy management. Results show that with an LCOE of 0.067 €/kWh, the system generates 33.2 GWh of clean energy per year, covering 78% of the community's needs and cutting CO2 emissions by 13,452 tonnes annually.	[85]

As previously stated, none of the study in the literature examined the community energy market along energy management systems and DMS so, there is still a significant deficiency in the capacity to rapidly simulate optimisation calls for efficient control of hybrid-based resources in real-time, especially within the framework of an interconnected local energy market system for energy trading between the prosumers and consumers avoiding the capacity payments , this will reduce the cost of energy, grid dependency, transmission and distribution loses and power stability. Moreover, previous research has not adequately addressed the incorporation of capacity payment at local power networks to provide incentives to consumers within a decentralised framework. This research aims to bridge these gaps by implementing a novel approach that addresses these challenges and contributes to the progress of the field.

Chapter 03: Research Methodology

To construct a dynamic model of the microgrid system, we will utilise MATLAB Simulink and perform the subsequent steps:

3.1 Microgrid components

Components are individual parts or elements that make up an overall structure. They are different and distinct components that make up the whole system or object.

Renewable Energy Sources: The objective is to stimulate the process of generating electricity by using solar panels and wind turbines, which get the sunlight and wind energy, respectively. These parts will consider factors such as sun radiation and wind speed to calculate their power output.

Backup Generation: Backup Generation: The diesel generator will be the backup to provide the alternative power when the renewable energy sources are not able to meet the microgrid's demand. The model will include the of the efficiency factors to exactly simulate the working of the generator.

The load Profiles: the load profiles that will exactly represent the electrical demand of the microgrid will be created; with time, the profiles will be progressively altered to coincide with the actual consumption patterns, this will include the high demand periods and the power usage variations.

3.2 Local energy market components and modelling

A complex mathematical depiction of the photovoltaic effect's conversion of solar irradiance to electricity will be constructed. This intricate model accounts for panel productivity and temperature's impact. Aerodynamic and mechanical aspects of wind turbines will be demonstrated through multifaceted mathematical models. These representations consider variables including wind velocity, turbine and generator effectiveness in calculating output. The generator's reaction to fluctuating load demands will be flexibly portrayed through a diesel model incorporating efficiency factors. Extensive time-series information will generate load profiles spanning a specified period, visualizing electrical requirements. Wind speed, solar irradiance and load demand related data is taken from the latest research paper [86]. These profiles simulate and assess microgrid performance under variable load demand. This elaboration reconstitutes interactions between renewable sources, backup production and demands in diverse operating scenarios. It underpins optimization, control and analysis of operational proficiency.

While simulation allows evaluation of multiple scenarios, real-world implementation poses synchronization challenges across different component fluctuations. Overall, developing reliable profiles establishes a framework for evaluating this integrated system's resilience under changing consumption patterns.

3.3 Simulation and Analysis

After the implementing of the components and the mathematical models, the simulation of the microgrid system using MATLAB Simulink is to be conducted. Performance parameters to be derived include grid dependency, renewable energy utilisation and carbon emitted based on which the efficiency of the microgrid energy management system is to be evaluated.

3.4 Simulation Studies

To conduct simulation studies and evaluate the microgrid performance under the different scenarios, the simulation shall be done using MATLAB Simulink. The scenarios in this simulation include:

The **base case** where the microgrid is only connected to the main grid.
Case 1: The solar panels configuration such that they are configured to reduce the grid reliance.
Case 2: The solar panels and wind turbines where the microgrid is connected to the sun and the wind, and these is to increase the grid autonomy:

Case 3: This case is the combination of solar panels, wind turbines, and a diesel generator which is the backup power. Carry out a simulation of the microgrid's performance over a long period to check if it can deal with and recover from the challenges, its reliability, and its economic feasibility in different environmental and load situations.

Case 4: Multi-Source Generation with DSM Integration. This case combines case 3 with DSM technique to shift the load and saving energy during peak hours.

Case 5: Integration of local energy market (LEM) direct energy selling to local communities connected to grid instead of supplying energy using feed in tariff energy is directly sold to consumers by using community energy market model avoiding capacity charges.

3.5 Performance measures

Specify performance measures for assessing the efficiency of any microgrid arrangement, including Grid reliance refers to the proportion of electricity obtained from the main power grid compared to renewable energy sources and backup generation.

Carbon emissions: Estimation of carbon dioxide emissions linked to electricity production, considering the combination of fuels and the efficiency of each power source. Cost analysis involves the computation of operational expenses, such as fuel costs, maintenance expenditures, and the potential income generated from selling excess energy. The workflow of this study using MATLAB model is presented in flowchart form in the **Figure 3.1**.

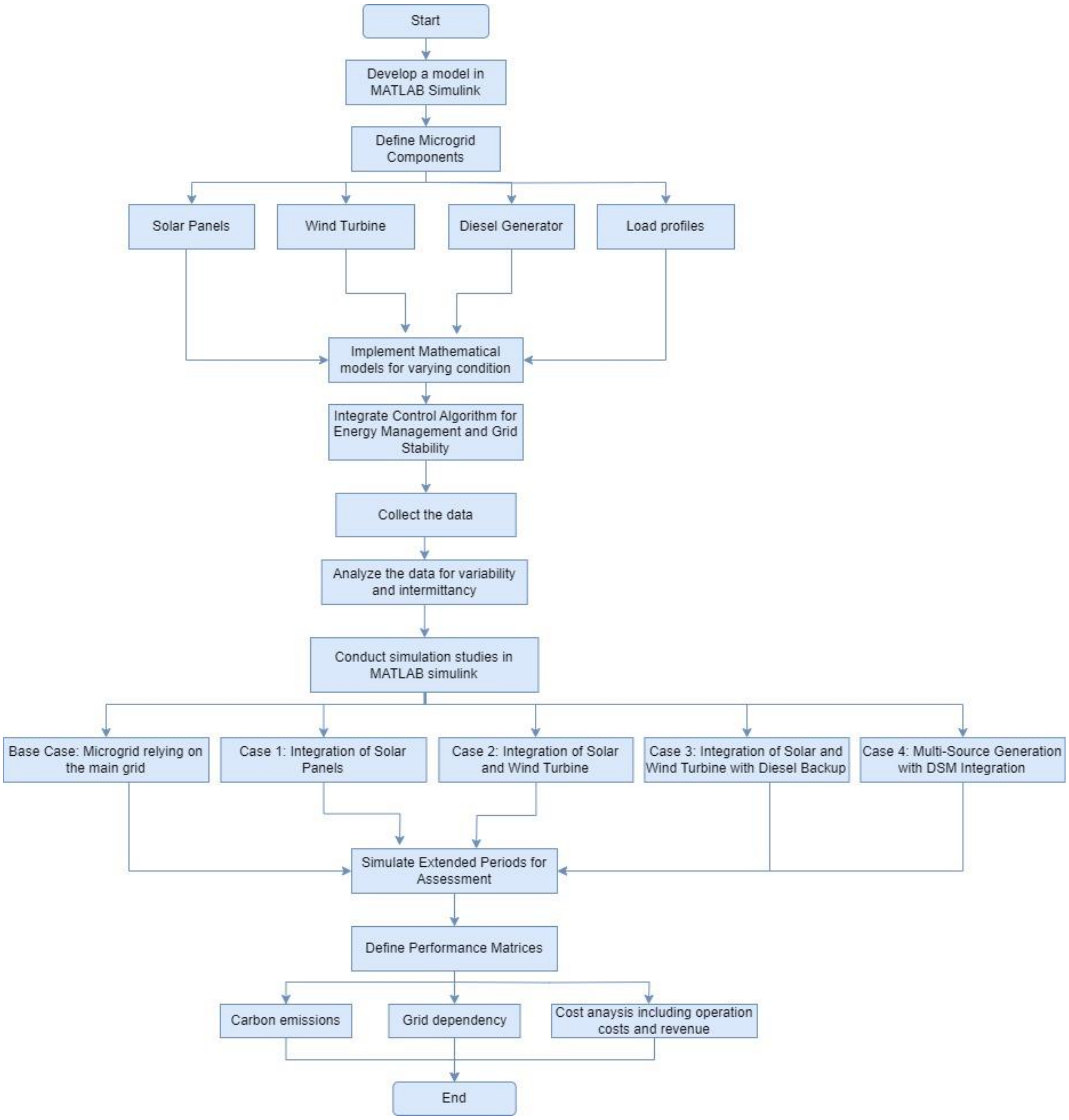

Figure 3- 1 Workflow representation in flowchart form

3.6 System Architecture and Modelling.

3.6.1 System Architecture

The architecture of the proposed test system has a structural foundation, which is shown in **Figure 3.2**. This structure is the basis of the combination of the multiple components. The main points to be considered among these components are the integration of Photovoltaic (PV) systems, wind energy conversion system, diesel generator, Energy Management Systems and a Local Energy Market System. This combination is the basis of the whole framework which aims at the energy efficiency improvement, the resource consumption optimization, and the promotion of the economic viability within the energy system.

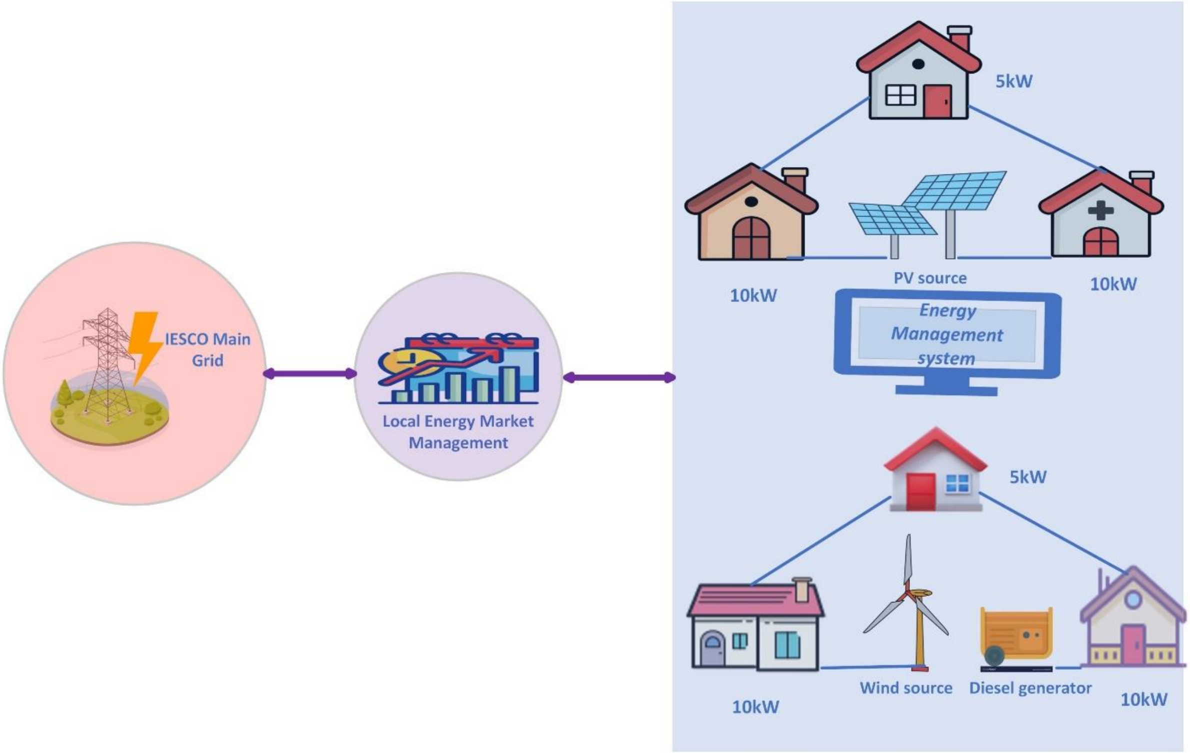

Figure 3- 2 Architecture of microgrid energy management system

Moreover, the system has been created for the purpose of increasing the use of the surplus electricity generated by the PV system, the wind energy conversion system and the diesel generator. Consumers are given the possibility to return the excess energy to the grid by using the Renewable Energy Resource (RER) which leads to a valuable contribution to the grid stability and the sustainability initiatives. This bidirectional energy exchange mechanism not only reinforces the energy infrastructure but also provides consumers with chances to earn money from the sale of the surplus energy.

The proposed testing system is an integrated solution that combines modern technology with market operations to manage energy effectively. It is anticipated to yield benefits in terms of energy use, cost reduction, and the promotion of sustainable energy standards. This system aims to cultivate a forward-thinking approach to address current issues and facilitate the advancement of sustainable energy. It achieves this by effectively combining photovoltaic systems with demand side management strategies and proactively participating in the local energy market system.

Table 3-1 Power ratings of microgrid components

Components	Power rating (kW)
PV source	100kW
Wind source	80kW
Diesel generator	5kW

3.6.2 Modelling of microgrid components

We are considering a grid connected microgrid. Microgrid includes multiple components that remain separate from each other. Each component plays a critical role in the functioning and controlling of microgrid. Furthermore, the microgrid is designed to utilize renewables such as wind and photovoltaic systems as well as non-renewable sources such as diesel generator. Moreover, the microgrid has dynamic loads that show the random use of power that occurs within the system.

