ENERGY AND CLIMATE PANORAMA

CLIMATE RESILIENT SMART GRID AND HYBRID RENEWABLE ENERGY SYSTEMS

U.S.-Pakistan Center for Advanced Studies in Energy

ABOUT US

Who we are

We are a dedicated team of researchers and experts who recognize the urgent need for action in addressing climate resilience and energy transition in Pakistan. Our mission is to develop and implement effective policies for cleaner, renewable energy sources like solar and wind, aligning with Pakistan's 2030 goal of 30% renewable energy in its electricity mix. As a multidisciplinary team, we leverage expertise in three key disciplines of study—Energy Systems Engineering, Thermal Energy Engineering, and Electrical Power Engineering—to drive our mission forward. We are united by a shared vision of creating a sustainable and resilient future for Pakistan, where cleaner energy sources play a pivotal role in reducing the nation's vulnerability to climate-related challenges.

What we do

We conduct in-depth, evidence-based research to analyze and improve energy policies in Pakistan. Our focus is on advancing renewable energy solutions and engaging stakeholders to ensure effective policy implementation. Our methodology involves a critical examination of current energy policies to pinpoint areas of improvement and formulate strategies for the widespread adoption of renewable energy sources across various levels.

In line with our commitment to fostering sustainable practices, we have established a fellowship program as part of our broader initiatives that aims to facilitate evidence-based research for promoting energy transition in Pakistan. Through research studies, surveys, and forecasting, we plan to assess various aspects of energy transition, including the adoption of renewable energy technologies and their impact on climate change. Our approach involves active engagement with stakeholders to address their concerns and facilitate the effective implementation of policies, fostering the growth of renewable energy manufacturing and marketing facilities.

CONTACT US

Industry Liaison & Outreach Office

Bilal Mehmood Bhutta
Phone: +92-51-90855274
Fax: +92-51-90851302
Email: ilo@uspcase.nust.edu.pk
USPCAS-E Building, National University of Sciences & Technology, H-12, Islamabad.

PRIMARY CONTRIBUTORS

DR. SYED ALI ABBAS KAZMI
PRINCIPAL INVERSTIGATOR
Associate Professor

ABDUL HASEEB SAJID
RESEARCH ASSISTANT
MS in Electrical Engineering (Power)