3.6.3 Community Load

The microgrid dynamic load library which comprises of a variety of functions is accurately applied in the simulation to design the electrical load behaviour. It assists to simulate the load features and their reaction to the changes in the voltage levels at different times. When the voltage of the load terminal is below the set limit, the load impedance is regarded to have a constant value. As a result, the microgrid system is stabilized to restrain the voltage from falling much that can jeopardize the operations of the system. The voltage scope matches the impedance value an assurance to the constant activity of the system and an opportunity for analysis.

Variations in the magnitude of voltage lead to changes in active and reactive power loads. The load adjusts its consumption of power depending on the voltage variations happening in the system to maintain balance. Such an adaptative behaviour ensures that the microgrid recovers energy resources adequately and meets the demands. The corresponding mathematical relationship between the behaviour of the load and the magnitude of voltage can be expressed as follows:

Active power

$$P_{active}(t_m) = P_{ref} \times \left(\frac{V_m}{V_{ref}}\right)^{n_p} \tag{3.1}$$

where:

The consumption of active electrical power by dynamic loads, represented as P_{active}, fluctuates in response to variances in the actual voltage magnitude V_m at terminal points connecting them to distributed energy resources, such as solar panels or wind turbines. P_{ref} signifies the baseline or standard level of power intake against which P_{active} is compared. Meanwhile, V_{ref} is the nominal voltage that loads are designed to receive, any deviation from which—whether upwards or downwards—tends to proportionally increase or decrease P_{active}. The exponent n_p quantifies precisely how elastic this relationship is between voltage fluctuations and alterations to power usage.

Reactive power

$$Q_{reactive}(t_m) = Q_{ref} \times \left(\frac{V_m}{V_{ref}}\right)^{n_q} \tag{3.2}$$

where:

$Q_{reactive}$ represents the variable consumption of reactive power loads that fluctuate based on voltage variations.

Q_{ref} is the benchmark level for reactive power intake determined to maintain optimal system performance.

V_m indicates the real voltage magnitude delivered to loads which may deviate from intended levels.

V_{ref} establishes the ideal voltage that loads require to function dependably yet allow flexibility through minor fluctuations.

The sensitivity coefficient n_q governs the rate at which reactive power demand alters in response to voltage deviations, maintaining balance as supply and demand flow.

Microgrid load dynamics pose critical challenges to maintaining reliability and efficiency. Mathematical models capturing load variances under diverse voltage conditions facilitate sophisticated simulation and analysis.

3.6.4 PV source

The integration of a photovoltaic (PV) source in MATLAB Simulink involves applying mathematical models to genuinely replicate the functionality of the solar energy system. Equation 3.3, quantifies the ability produced by the photovoltaic (PV) source, considering factors like solar irradiance and inverter efficacy [86][87]

$$P_{pv_{source}}(t_m) = P_{nominal} \times \eta_{pv} \times \frac{Irr(t_m)}{10^3} \tag{3.3}$$

Where:

$P_{nominal}$: Nominal output power of the PV system in (W).

n_{pv}: The efficiency of the solar system.

$Irr(t_m)$: Irradiance of solar at time tm.

The irradiation from the solar ($Irr(t_m)$) is a must when determining the output power of the PV system using this equation which is the measurement of the amount of solar energy that is received by a specific area during a given period of time. It is commonly expressed in units of watts per square metre (W/m²). Dividing by 10^3 is commonly used to standardise the solar irradiation to the correct scale.

The efficiency of the solar system measures the effectiveness of the PV system in converting solar energy into electrical power. The PV inverter is responsible for compensating for various losses in the PV system, including electrical losses and mismatch losses. Its main function is to optimise the power output of the PV source.

Specification of technical parameters related to capital cost and maintenance cost for wind source, PV system and diesel generator is taken from research paper in [87]

Table 3-2 Capital cost and operational and maintenance cost of PV system

Capital cost \$/kW	\$400
O&M cost \$/kW/year	\$20

3.6.5 Wind energy system

Equation 3.4 is used in a wind power system to calculate the power output (P_{wind_source}) of the wind turbine at a specific time T. This equation contains multiple parameters, including wind speed, air density, rotor swept area, and performance coefficients, to precisely model the behaviour of the wind source. The wind turbine's power output at a given time is denoted as (P_{wind_source})[87][88].

$$P_{wind\_source}(t_m) = \left\{ \begin{matrix} 0 & u(t_m) < u_{min} \\ \frac{1}{2} C_N \rho A_s u(t_m)^3 & u_{min} < u(t_m) > u_{nom} \\ P_{nom} & u_{nom} \leq u(t_m) \leq u_{max} \\ 0 & u(t_m) > u_{max} \end{matrix} \right\} \qquad 3.4$$

Where:

C_N is the performance coefficient of the wind turbine.

ρ represents the air density.

A_s denotes the rotor swept area of the wind turbine.

$u(t_m)$ is the wind speed at time.

u_{min} is the cut-in wind speed.

u_{nom} is the nominal wind speed.

u_{max} is the maximum wind speed.

P_{nom} is the nominal power generated by the wind energy system.

The wind speed, $u(t_m)$, determines the wind turbine's power output in this equation. The power output is computed using the cubic relationship between wind speed and power output when the wind speed is between u_{min} and u_{nom}. The power output stays constant at the nominal power P_{nom} as long as the wind speed is higher than the nominal value u_{nom} and falls between u_{nom} and u_{max}. Nevertheless, the power output drops to zero and the wind turbine shuts down to prevent damage if the wind speed surpasses the maximum value, u_{max}.

Researchers can utilize Equation (4) to model the performance of wind turbines across different wind conditions and enhance the design and operation of wind power systems to achieve optimal efficiency and dependability.

Table 3-3 Capital cost and operation and maintenance cost of wind source

Capital cost \$/kW	4000\$
O&M cost 20\$/kW/year	40\$

3.6.6 Diesel generator

The diesel generator is a crucial element of the microgrid system because it is used as a power source of last resort and supplements energy demand during times of scarcity or when renewable energy sources are insufficient. The mathematical expression of the power output of the diesel generator at the time t_m is provided by Equation 3.5[88].

$$P_{Diesel\_source}(t_m) = P_{rated} \times \eta_D \times T_{on} \qquad 3.5$$

In this case, the following variables are used: P_{rated}, the nominal output power of the diesel generator; η_D, the efficiency of the diesel generator; - T_{on}, the period the diesel generator operates at the rated power.

The diesel generator efficiency η_D is a combination of the numerous losses within the generator system, including mechanical, electrical, and thermal losses. It is, however, the direct efficiency of turning diesel fuel into electrical power. The Ton is the time during which the diesel generator is able to work at its maximum power output. It is usually calculated from the system's needs, the available diesel fuel, and the load demand. The diesel generator runs at a constant power output during this time to meet the microgrid energy demand and ensure continuous operation and stability.

Table 3-4 The amount of energy taken from diesel during specific tariff.

Tariff	Time	Diesel generator (kWh)
Off-Peak	12:00am – 5pm	21.38
Peak	5pm - 11pm	35
Off-peak	11pm – 12pm	4.766

Table 3-5 Capital cost and operation and maintenance cost of diesel generator.

Capital cost $/kW	500$
O&M cost $/kWh	0.030$

3.7 Microgrid grid local energy management optimization

The goal in optimizing microgrid management is to decrease the overall cost while efficiently meeting the energy demand of the microgrid. This optimization issue is formulated using MATLAB's optimization toolbox and utilizes a time-slotted technique. In this approach, a day is divided into M discrete time intervals, with each interval having a period of dt_m (where M=288 and dt_m=300 seconds). Equation (6)[86] is the objective function, which computes the total cost of managing the microgrid throughout an entire day.

$$C_{net}(t_m) = \sum_{M=1}^{288} \left(E_{req}(t_m) \times C_{Grid}(t_m) \times dt_m - E_{exc}(t_m) \times C_{FIT}(t_m) \times dt_m\right) \qquad 3.6$$

Where:

Where $E_{req}(t_m)$ is the energy required by the microgrid from the main grid at time tm and $C_{Grid}(t_m)$ is the grid cost at time tm, dt_m is the time interval duration. $E_{exc}(t_m)$ is the excess energy generated by the microgrid sold to the main grid at time tm and $C_{FIT}(t_m)$ is the feed-in tariff rate at time t_m. The overall cost of obtaining energy from the main grid is calculated. This is the product of $E_{req}(t_m)$, $C_{Grid}(t_m)$, and dt_m expressed by the formula. Further, the net revenue is calculated using the formula: surplus of energy sold to the main grid * cost of energy – income generated during the work of the whole day.

The optimisation problem is subject to the following constraint[85].

$$P_{pv_{source}} + P_{Diesel\_source} + P_{wind\_source} + P_{Grid} = P_{Demand} \qquad 3.7$$

This constraint makes sure that throughout each living interval, the sum of power generated by all sources must be equal to the global power needs of the microgrid. Moreover, additional constraints can be included in the optimization problem to account for limitations of the system, available resources, and operational requirements. In such a way, it is guaranteed that the developed optimized management plan of the microgrid is not only optimal in some respects but is also feasible and reliable.

3.8 Local Energy Market Systems (LEMS)

The trading of energy inside a defined geographic locality, such a community, neighbourhood, or university, is made easier by a decentralised platform called a Local energy Market System (LEMS). Through direct sales and purchases, this system maximises the local level balance between supply and demand for power generated locally and used locally [89]. A local electricity market system enables direct power trading between homes, companies, and other organisations that have distributed energy resources (DERs), such as wind turbines, solar panels batteries. Further LEMS transmission losses and raise the grid's overall efficiency by balancing local supply and demand [90]. Balancing supply and demand locally, the whole power system can be made more stable and less stressed. By selling extra energy, participant s may be able to create new revenue sources and cut their electricity expenses [91].

The architecture for the proposed local energy market systems (LEMS) offers a creative plan for setting up a productive energy trading system in nearby areas. Fair energy exchange between prosumers and consumers is made possible by this system, which is managed by an energy management system (EMS). The LEMS design minimises dependency on centralised grids and encourages the use of renewable energy sources to overcome the difficulties presented by the changing energy scenario [92]. By actively bargaining energy costs and quantities, consumers and prosumers optimise the local energy balance through energy trading. The objective function of LEMS can be calculated using equation 3.8,

$$\mathrm{Cost(obj)} = \Sigma\Big(P^{i\mathrm{G}}\, GT^{Impt} - P^{exp.G}\, FIT^{\mathrm{exp}} + \alpha\Big(P^{exp.LEMS} + P^{imp.LEMS} - P^{HRE}\, C^{RE}\Big) \quad 3.8$$

Where;

The total power balance in LEMS is shown in equation 3.9. This formula guarantees that each the prosumers total pricing for buying and selling to and from the grid equals that prosumers energy generation and demand. The interaction between energy transactions and LEMS price is captured by equation 3.9, which guarantees a balanced energy distribution that satisfies community demands and conforms to the dynamics of the local energy market [93].

$$P^{exp.\mathrm{G}} - P^{i.\mathrm{G}} + P^{exp.LEMS} - P^{imp.LEMS} + \mathrm{L} - P^{HRE} = 0 \qquad 3.9$$

Where;

An important local power balancing limitation that focuses the requirement for consistency between the energy received and sold in a limited capacity. The equation 3.10 functions as a basic rule LEMS, guaranteeing that the area's energy transactions stay in balance and that any energy import and export must be balanced [94].

$$\Sigma_{LEMS}\left(P^{exp.LEMS} - P^{imp.LEMS}\right) = 0 \qquad 3.10$$

Using the procedures indicated in 3.11 and 3.12, residents are permitted to send and receive energy from the upstream grid within the specified capacity.

$$P^{exp.G} - P^{Imp.G} \leq \mathrm{C}^{\mathrm{exp.}} \qquad 3.11$$

$$P^{Imp.G} - P^{exp.G} \leq \mathrm{C}^{\mathrm{imp}} \qquad 3.12$$

3.8.1 Local energy market optimization

This section presents numerical case study evaluating the effectiveness of the proposed decentralized approach for energy trading among small homes. The analysis was conducted using the General Algebraic Modelling System (GAMS) software. It is crucial to highlight that the results of this approach, which aimed to optimize energy prices for consumers participating in the market, relied on comprehensive data. This included 24-hour information on the load demand of all households, PV data, grid import and power prices.

3.9 Economic Feasibility

The investment in PV, wind and residential batteries is very expensive, and the parameter of capital cost may have a significant impact on the presented result. The savings are the average reduction in the electricity costs per year when introducing P2P trade for the load communities. Economic analysis is crucial for assessing the feasibility of power plants, with the levelized cost of energy or electricity (LCOE) being a key financial metric. As noted in the literature, LCOE allows project managers to evaluate the economic viability of various types of power plants. It provides a means to compare the cost of producing one kilowatt-hour (kWh) of electricity across different technologies, aiding in the selection of the most appropriate installation types and locations. The actual LCOE is calculated as follows; [95][96]

$$LCOE = \frac{CPX + \sum_{t=1}^{N} \frac{OPX_t}{(1+Dc\,)^t}}{\sum_{t=1}^{N} \frac{Eg_t}{(1+dc\,)^t}} \qquad 3.13$$

Where, CPEX is total capital expenditure, including engineering procurement and construction costs of the project, OPX is operation and maintenance expenses during the project life cycle, and Dc is discounted rate assumed 8%, Eg is the electricity generated in year t. cost parameters are furthers divided and examined in equations.