MUHAMMAD MUSTAFA AMJAD
PROGRAM DIRECTOR
Renewables First

LAYOUT DESIGN

ABDUL REHMAN
RESEARCH ASSISTANT
MS in Thermal Energy Engineering

FATIMAH ARSHAD
RESEARCH ASSISTANT
MS in Thermal Energy Engineering

SEHAR BOKHARI
RESEARCH ASSISTANT
MS in Energy System Engineering

Table Of Content

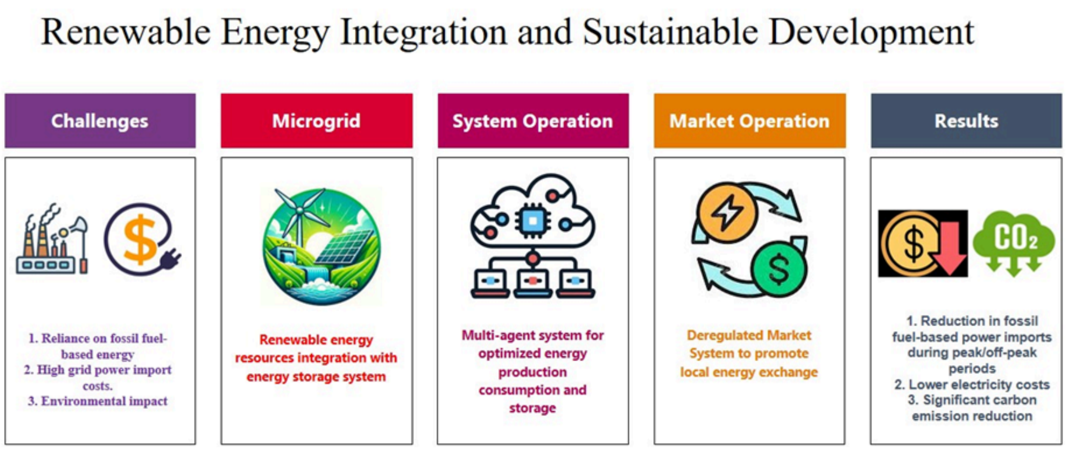
Table Of Content

Executive Summary

This study focuses on the major issues of the energy sector of Pakistan such as the over reliance on fossil fuel-based power, increasing cost of electricity, and environmental concerns. Thus, the integration of RES including solar and wind power into microgrids and the use of energy storage system to enhance the generation, consumption, and trading of electricity to improve the reliability and sustainability of the power system. The study presents the comprehensive approach to address these issues by leveraging multi-agent system for optimized system operations through demand side management approach and optimized energy storage scheduling to decrease the reliance on fossil fuel-based power generation during peak tariff period, which in turn will help to reduce the electricity grid expenses for consumers within the microgrids and Pakistan's environmental sustainability goals. Furthermore, the study focuses on the importance of fostering the deregulated energy market, where microgrids can purchase and sell renewable energy in the most efficient manner and at the lowest cost possible. This shift not only improves the local energy trading but also promotes the development of Pakistan's power sector and supports the country's overall economic and environmental objectives.

Besides, the study contributes to improve energy efficiency and self-sufficiency and has a positive impact on the environment by minimizing carbon emissions. This align with Pakistan's commitments to global climate goals and Sustainable Development Goals (SDGs), including the SDG 7, SDG 9, and SDG 11, by encouraging innovation in energy systems, enhancing sustainable community development, and minimizing the environmental impact of power generation.

The study provides a roadmap for Pakistan to shift towards a sustainable, reliable and low-cost energy system through the integration of renewable energy, demand side management, energy storage system, and deregulated energy market structure. This approach greatly helps in decreasing the dependency on the fossil fuels and promoting the sustainable development of Pakistan.



Abstract

This study provides a detailed framework for the improvement of microgrid performance and energy management in the context of Pakistan's electricity sector. The study employs MATLAB Simulink to create dynamic models of microgrid components including renewable energy sources like solar panels and wind turbines, battery energy storage systems and load profiles. The study incorporates a multi-agent system to manage energy production, consumption and storage efficiently, with a focus on utilizing locally produced renewable energy to minimize dependence on the main grid and lower electricity costs. The adoption of a deregulated market system enables competitive energy trading, which is vital in addressing key problems in the Pakistan power sector including generation capacity, fossil fuel dependency, and circular debt. This framework allows microgrids to participate in bilateral contracts and trade energy based on market clearing prices, thus promoting the integration of renewable energy projects and decreasing reliance on conventional, carbon-intensive power generation. The study also shows how microgrids can achieve the highest level of profitability by selling excess energy at the market clearing price to adjacent microgrid and buying energy from renewable sources cheaper than from the utility grid. The results indicate that the proposed approach results in a reduction of the power import from the main grid and CO_2 emissions in all the scenarios. In off-peak hours, Case 2 is able to attain a 42.73% reduction in energy imports, Case 3 achieves 38.69%, and Case 4 achieves 38.92%. During peak hours, Case 4 has minimized the importation of power by 70.3%. It significantly lowers carbon emissions by 70.3% during peak periods, contributing to reduce the impact on the environment. These findings demonstrate how optimized energy management can help decrease the use of fossil fuels and decrease carbon emissions, thus supporting SDG 7 on affordable, reliable, sustainable, and clean energy in Pakistan's power sector. This study also plays a major role in the achievement of SDG 9 and SDG 11 by encouraging innovation in microgrid technology and sustainable development. The findings of this study are useful in understanding the prospects of transforming the Pakistan's energy landscape through proper energy management and enabling competitive energy market structure, microgrids present a viable solution to enhance the reliability and efficiency of the power sector in Pakistan.

1.Introduction

1.1 Background and research motivation

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 27303MWs. To cover the demand total current installed power capacity is around 43,728 MWs. Figure 1.2 depicts the total power sources and their share in nation power. According to system operator NTDC (National Transmission and dispatch company), the major generation source is thermal power (coal, oil and gas) contributes 61%, hydel power is 24% followed by nuclear 8%, the only input of renewable energy to national grid is 6% which is very small.

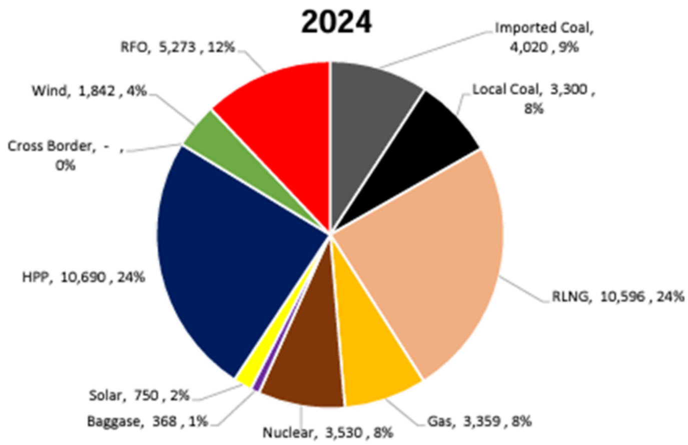


Figure 1.1. *The total power sources and their share in nation power [5].*

In recent years, energy generation 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.

1.2 Meeting demand and ensuring reliability

The main objective of microgrids is to meet three essential criteria: providing the necessary amount of electricity precisely when needed, while also guaranteeing a reliable and consistent supply of power and facilitating efficient interaction between energy supplier and consumers. For meeting the diverse energy demand from residential and industrial sector, microgrid system is crucial in ensuring stability in the global economy and sustainability of the environment.

1.3 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.

1.4 Enhancing Energy Solutions by Utilising Multi-Microgrid system

An optimal approach would involve implementing a cluster arrangement of microgrids, comprising of renewable energy sources such as wind and solar along with battery energy storage system. 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 of time 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.

1.5 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 [6]. 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.

1.6 Reducing expenses and managing the ratio of peak demand to average demand

The lowering of the consumption costs and PAR critically depend on the accessibility of RTP information [7]. 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 [8].

1.7 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 [9]. 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 battery energy storage system is suitable to reduce intermittency [10]. 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 [11].

1.8 The Benefits of Microgrid in Upgraded Power System

In the modern power system, Microgrids has a lot of advantages over the conventional grid infrastructure. 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 [12]. 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 [13]. Multi-Microgrid system 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 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 [14] and [15]. Each agent in this paradigm has the proactive, reactive, and social capabilities [16]. A key advantage of the MAS technique is its solid and reliable character, as well as its flexibility and dedication to enenvironmental sustainability [17]. The combination of MAS improves the overall performance and creates a self-governing network to ensure the effective production control.

1.9 The Economic Influence of a Deregulated 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 [18]. Also, the market system stimulates the competition among suppliers, hence, the innovation is boosted and finally, they get the service reliability and customer satisfaction.

1.10 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.

1.11 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 [19]. 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.

1.12 Reduction of operational costs

Cost-saving is another attractive characteristic of microgrid operation achievable through the deregulated 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 deregulated 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 [20]. 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 [21]. 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.

1.13 Objectives

1. This study aims to minimize the reliance on fossil fuel for power generation in microgrids by enhancing the incorporation of RES, thus decreasing the importation of fuel.
2. The study aims to management of demand side to improve energy efficiency, reduce the importation of power from the main grid during peak demand and lower the overall cost of electricity to consumers.
3. The objective of the study is to enhance energy autonomy and reliability by integrating battery energy storage systems (BESS) to guarantee power availability during peak and off-peak times.
4. This study aims to enhance the operational efficiency by managing energy production, consumption and storage across interconnected microgrids by the multi-agent system.
5. This study aim to integrate deregulated energy market system for enabling local energy exchange and reducing reliance on main grid.
6. This study involve analysing the potential reduction in carbon emissions and cost saving through the reliance on renewable energy and optimized storage scheduling.
7. The study aim to achieve the SDG 7, 9, and 11, through the provision of affordable, reliable, and sustainable energy solutions, encouraging innovation in energy infrastructure, and enhancing sustainable community development in Pakistan.