3.10 Capacity Payments (CP)

Calculating capacity payments for a power plant involves determining the fixed costs required for financial viability while ensuring capacity availability for the grid. This includes fixed O&M costs, capital expenses, and a reasonable return on investment (ROI). By integrating these elements, the capacity payment ensures the plant covers its fixed costs and achieves a satisfactory ROI. The equation 3.14 gives the CP as under [97],

$$Capacity\ Payment = ROI + \left(\frac{FC + CRF \times TCC}{CF}\right) \qquad 3.14$$

Where, ROI is return on investment, FC denotes fixed costs (annual fixed O&M costs, insurance, property taxes), CRF is capital recovery factor, TCC is total capital cost and CF is capacity factor. Thes factors varies according to type of power plants and power purchase agreement.

Chapter 04: Results

4.1 Case study

The electrical load profile for the study was obtained from the Islamabad Electric Supply Company (IESCO) in Pakistan for the year 2023, as shown in Figure 4-2. Annual data on solar radiation, ambient temperature, and wind speed were collected from the site's weather station and the meteorological department [98], as depicted in Figures 4-2 and 4-3. To forecast the power output for PV-Wind systems located near village Khairpur, Chakwal, Pakistan, a simulation covering 24 hours was conducted. This simulation utilizes the Typical Meteorological Year data, based on the geographical coordinates of 32.7046° N latitude and 72.7749° E longitude. Figure 4-1 illustrates the location of the community.

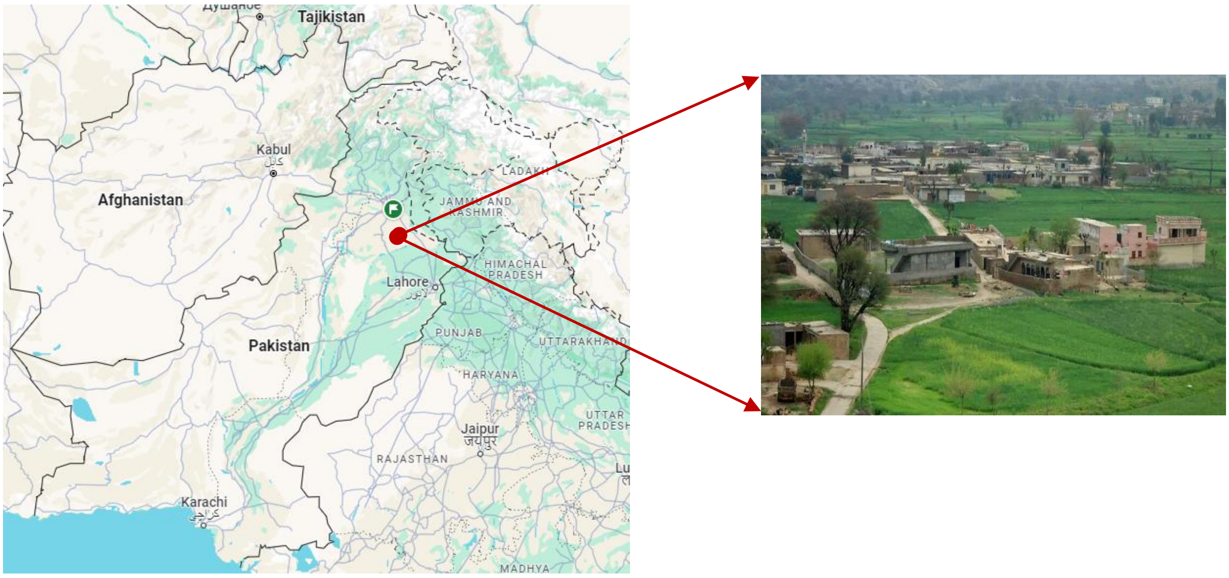

Figure 4-1 Location of Community

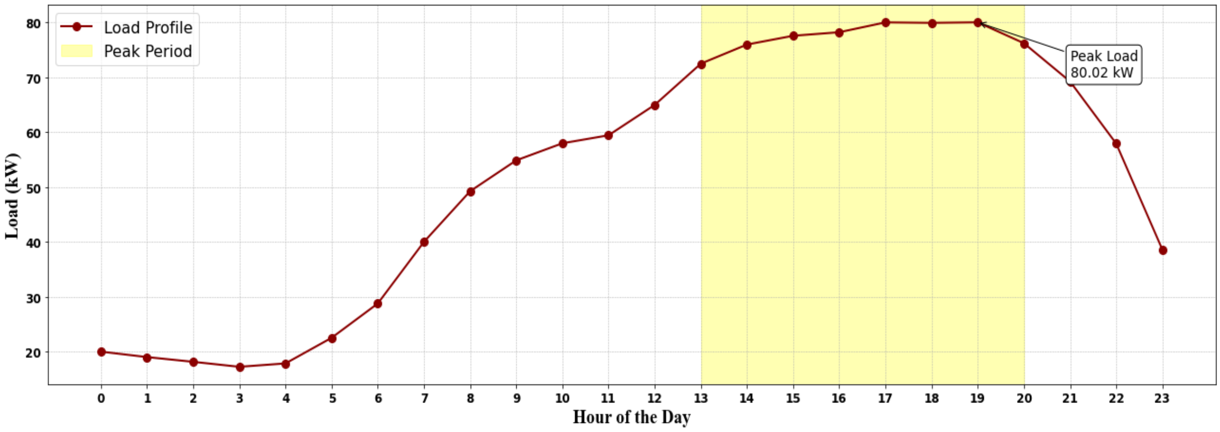

Figure 4-2 Daily load profile of community (2023)

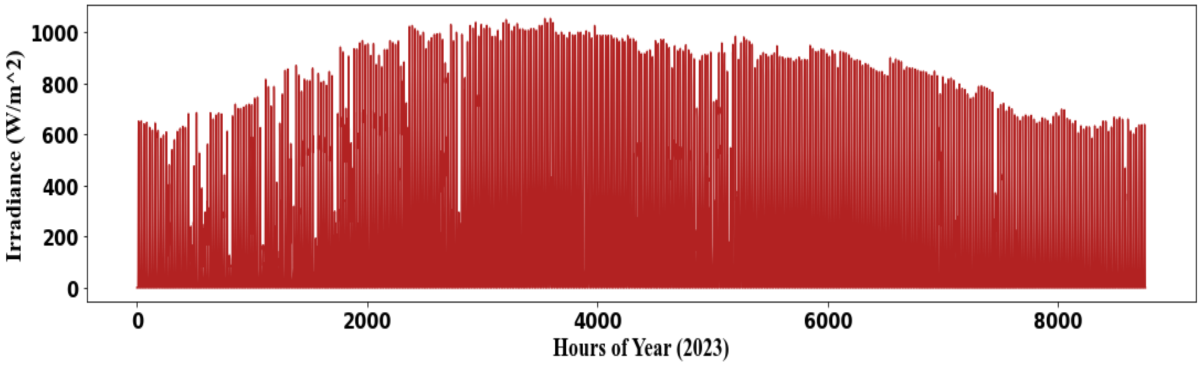

Figure 4-3 Area Yearly Solar Irradiance (2023)

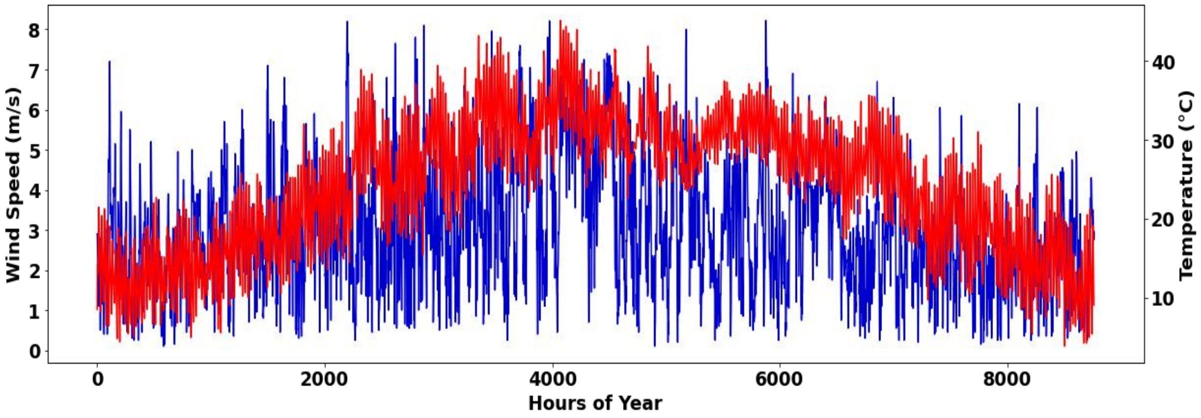

Figure 4-4 Area Wind Speed and Temperature

4.2 Base Case: Dependency of microgrid load on the main grid

In this scenario, where the microgrid load relies solely on the main grid, the microgrid effectively functions as a conventional power consumer, as shown in **Figure 4.5**. The system derives its whole power requirements directly from the main electrical grid, as depicted in **Figure 4.6**, which usually depends on conventional power plants fuelled by resources like as coal, natural gas, nuclear, or hydroelectricity.

The ability of the microgrid to fulfil its electrical energy needs is totally dependent on the dependability and accessibility of the main grid, as there are no local power producing sources. As a result, consumers within the microgrid experience substantially increased energy bills, as demonstrated in **Table 4.1**. The grid cost at which energy is being taken from the main grid, as presented in **Figure 4.7**. In the event of any disturbances or failures in the main power system, the microgrid may also experience power disruptions, which could result in periods of inactivity, inconvenience, and economic losses for the connected consumers.

In addition, depending exclusively on the main power system for electricity can make the microgrid susceptible to fluctuations in energy costs and interruptions in supply due to factors such as severe weather conditions, failures of equipment, or congestion in the grid.

On the whole, a microgrid that relies solely on the main grid may be simpler to construct and operate, but it lacks the ability to withstand challenges, promote environmental sustainability, and achieve significant cost savings that come with integrating local renewable energy generation.

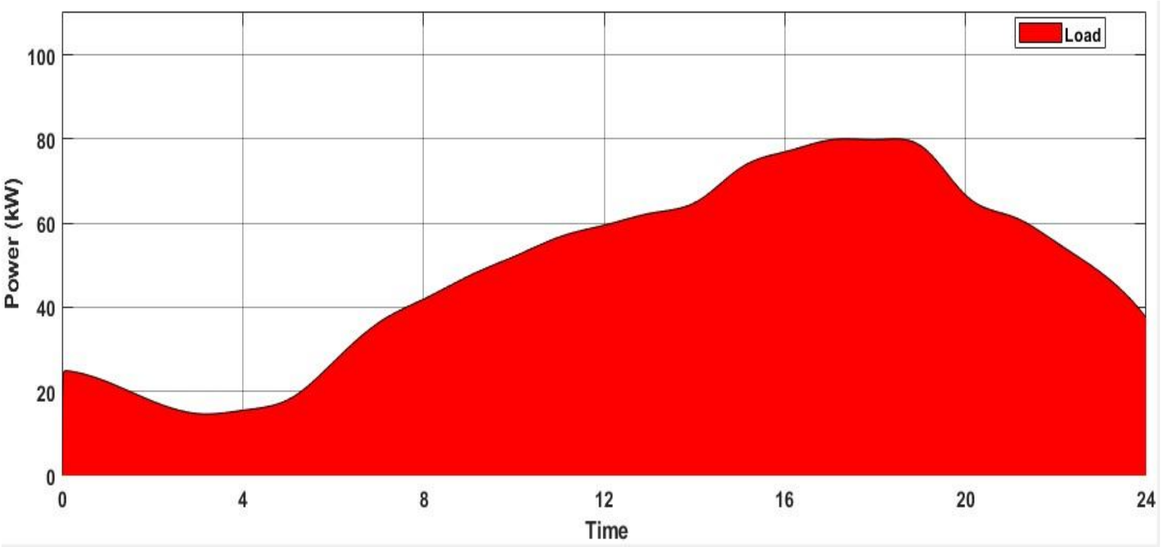

Figure 4-5 Load demand of the community microgrid

Figure 4-6 The amount of power taken from the main grid to satisfy the demand.