1.14 Report Organization

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

1. Introduction (Section 1) provides an overview of the study's goals and its context.
2. The Literature Review (Section 2) examines and evaluates the existing literature and research. This process develops the fundamental basis for the study's framework and methodologies.
3. Proposed Methodology (Section 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.
4. The section 4 on System Architecture and Modelling provides a comprehensive explanation of the design and modelling methods used in the study. It specifically highlights how photovoltaic (PV) sources, wind source and battery energy storage system are integrated into the system framework.
5. Results and discussion (Section 5) 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.
6. Conclusion (Section 6) provides a clear summary of the main results of the study, and suggests prospective directions for further research and advancement.

2. 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 energy tariffs for energy transactions within given communities [22]. According to Lezama et al. (2019) [23], 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 [24] [25].

In [26], 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 [27] for comparison analysis to validate the findings. It is suggested in [28] 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 [29], 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 [30] 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 [31]. The strategy proposed in [32] 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 [33] suggested an efficient energy management strategy. Meanwhile, the work presented in [34] 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 [35]. 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 [36] the author has proposed a meta-heuristic method to optimise the resource allocation under energy market framework. In [37] 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 [38] the paper presented an Energy Management System (EMS) that employed agent-based technology designed to implement demand response legislation. The author in [39] presented a plan that utilises Feed-in Tariff (FIT) and Time-of-Use (TOU) pricing to reduce peak prices. In [40], 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 [41], 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 [42]. 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 [43]. Multiple researchers have suggested multiple approaches to encourage energy trading between nearby prosumers [44]. Moreover, there have been numerous efforts to analyze 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 [45]. 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 [46].

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 [47], reducing the peak to average ratio (PAR) [48], and minimising emissions [49]. The HEMS literature thoroughly explores these many objectives. In this study [50], the author presented to develop a Matlab/simulink-based energy management for optimizing renewable energy deployment into the power system. The study in [51] 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 [52] 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 [53] 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 [54], 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 energy management within the microgrids. Nevertheless, there is still a significant deficiency in the capacity to rapidly simulate and optimize energy management decision for multi-microgrid system through multi-agent system in real-time. Moreover, previous research has not adequately addressed the incorporation of integrating the multi-agent system with the deregulated market system to create a decentralized and robust framework for energy production, consumption and trading. The key strategies for effective management of demand-side, efficient storage scheduling and strategic trading of energy make sure that the micrograds are capable of running efficiently, economically and in a reliable manner within a deregulated market structure. This research aims to bridge these gaps by implementing a novel approach that integrates the multi agent system with deregulated energy market. The propose framework contribute to the development of more resilient and sustainable microgrid operation within competitive market environment.

3. Methodology

The methodology is structured into five key phases: literature review, defining microgrid components, mathematical modelling, system operations using multi-agent system, market operation through deregulated system and performance measures. This study employed a comprehensive approach that integrated system operation through a multi-agent system to manage and optimize energy production and consumption within the microgrids and market operation via deregulated market system to ensure efficient energy transaction between the microgrids and the main grid using MATLAB Simulink. The research process, tools and techniques during the study are briefly discussed.

3.1 Literature review and data collection

In order to conduct the energy management of multi-microgrid in smart grid paradigm, the study referred to the range of research papers covering topics related to optimized management of energy resources, integration of renewable energy resources, multi-agent systems and deregulated market system. These research papers provided valuable insights for energy management aspects of multi-microgrid. In this study, the load demand data for the Pindorian and Mahfooz Shaheed regions in Islamabad is collected from the Operation Sub-Division Officer. The TOU pricing data used in this paper is based on the latest NEPRA report of IESCO [55]. Also, the wind speed and the solar irradiance data are obtained from the U.S. Pakistan center for advanced study in energy (USPCASE) weather station.