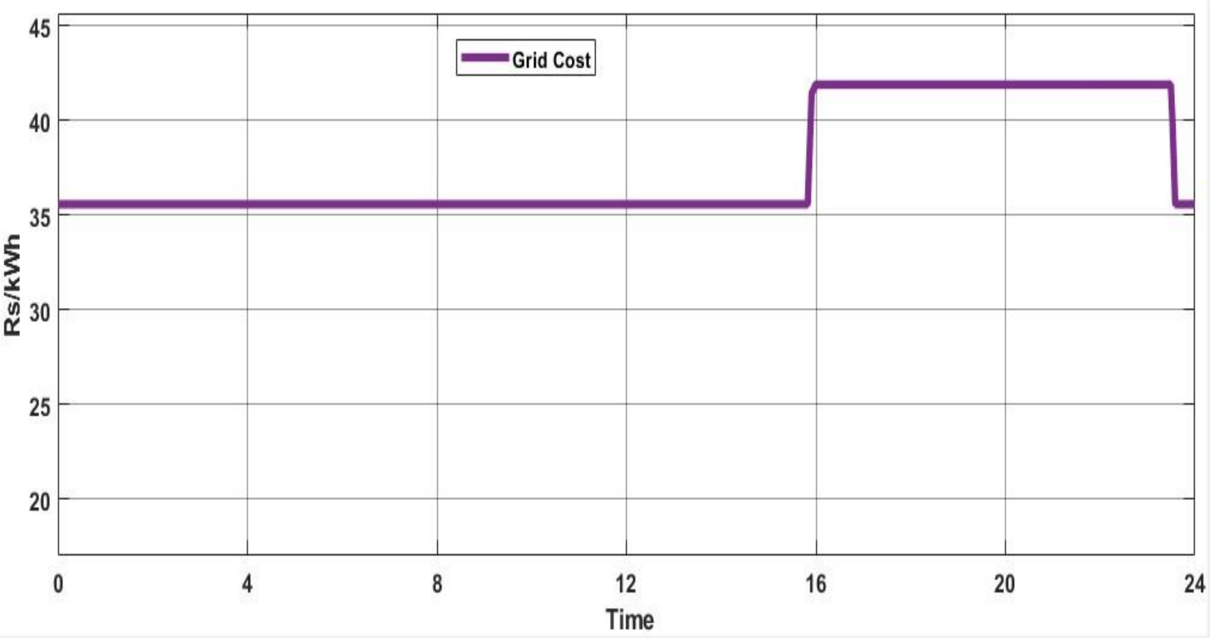

Figure 4-7 The grid cost at which amount of power taken from the grid.

Table 4-1 Community microgrid billing for main grid energy imports

Base Case	Import Energy (kWh)	Import Bill (PKR)
Microgrid	1188	45540

4.3 Case 1: Integration of PV System

In Scenario 1, where the microgrid load is supplemented by a renewable energy source such as solar panels (PV), the microgrid gains advantages from an alternate energy supply. Solar panels transform sunshine into electrical energy, offering an environmentally friendly and renewable power supply to the microgrid. Excess electricity generated by the solar panels is redirected to the main grid when the microgrid's immediate requirement is met, as depicted in **Figure 4.8**.

Grid-tie inverter assist in the conversion of the solar panels' direct current (DC) power into alternating current (AC) electricity that is compatible with the grid. The excess electricity is sent through the microgrid's connection point with the main grid, thus optimizing the overall energy supply of the system.

Net metering systems are frequently utilized in such scenarios. In a net metering agreement, the operator of the microgrid is given credits or payment for any excess electricity that is sent back to the main power grid, as presented in **Figure 4.10**. Feed In Tariff cost at which energy is being sent back to the grid, as displayed in **Figure 4.11**. These credits can be used to compensate for electricity usage from the main grid when the solar panels are unable to generate enough power, such as at night or during cloudy weather, as shown in **Figure 4.9**.

Grid-tie system offer multiple benefits. Microgrid operator can lower their power expenses by using the electricity produced by their solar panels to balance out their consumption, as illustrated in **Table 4.2**. In addition, microgrid operator enhance the overall renewable energy capacity of the grid and promote sustainability by exporting excess electricity to the main grid, so lowering dependence on fossil fuels.

Overall, Case 1 illustrates a scenario in which incorporating renewable energy source, such as solar panels, into the microgrid's energy composition not only improves sustainability but also provides economic benefits and strengthens the resilience of the larger electrical grid.

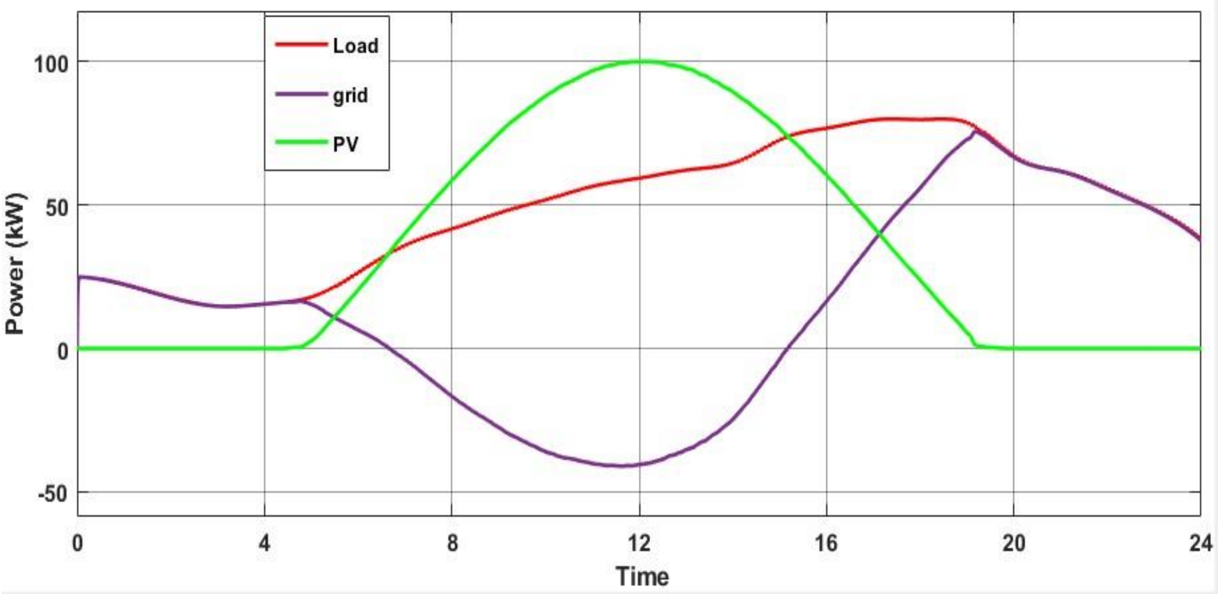

Figure 4-8 Load is supplemented by a renewable energy source (PV) with the main grid

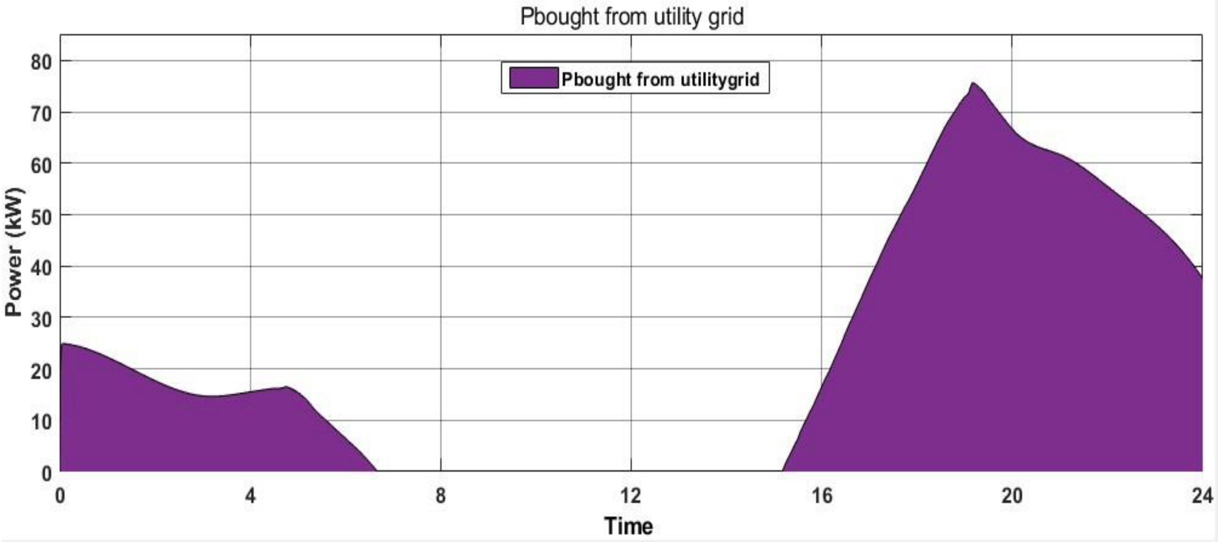

Figure 4-9 The amount of power taken from the grid after the installation of PV

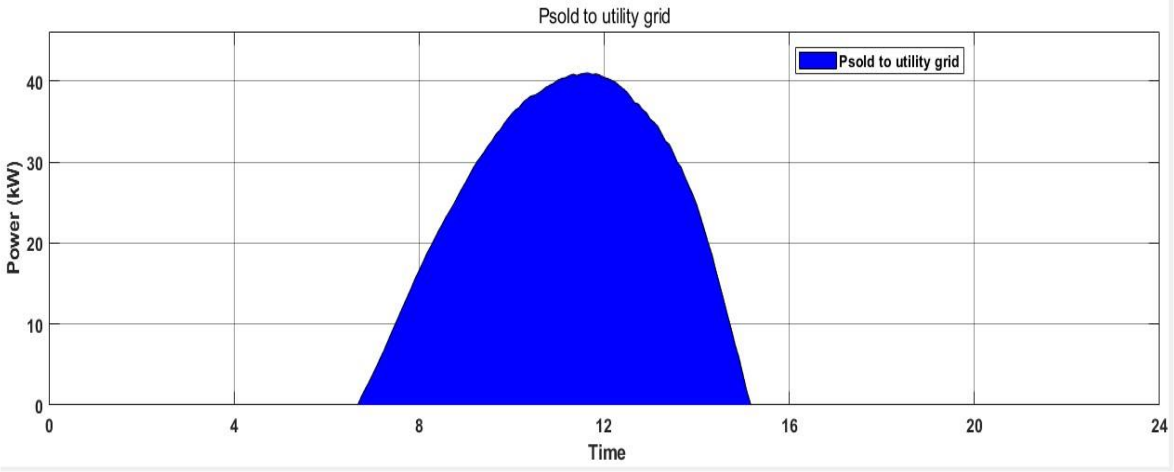

Figure 4-10 Surplus power sent back to the main grid.

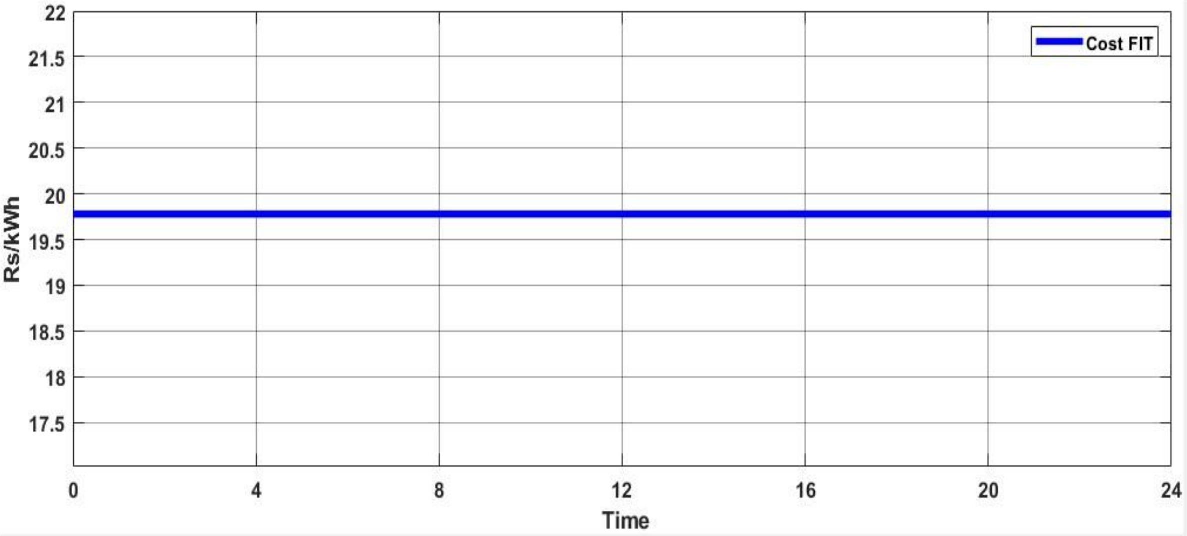

Figure 4-11 Feed-in tariff cost at which energy is sent back to the grid.

Table 4-2 Microgrid Billing for Energy Imports and Exports with the Main Grid

Case 1	Import Energy (kWh)	Import Bill (PKR)	Export Energy (kWh)	Export Bill (PKR)
Microgrid	539.3	21800	228.1	4512

4.4 Case 2: Integration of PV source and Wind Power

In Case 2, the microgrid load is satisfied by utilizing multiple sources of power, including the main grid as well as renewable energy sources like solar panels (PV) and wind turbines, as presented in **Figure 4.8**. The inclusion of various energy sources in the microgrid not only increases its overall capacity but also strengthens its ability to withstand disruptions and decreases reliance on centralized grid infrastructure.