3.2 Mathematical modelling of microgrid components

The mathematical models are implemented using block-based approach in MATLAB Simulink environment, where each block represents the specific component. Each component of microgrids is playing the vital role in the overall system:

3.2.1 Renewable energy resources:

Microgrid components solar system and wind turbines are modelled using to simulate power generation by harnessing solar radiation and wind energy. The models include equations for power generation based on various factors such as solar irradiance, panel efficiency, performance coefficient of wind turbine, rotor swept area, air density and wind speed.

3.2.2 Battery energy storage system:

The energy storage system is modelled to ensure optimal charging and discharging cycles based on retail grid tariff, taking into account the state of charge (SOC), depth of discharge (DOD) and efficiency.

3.2.3 Dynamic load:

The load is modelled to reflect the time varying of power consumption within the microgrid.

3.3 System operation using Multi-agent system

The system operation is governed by the multi-agent system to ensure optimal energy management within each microgrid. The multi-agent system comprises three agent: load agent, storage agent and generating agent.

3.3.1 Load agent

Load agent is responsible for managing demand side for shedding non-essential load upto 10% during peak demand tariff period. This reduces the overall energy consumption and operation cost.

3.3.2 Storage agent

Storage agent is managing the energy storage system within the microgrids that optimizing the charging and discharging cycle ensuring that they are charged during off-peak hours, typically drawing power from the main grid when energy prices are low. Storage agent ensure that stored energy is available during peak demand period, reducing reliance on main grid.

3.3.3 Generating agent

This agent ensures that the generated power is utilized efficiently to meet the immediate microgrid demand and bid to buy and sell energy to adjacent microgrid through the market according to the microgrid. On the last resort, this agent will bid to buy and sell energy to main grid microgrid through the market according to the requirement of respective microgrid. This agent prioritizes sourcing energy from the adjacent microgrid to meet the demand of the required microgrid, as this option is often more cost-effective and environmentally sustainable than purchasing electricity from the main grid. This approach reduces dependency on the main grid, shifts demand towards local renewable energy sources.

3.4 Market operation through deregulated market system

The market operation is facilitated by a deregulated market system that governs energy transactions between the microgrids and the main grid in a competitive environment. The main aim of this market model to determine the price and quantities of electricity traded through bilateral agreements.

3.5 Evaluate Performance measures

The effectiveness of the microgrid is assessed through the following performance measures that are defined.

3.5.1 Grid reslience:

This measure assess the proportion of electricity sourced from the main grid compared to renewable energy resources and battery energy storage system.

3.5.2 Carbon emissions:

This methodology includes the carbon emissions associated with electricity production, taking into account the energy mix of each power source that provide insight into the environmental impact of microgrid.

3.5.3 Cost analysis:

The cost analysis involves computing operational expenses, particularly focusing on the economic benefits of reduced dependency on the main grid. This analysis provides a clear understanding of the cost-effectiveness of the microgrid system.

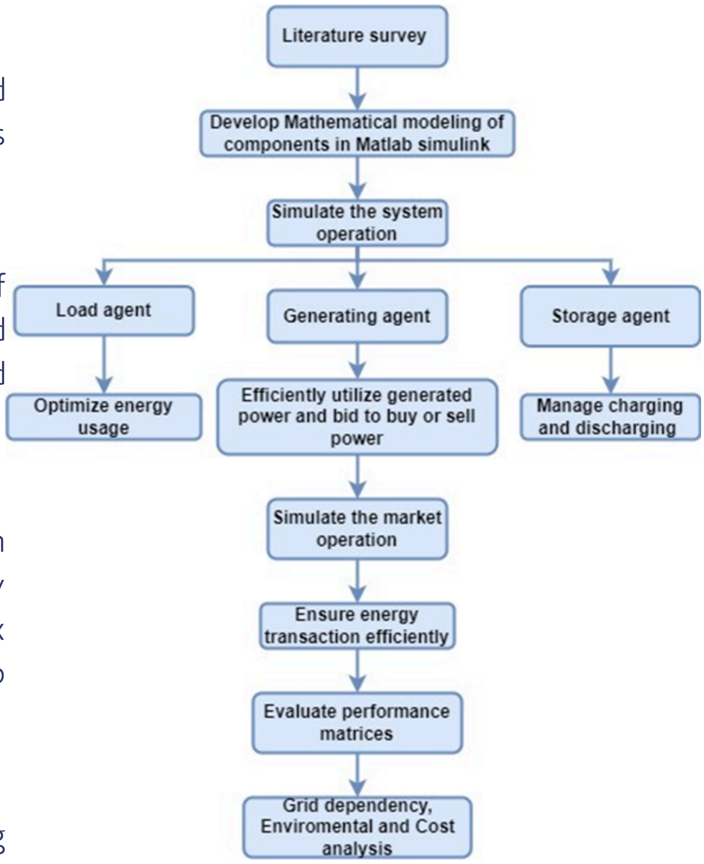


Figure 3.1. Representation of proposed work flow

3.6 Textual analysis

The research methodology followed during the study is summarized in Figure 3.1. The flowchart illustrates the step-by-step process that is undertaken to conduct the research. The role of each agent is presented in Figure 3.2. The methodology framework for optimized energy management using multi-agent system and sustainability assessment of grid connected multi-microgrid infrastructure in Pakistan is modelled to address the country's energy crisis.

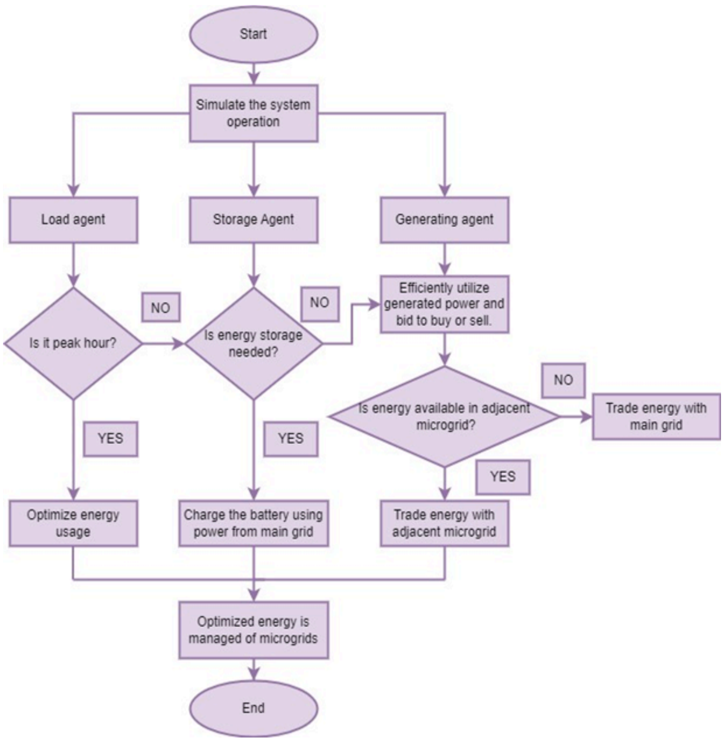


Figure 3.2. Representation of role of multi-agent system.

4. System Architecture and Modelling

4.1 System Architecture

The architecture of the proposed test system has a structural foundation, which is shown in Figure 4.1. This architecture allows for decentralized approach to multi-microgrid energy management through the multi-agent system. The primary focus is on seamless integration of Photovoltaic (PV) system and battery energy storage system (BESS) within microgrid-1, alongside Wind energy conversion system and BESS within microgrid-2.

The entire system is modelled and simulated within MATLAB Simulink environment, allowing for detailed analysis and optimized management of energy generation, storage and consumption across the interconnected microgrids. Meanwhile, the deregulated energy market system operator is responsible for overseeing the electricity buying and selling transaction. Detailed power ratings of resources utilized in this system are outlined in Table 4.1.