By incorporating both solar and wind power, the microgrid's energy generating capabilities are enhanced with additional levels of redundancy. Solar panels utilize sunlight to generate electricity, while wind turbines absorb kinetic energy from the wind, therefore adding to the energy supply of the microgrid. The use of multiple sources reduces the chances of supply interruptions that may arise from individual energy generating system, as variations in weather conditions might impact each source differently.

When the total production of renewable energy sources exceeds the immediate energy needs of the microgrid, any excess electricity is sent back into the main power grid. The bidirectional flow of energy not only maximizes the efficient use of resources but also promotes a mutually beneficial interaction between the microgrid and the main power grid, as depicted in **Figure 4.12 and Figure 4.13.** Case 2 has a significant benefit in its ability to enhance the microgrid's resilience. Through the process of diversifying energy sources, the microgrid reduces its vulnerability to individual points of failure and enhances its ability to sustain interruptions caused by environmental variables, equipment problems, or grid disturbances. Moreover, the incorporation of renewable energy technology is in line with sustainability goals, since it decreases carbon emissions and minimizes environmental harm.

The incorporation of renewable energy sources is leading to decreased energy costs, as demonstrated in **Table 4.3**. In addition, Case 2 represents a progressive strategy for decentralization and energy sufficiency. The microgrid improves the reliability of electricity and encourages local economic growth by reducing its need on long-distance transmission infrastructure and centralized power plants by utilizing locally available renewable resources.

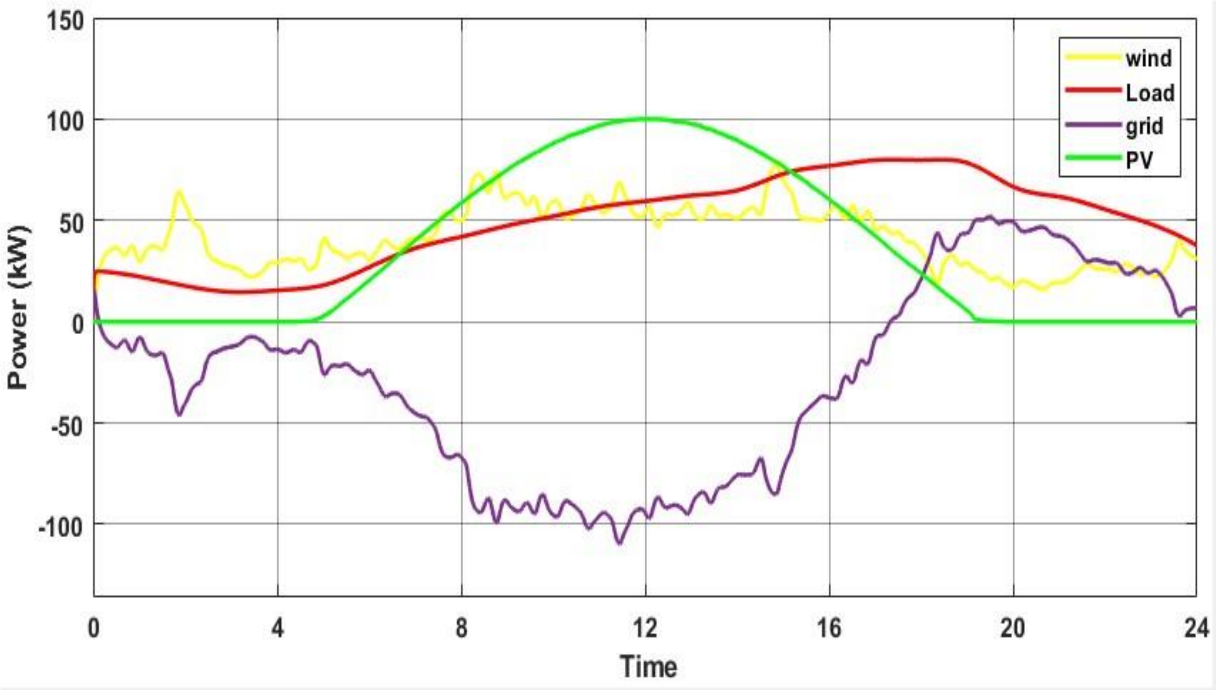

Figure 4-12 Load is supplemented by renewable energy sources (PV and wind) with the main grid

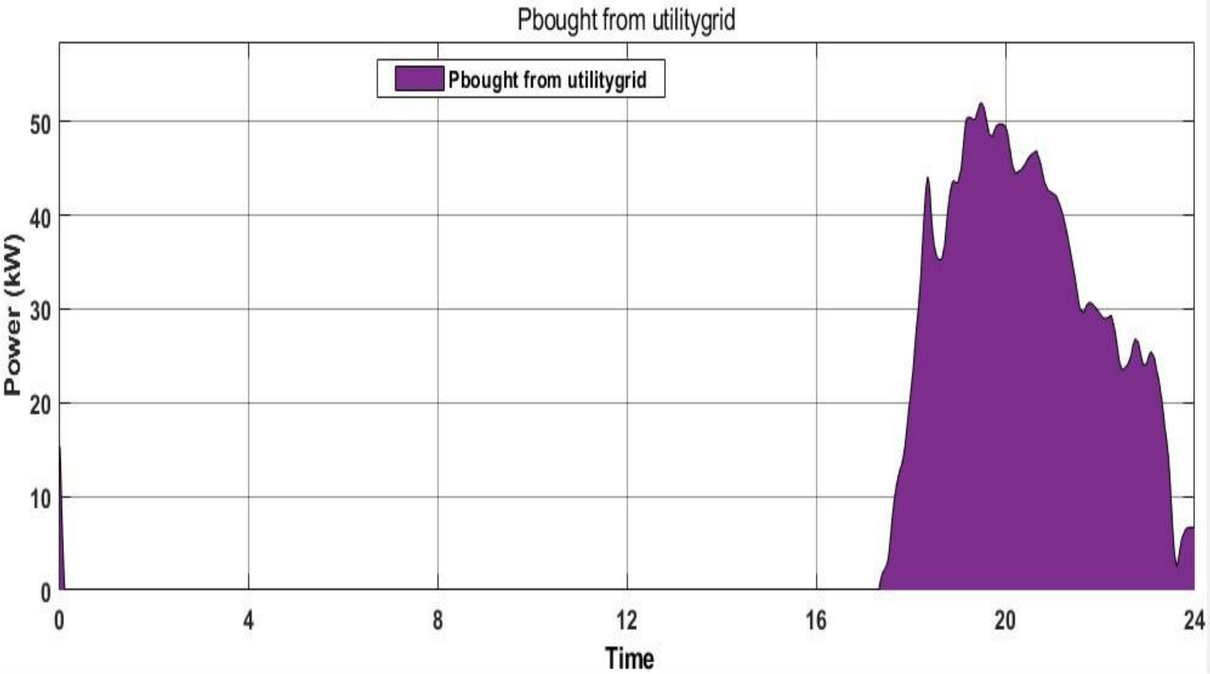

Figure 4-13 The amount of power taken from the main grid.

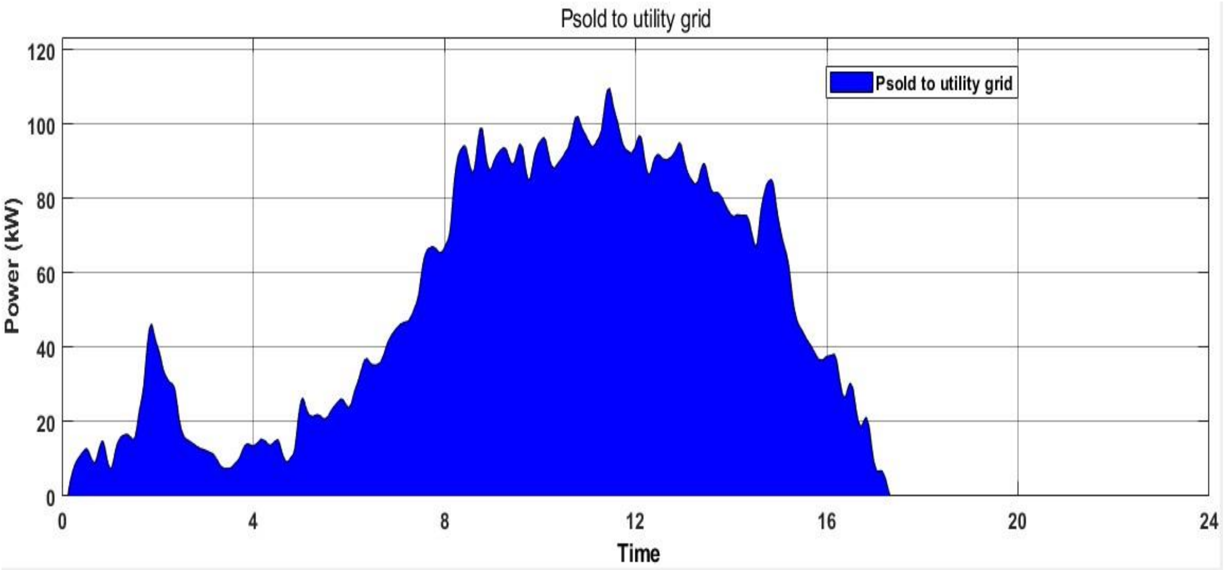

Figure 4-14 The amount of power sent back to the main grid.

Table 4-3Community Microgrid Billing for Energy Imports and Exports from the Grid

Case 2	Import Energy (kWh)	Import Bill (PKR)	Export Energy (kWh)	Export Bill (PKR)
Microgrid	212.8	8895	895.8	17720

4.6 Case 3: Multi-Source Generation with PV, Wind, and Diesel.

In Case 3, the microgrid fulfils its energy needs by utilizing a hybrid approach that combines renewable energy sources such as solar panels (PV) and wind turbine with a backup generator, often fuelled by diesel, as shown in **Figure 4.11**. This integrated system mitigates the intermittent nature of renewable energy generation and guarantees uninterrupted electricity provision to the microgrid, especially during periods of reduced solar radiation or wind velocities.

Renewable energy sources, such as photovoltaic (PV) and wind power, enhance the energy composition of the microgrid by utilizing natural resources to produce electricity. Solar panels use solar radiation to generate electricity, while wind turbines harness the kinetic energy of the wind, so enabling the production of sustainable and eco-friendly power. On the other hand, dealing with fluctuation seems to be the other problem that might affect the reliability of the main source of the microgrid. The variability can be minimized by shifting the demand during unfavourable weather conditions or the night sections can be reduced as illustrated in **Figure 4.12**. The intermittent nature of renewable energy is further addressed by additional resources, such as the diesel generator is used as a reliable substitute power supply in case 3. Diesel generators are excellent for meeting extra power needs and addressing poor renewable energy generation. They can quickly raise their output to help the microgrid manage momentary spikes in energy usage, making them a versatile and stable power source.

With the incorporation of diesel generator, the microgrid is bolstered in its resilience to survive and fulfil its power provision mandate even under difficult circumstances or lack of renewable energy sources, especially for a prolonged period. The backup plan ensures that critical services remain operational.

Furthermore, Case 3 maintains the capacity to generate surplus power that surpasses the present energy demands of the microgrid. The excess energy generated by renewable sources, or the backup generator is sent back to the main power grid, as depicted in **Figure 4.15**, adding to the overall energy supply and potentially resulting in economic benefits for the microgrid operator through feed-in tariff, while **Figure 4.16** and **4.17** shows energy import/export to grid as illustrated in **Table 4.4**.