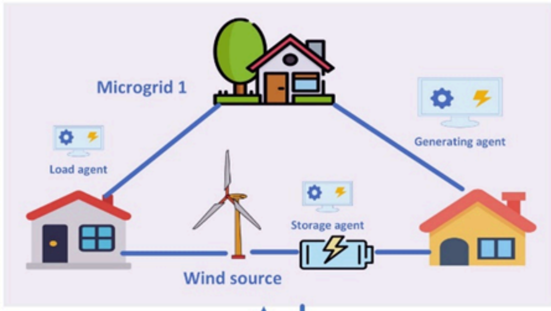
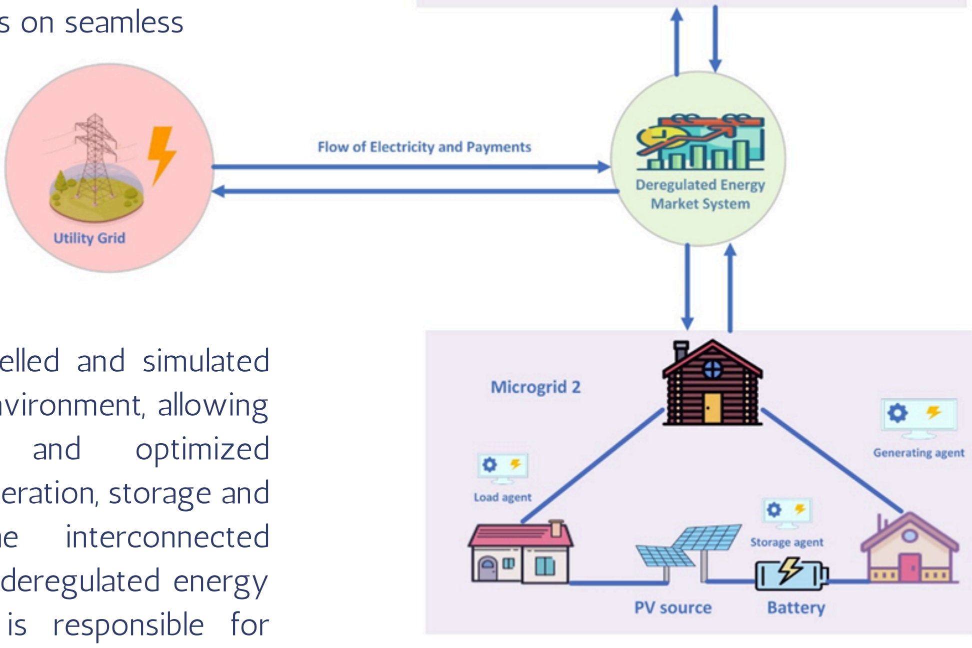



Figure 4.1. *Architecture of multi-microgrid energy management system*

Table 4.1. *Each building consists of resources that possess specified power ratings*

Microgrid	PV (kW)	Wind (kW)	Battery (kW)
MG-1	2600	-	1000
MG-2	-	3000	1000

4.2 Modelling of microgrid components

Grid connected microgrid is modelled with distinct components. 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 battery energy storage system (BESS). Moreover, the microgrid has dynamic loads that show the random use of power that occurs within the system.

4.2.1 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. 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 adaptive behaviour ensures that the microgrid recovers energy resources adequately and meets the demand. The corresponding mathematical relationship between the behaviour of the load and the magnitude of voltage is expressed as follows:

A. Active power

$$P_{active}\left(T_m\right)=P_{ref}\times\left(\frac{V_{mag}}{V_{ref}}\right)^{\left(n_p\right)} \qquad (1)$$

The consumption of active electrical power by dynamic loads, represented as Pactive, fluctuates in response to variances in the actual voltage magnitude Vmag at terminal points connecting them to distributed energy resources, such as solar panels or wind turbines.

Pref signifies the baseline or standard level of power intake against which Pactive is compared. Meanwhile, Vref is the nominal voltage that loads are designed to receive, any deviation from which—whether upwards or downwards—tends to proportionally increase or decrease Pactive. The exponent np quantifies precisely how elastic this relationship is between voltage fluctuations and alterations to power usage.