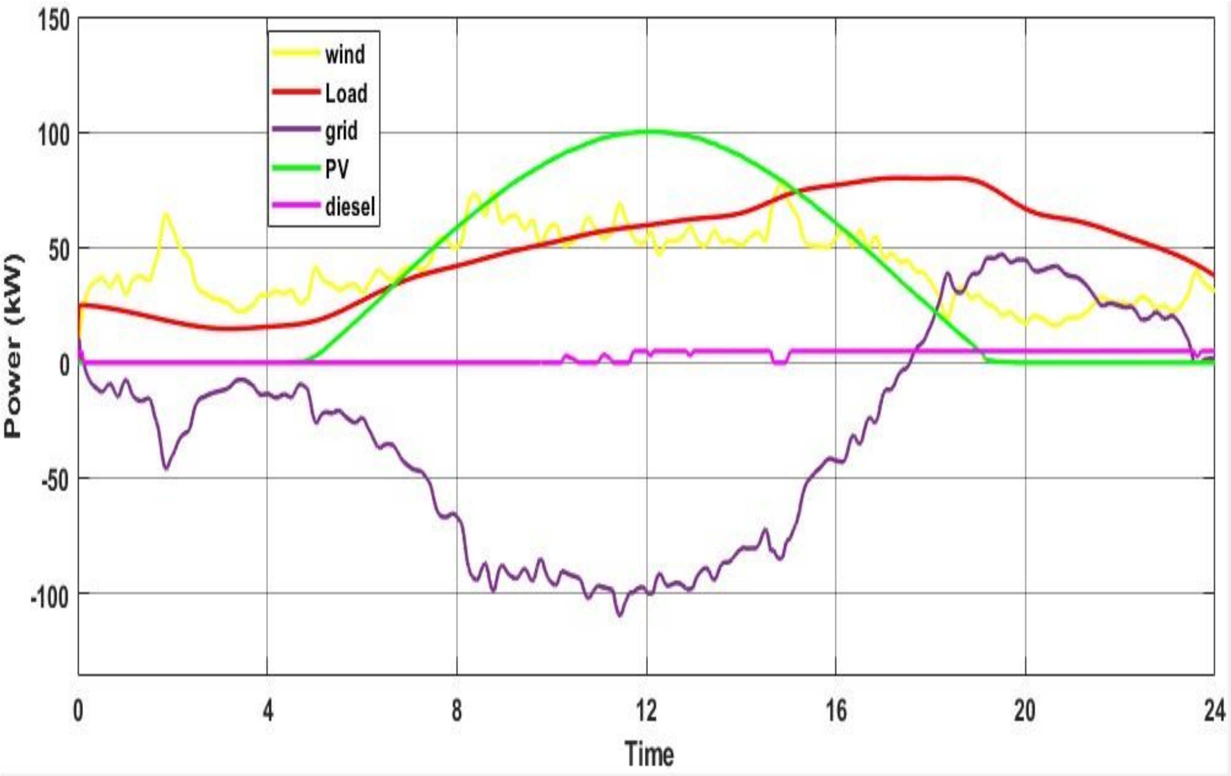

Figure 4-15 Hybrid approach that combines renewable energy sources (PV and wind turbine) with a backup generator

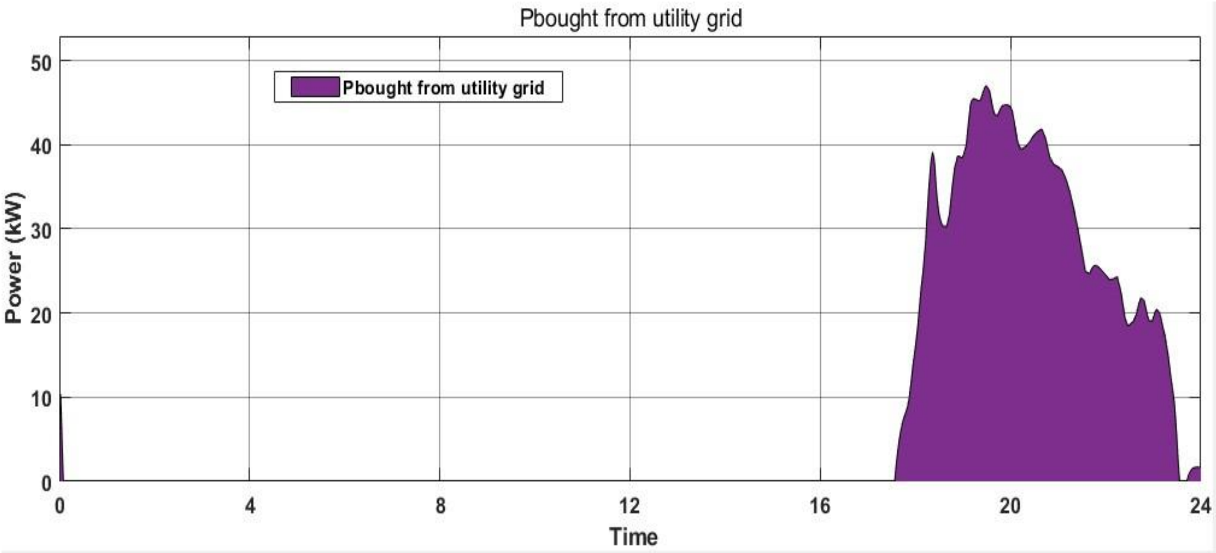

Figure 4-16 The amount of power taken from the main grid after the incorporation of hybrid resources

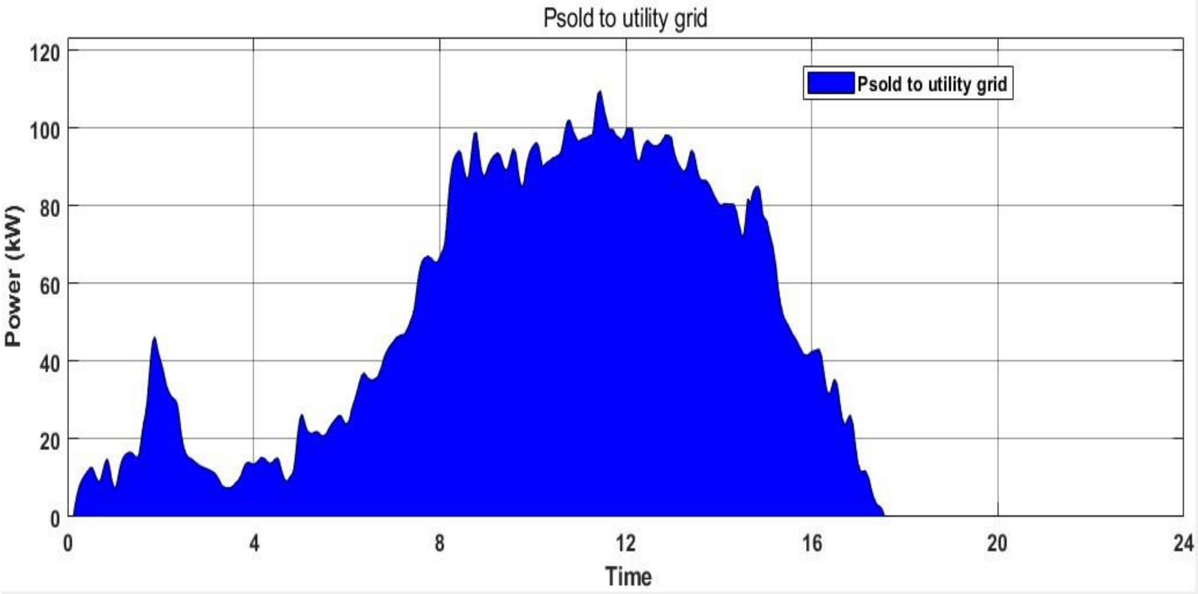

Figure 4-17 The amount of power sent back to the main grid after the incorporation of hybrid resources

Table 4-4 Microgrid Billing for Energy Imports and Exports from the Grid

Case 3	Import Energy (kWh)	Import Bill (PKR)	Export Energy (kWh)	Export Bill (PKR)
Microgrid	179.8	7527	924	18280

4.7 Case 4: Multi-Source Generation with DSM Integration

In Case 4, the configuration is identical to Case 3, where the microgrid's energy demand is met by photovoltaic (PV) panels, wind turbines, diesel generators, and the main power grid. The integration of Demand side management technique is presented along with the distributed energy resources in the **Figure 4.18**.

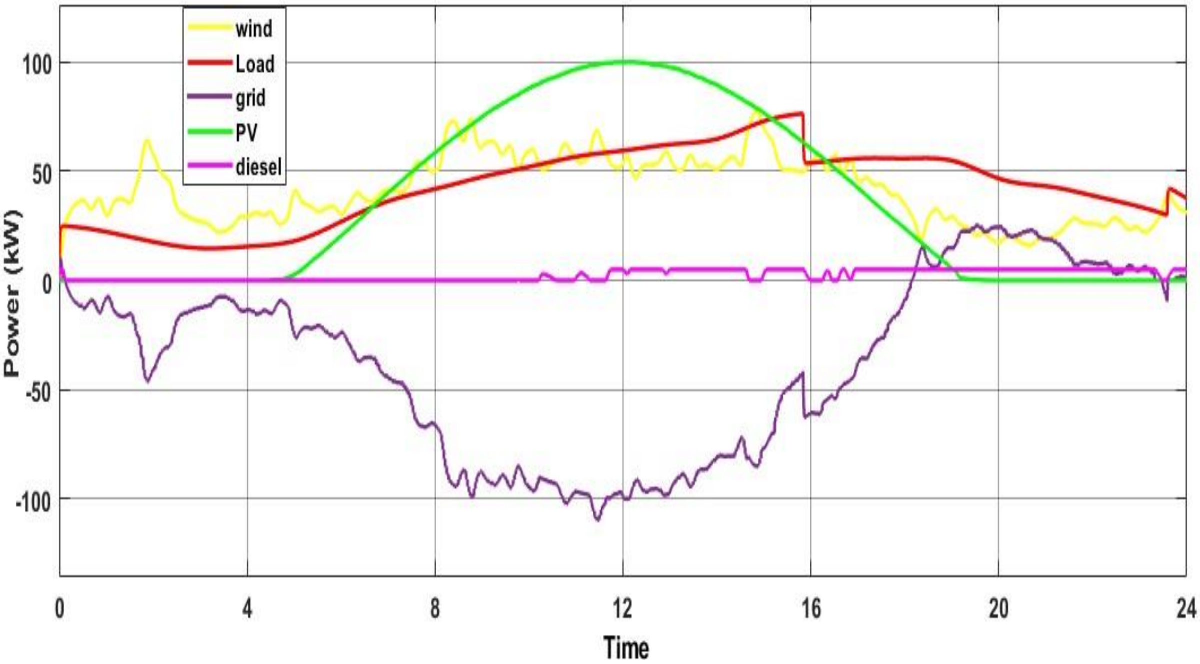

Figure 4-18 Load supplemented by renewables (PV, wind) and main grid with DSM integration

DSM, or Demand Side Management, is a strategic approach employed to regulate and enhance energy usage in a microgrid. The main objective of DSM is to mitigate peak demand, which corresponds to periods of maximum electricity consumption. Peak demand can be managed fairly and transmitted at a lower expense by microgrid operators, greatly reducing the necessity for high-cost peak power generation and allow the grid to respond more effectively with peak demand magnitude. The identification and classification of non-essential load are among the most important aspects of DSM in microgrid. Non-essential loads are all devices, appliances, or machinery and processes that can be readily deactivated, or their power usage reduced without adversely affecting operations or comfort. Automatic or manual DSM systems employ load shedding at peak load times. Load shedding is a term that refers to the temporary non-usage of the non-essential load.

Using DSM, microgrid operators can gain the following benefits:

Cost savings: microgrid operators can reduce the amount of their peak load, which allows them to reduce or avoid expensive peak load charges that electricity providers charge, as shown in **Figure 4.19**. Moreover, energy optimization can lead to the reduction of total electricity costs, for example, as seen in **Table 4.5**.

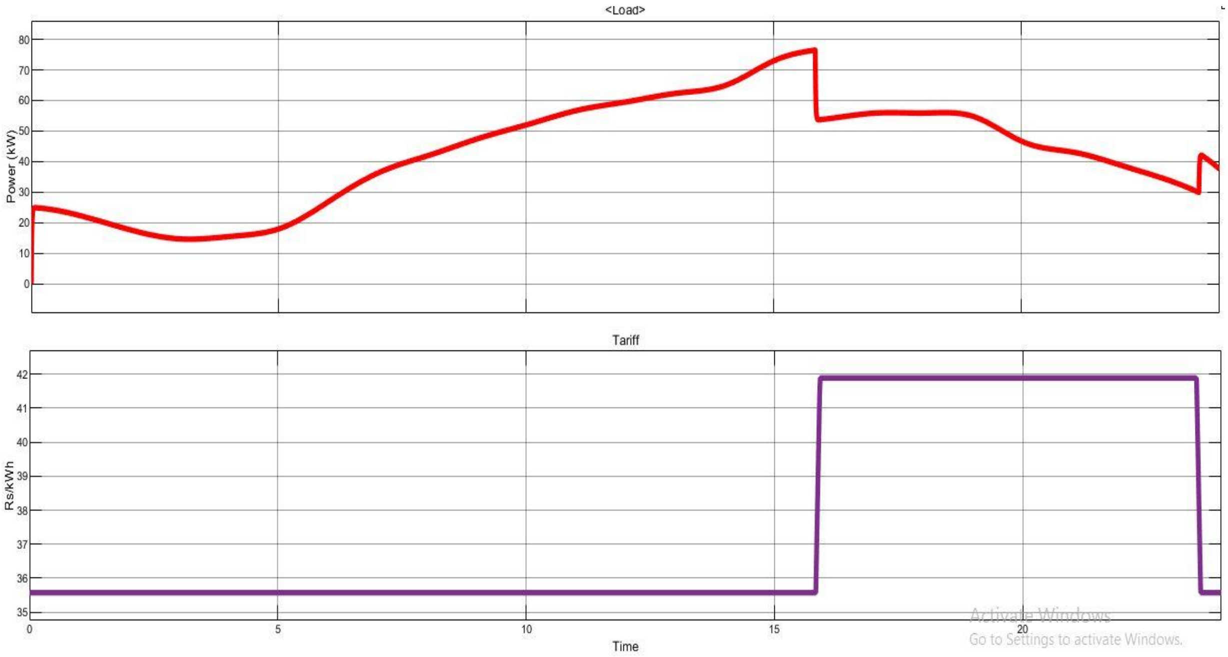

Figure 4-19 non-essential load is being clipped off during peak demand tariff.

DSM reduces stress on the system when the grid is under the heaviest demand contributes to grid stability and reliability. By reducing the use of transmission and distribution systems, it reduces stress on these systems, which reduces the likelihood that aging infrastructure will fail, leading to either large-scale power outages or voltage decreases.

DSM can benefit the environment by eliminating the need for peaking plants that depend on fossil fuels. Greenhouse gas emissions can be decreased by improving energy utilization and increasing reliance on renewable energy sources in the microgrid. DSM promotes enhanced energy efficiency by encouraging the more efficient utilization of energy resources within the microgrid, resulting in overall gains in energy efficiency. This not only minimizes energy inefficiency but also prolongs the durability of equipment and decreases maintenance costs. Reducing grid dependency is resulting in grid cost, it is illustrated in **Table 4.5.**

In the local energy market environment, prosumers can not only generate their own power but also actively participate in the electrical market. Consumers have the opportunity to generate revenue from their surplus energy production by means of net metering and feed-in tariff scheme, which enable them to either sell it back to the grid or get reward for their contributions to the total energy supply. The amount of power taken from the grid by the microgrid is further reduced as compared to previous cases after the implementation of DSM technique, as shown in **Figure 4.20**. The amount of power sent back to the grid from the microgrid after the implementation of DSM approach, as shown in **Figure 4.21**.

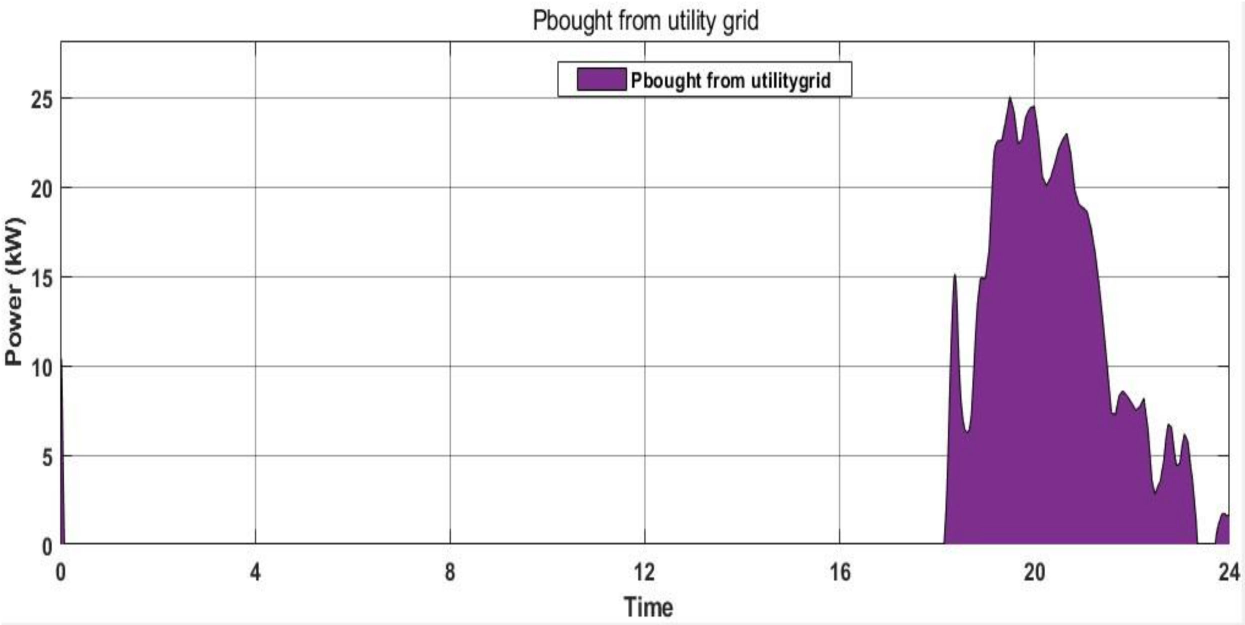

Figure 4-20 The amount of power taken from the grid after the implementation of DSM technique.

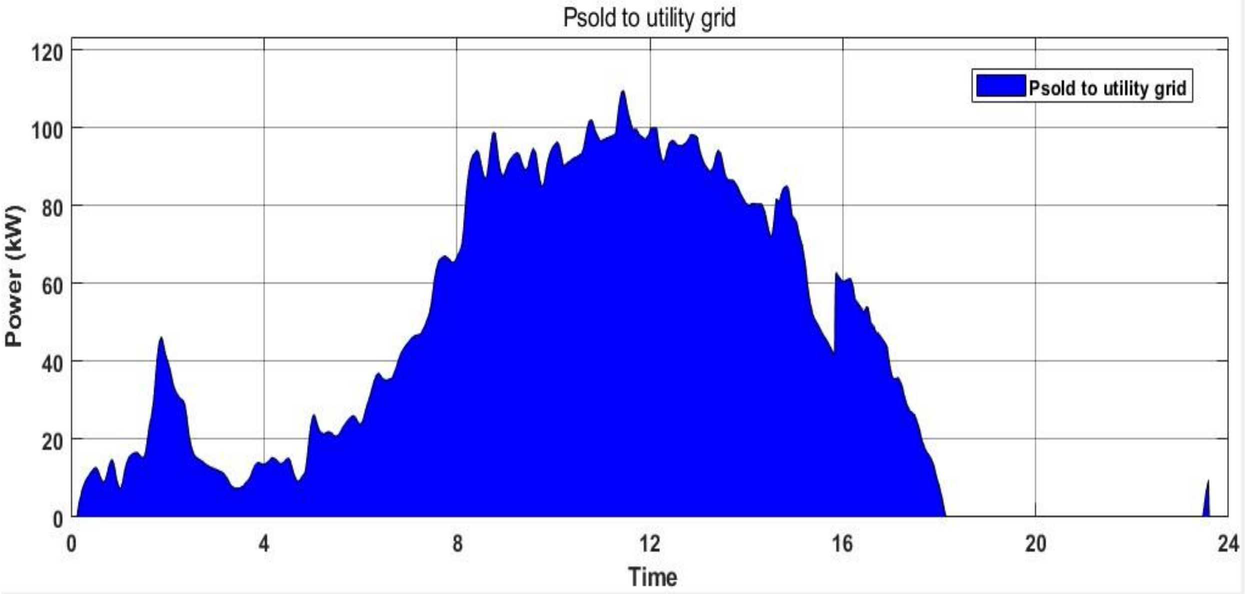

Figure 4-21 The amount of power sent back to the grid after the implementation of DSM approach

Table 4-5 Microgrid Billing for Energy Imports and Exports After DSM Implementation

Case 4	Import Energy (kWh)	Import Bill (PKR)	Export Energy (kWh)	Export Bill (PKR)
Microgrid	72.23	3020	969.3	19170

4.8 Case 5: Local energy market system

In case 5 the essential role in supporting cost savings for customers by enabling the import and export procedures of electricity. Within the framework of a local energy market, consumers are provided with the chance to engage in the electrical market by autonomously generating their own electricity through the utilization of hybrid sources, such as solar photovoltaic (PV) system, wind energy conversion system and diesel generator. The process of decentralizing power generation enables customers to assume authority over their energy production and consumption, thereby fostering a more robust and environmentally friendly energy infrastructure. Consumers that engage in the implementation of renewable energy technology, such as rooftop solar panels and wind energy conversion system, have the capacity to create electricity on their premises, thereby potentially surpassing their energy use during specific time intervals, particularly when sunlight and the wind speed is plentiful. These people can profit from their extra energy output through feed-in tariff scheme or net metering in the local energy market system. Net metering enables consumers to reduce their overall electricity bills by utilizing the surplus energy they generate to offset their electricity consumption.

An important advantage of participating in the production of renewable energy is the chance to take part in net metering programs. Net metering allows consumers to reduce their electricity costs by selling any surplus power produced by their solar PV system and wind energy conversion system to the main power grid. The excess energy is effectively allocated to their accounts, enabling them to generate revenue or obtain credits for subsequent energy usage. These incentives not only encourage the use of renewable energy resources, but also make the energy industry more accessible to a wider range of people by allowing them to become prosumers, meaning they can both use and produce electricity. **Figure 4-22** shows the solar PV production for 24 hours.

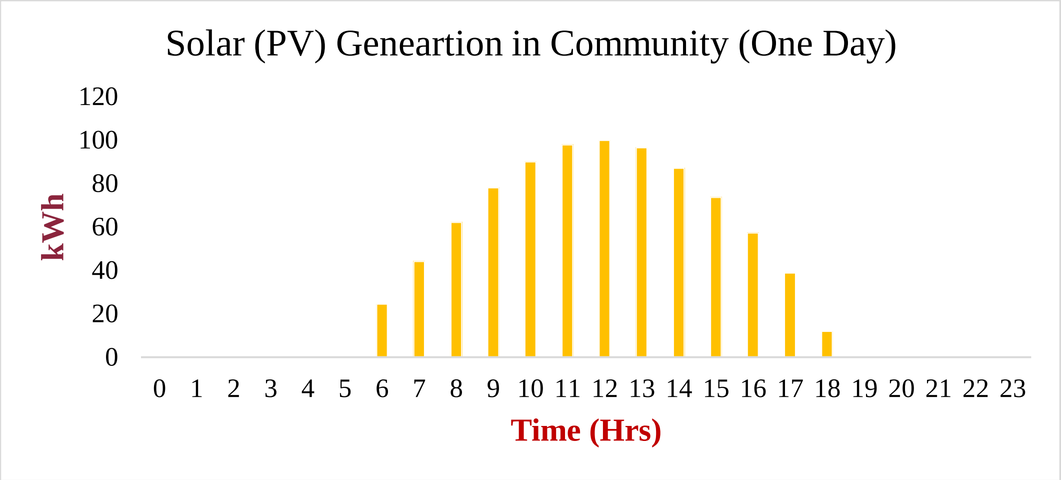

Figure 4-22 Daily PV energy generation

Figure 4-23 giving the community daily energy demand and supply including the community market energy trading between consumers with communal area.

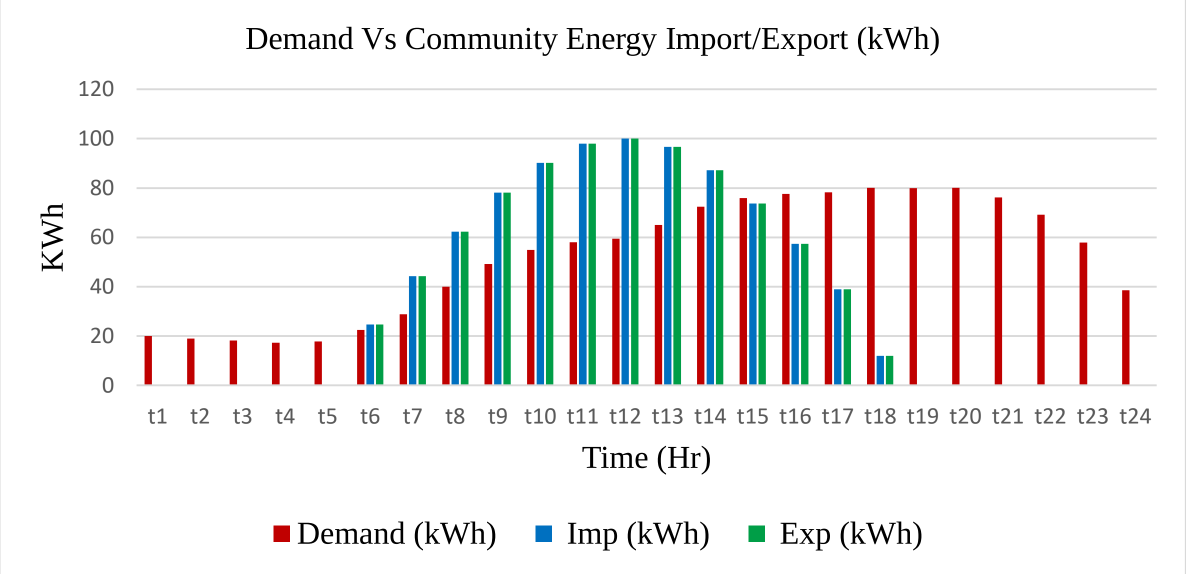

Figure 4-23 Community daily demand and energy import/export

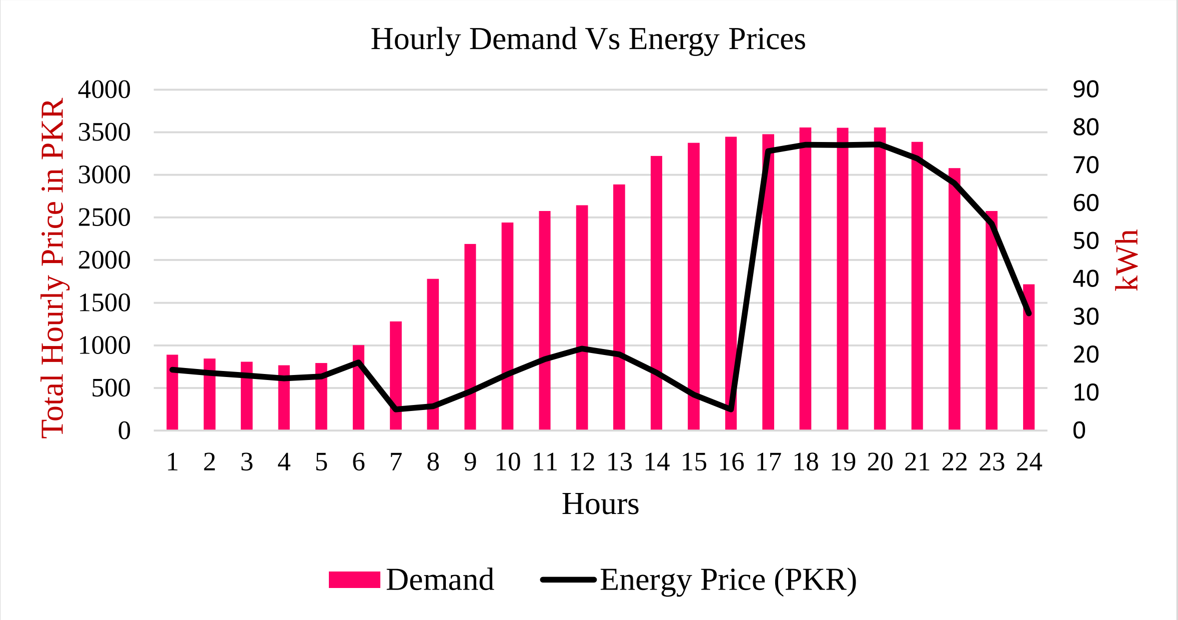

Figure 4-24 Community hourly demand vs intra-market cost

Figure 4-24 shows daily variations in electricity tariff within community, average price of electricity is Rs.9.75 per kWh when PV is suppling energy from 07:00 to 16:00 hours.

Figure 4-25 shows the LEMS optimized results of hourly energy price reduction with PV energy.

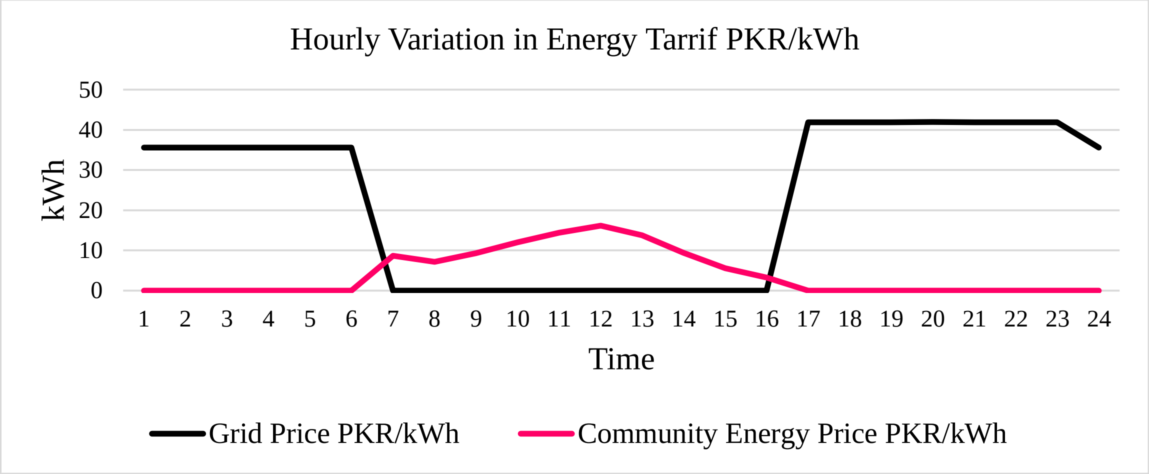

Figure 4-25 Hourly energy cost variations in LEMS

Figure 4-26 depicts total electricity exchange between community and grid for one day, the negative part shows electricity is imported from grid, while surplus is exported to grid details are listed in Table 5-6.

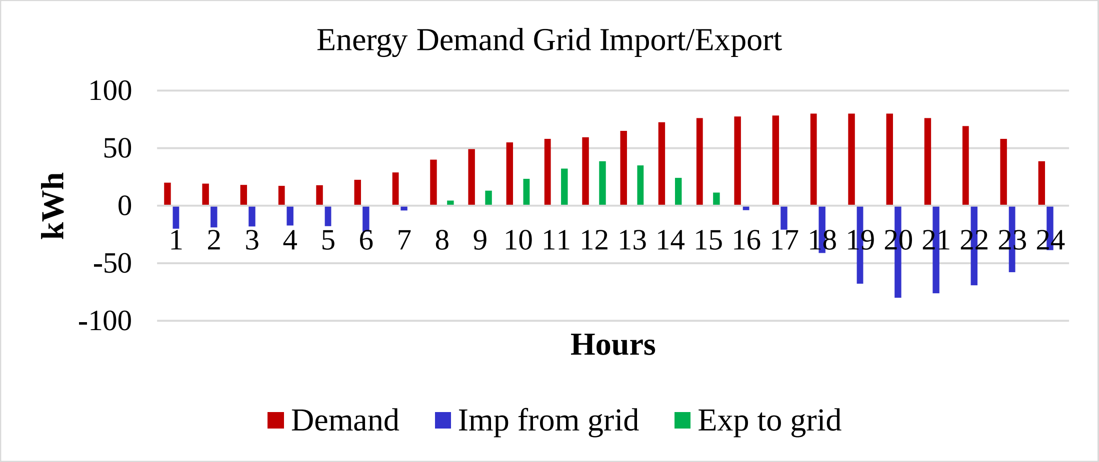

Figure 4-26 Energy import and export from the community and grid

Table 4-6 Daily Energy Import/Export in LEMS

Total Demand (kWh)	Total RE Generation (kWh)	Energy Imp/Exp from Community (kWh)	Energy Export to Grid (kWh)	Energy Imp from Grid (kWh)
1188	863.76	681.87	181.88	324.24

4.9 Comparative analysis

Reducing grid dependency is resulting in grid cost in the respective cases, it is illustrated in **Table 4.7.**

Table 4-7 Analysing the five scenarios of billing for energy import and export by the microgrid from grid

Cases	Units imported (kWh)	Import Bills (PKR)	Cost Reduction (PKR)	Percentage Saving
Base case	1188	45540	-	-
Case 1	539.3	21800	23740	52.13
Case 2	212.8	8895	36645	80.47
Case 3	179.8	7527	38013	83.477
Case 4	72.23	3020	42520	93.37
Case 5	334.60	16210	29330	64.40

4.10 Analysis of power tariff in LEMS neglecting capacity payments.

Overall, capacity payments to power producers specially for net-metering consumers are essential for encouraging renewable energy use, maintaining a stable power grid, and giving consumers a financial reason to invest in clean energy technologies, however current payments in gave rise to general power price up to Rs. 18/kWh, implementation of community energy market resulted in less grid import as well as zero CP to energy tariff. Table 4.8 gives the percentage saving in term of capacity payments,

Table 4-8 Impact of Capacity Payment in LEMS

Cases	Electricity (kWh)	Total Electricity Price Rs.	Capacity Payment (Rs 18 /kWh)	CP in Total (%)
Base case	1188	45540	21238	47.3
Case 1	539.3	21800	9707	21.2
Case 5	324.24	16210	5836	12.8

Total of 87.2% amount can be saved by trading 681.87 kWh per day using LEMS.

4.11 Environmental benefits

The incorporation of renewable energy technology is in line with sustainability goals, since it decreases carbon emissions and minimizes environmental harm, the grid emission factor is 0.4780.478 (kgCO_2/kWh) as illustrated in **Table4.9.**

Table 4-9 Grid Emissions Reduction per Day

Cases	Energy (kWh)	CO_2 Emission 0.478 (kgCO_2/kWh)	Emission reduction (%)
Base case	1188	567.864	0
Case 1	539.3	257.78	54.60
Case 2	212.8	101.71	82.18
Case 3	179.8 + 61.15(DG)	115.174	79.71
Case 4	72.23+56.23(DG)	128.46	77.42
Case 5	324.24	154.99	72.70

Chapter 5: Discussion and Conclusion

The analysis of multiple scenarios highlights the essential significance that microgrid systems have in defining the future of energy delivery. In the face of global concerns such as climate change, energy security, and economic sustainability, microgrids present themselves as a feasible solution that provides resilience, flexibility, and sustainability. In the base case, scenario that clearly demonstrates the vulnerabilities that arise from reliance on a centralised electric power system. The expensive utilisation of the power grid and the excessive daily power cost is around Rs.45540 for 1188 kWhs and release 567.864 kgs of CO2 emissions from conventional power generation techniques indicate the urgent need for the implementation of alternative energy sources.

However, the Case 1 analysis reveals an advantageous scheme. Solar panel installation will reduce the microgrid's reliance on the national grid. This not only reduces energy consumption costs but also represents a significant advancement in the battle by reducing cost of energy Rs. 23740 saving 52.13% and 257.78 kgs carbon emissions. Solar power operates as the foundation for a more sustainable energy framework by harnessing the sun's plentiful energy to generate environmental and economic advantages. In the base scenario, the microgrid's entire dependence on the main grid leads to increased costs and a substantial carbon footprint because of this reliance on the grid. However, the amount of grid reliance and carbon emission is significantly reduced to 54.60% after the installation of solar panels.

Case 2 demonstrates the self-reliance of the microgrid due to the integration of solar panels and wind turbines. Integrating supplementary energy sources will enhance the reliability of the grid and reduces the import to 212.8 kWh and cost only Rs. 8895 but due high capital cost of wind energy system cost of energy is around Rs. 64 per kWh when excluding govt subsidy CoE is very high, so integration of wind power system is not feasible solution in this case, but green energy gives 82.18% decrease in greenhouse gas emissions. In Case 3, the integration of a diesel generator with the pre-existing solar cells and wind turbines results in a significant decrease in grid imported energy up to 179.8 kWh having cost Rs. 7527, making microgrid more environmentally friendly by decreasing 79.71% CO_2 emissions and substantial decrease in reliance on the main grid but cost of energy is very high as compare PV so case three is not feasible. Case 4 demonstrated the adaptability of microgrid in achieving sustainability objectives through the integration of demand-side management (DSM) method. The microgrid achieved a reduction in its reliance on the main grid by efficiently managing energy usage and actively decreasing non-essential load. By implementing this comprehensive strategy for energy management, total conventional energy supply reduced to 72.23 kWh from grid and 56.23 kWh from backup DG, saving 93.7 % energy bills and carbon emissions decreased significantly by 77.42%. Introducing DSM as the crucial solution for achieving greater energy efficiency and sustainability. Even though there has been a slight rise in emissions from diesel generation, the overall impact is still much better than the base case scenario.

Given the increased installation of DERs and the growing number of prosumers, LEMS are seen as a promising step in the future energy environment. This study developed a revolutionary LEMS structure that was aimed to reduce total costs in the energy market. The case 5 compares the proposed LEMS structure with a scenario where market participants trade only with the upstream grid and with in community. It highlights the benefits of LEMS in cost optimization and improved local energy trading.

Key findings include:

- **72.70 % Reduction in Exported Energy**: The LEMS allows for efficient use of locally generated energy 681.87 kWh inside community which is 57.39%, reducing the need to export surplus electricity only 181.88 kWh with 15.31%, allowing govt to reduce the grid tariff by minimizing capacity payments to prosumers.
- **27.30 % Grid Imported Energy**: The LEMS facilitates effective energy exchange within the community, minimizing reliance on external sources, by 324.23kWh.
- **87.2 % Savings in Capacity Payments:** LEMS Minimized the energy price by avoiding capacity payments to grid.

These results demonstrate that LEMS can enhance local energy utilization, supporting a more efficient and sustainable energy market. The findings further highlight the major benefits of the LEMS method in increasing energy self-sufficiency and lowering energy export and import reliance on the grid, only capacity payment portion of cost of electricity is 12.8% and saving 87.2%. By allowing communities to exchange energy inside their own network, energy saving is 64.4 % with 70.72% CO_2 declined. So, LEMS promotes a more sustainable and resilient energy ecosystem that benefits both market actors and the overall energy environment achieving the objectives.

Future research using DREs inside community promises significant advancements in energy efficiency and sustainability. Building on this study, future work can explore various design configurations and integration strategies, including DSM time scheduling, particular load shifting, further examining the impact of adding PV solar systems, both with and without energy storage, and experimenting with different solar technologies, biomass and wind turbine placements in small wind corridors. Additionally, conducting life cycle assessments and environmental impact studies will provide valuable insights into the overall sustainability and potential for reducing carbon footprints.

Acknowledgment:

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