B. Reactive power

$$Q_{reactive}\left(T_m\right)=Q_{ref}\times\left(\frac{V_{mag}}{V_{ref}}\right)^{\left(n_q\right)} \qquad (2)$$

Qreactive represents the variable consumption of reactive power loads that fluctuate based on voltage variations. Qref is the benchmark level for reactive power intake determined to maintain optimal system performance. Vmag indicates the real voltage magnitude delivered to loads which may deviate from intended levels. Vref establishes the ideal voltage that loads require to function dependably yet allow flexibility through minor fluctuations. The sensitivity coefficient nq governs the rate at which reactive power demand alters in response to voltage deviations, maintaining balance as supply and demand flow.

4.2.2 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) quantifies the ability produced by the photovoltaic (PV) source, considering factors like solar irradiance and inverter efficiency.

$$P_{PV}\left(T_m\right)=\frac{P_{Rated}\times\Box_{pv}\times\left(Ir\left(T_m\right)\right)}{10^3} \qquad (3)$$

Where:
PRated: Rated output power of the PV system in (W).
npv: The efficiency of the solar system.
Ir(Tm): Irradiance of solar at time Tm.
The irradiation from the solar (Ir(Tm)) 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/m^2). Dividing by 103 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.

4.2.3 Wind energy conversion system

Equation (4) is used in a wind power system to calculate the power output (PWECS) of the wind turbine at a specific time Tm. This equation contains multiple parameters, including wind speed, air density, rotor swept area, and performance coefficients, to precisely model the behaviour of the wind energy conversion system (WECS). The wind turbine's power output at a given time is denoted as (PWECS).

$$P_{WECS}(T_m) = \begin{Bmatrix} 0 & u(t_m) < u_{min} \\ \frac{1}{2} C_g \rho A_s u(T_m)^3 & u_{min} < u(t_m) > u_{nom} \\ P_{Rated} & u_{nom} \leq u(t_m) \leq u_{max} \\ 0 & u(t_m) > u_{max} \end{Bmatrix} \quad (4)$$

Where:
Cg is the performance coefficient of the wind turbine.
ϱ represents the air density.
As denotes the rotor swept area of the wind turbine.
u(Tm) is the wind speed at time.
umin is the cut-in wind speed.
unom is the nominal wind speed.
umax is the maximum wind speed.
Prated is the rated power generated by the wind energy conversion system.
The wind speed, **u**(Tm), 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 umin and **u**nom. The power output stays constant at the rated power Prated as long as the wind speed is higher than the nominal value unom 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.

4.2.4 Battery energy storage system (BESS)

The level of energy storage is determined by SOC in relation to its capacity. SOC is regarded as a fundamental ESS parameter. The SOC is determined by the ratio of the present capacity level (WPC(Tm)) to the rated capacity (WRated(Tm)) is expressed in Equation (1). The SOC value ranges from 0 to 100%. For optimal performance, it is recommended to maintain a charging range of 20% to 80% instead than constantly fluctuating between 0% and 100%. By maintaining the battery at the designed temperature, its lifespan can be significantly prolonged. Although it is not preferable to perform frequent full charges, it can be advantageous to periodically perform a complete charge cycle (0% to 100%) in order to calibrate the battery gauge. By accurately predicting the SOH level, mishaps involving batteries can be prevented.

$$SOC(T_m) = \frac{\left(W_{PC}(T_m)\right) \times 100}{\left(W_{Rated}(T_m)\right)}\% \quad (5)$$

The rated capacity of the ESS is represented by WPC(Tm), which is the remaining charge level of the battery over a specified duration. This paper [56] addresses the actual factors that can impact a battery, including factors affecting operation such as depth of discharge, charge and discharge rates, temperature sensitivity, and state of charge variation. Therefore, this paper implements the equations represented by Equation (2), Equation (3), and Equation (4) that are relatively accurate.

$$SOC(T_m) = 1 - \frac{\eta_{ch,dsh} W_{PC}(T_m)}{W_{Rated}} \times 100\% \qquad (6)$$

The discharged power of the battery over a specific time period (T) is denoted by ηch,dsh WPC(Tm)=WS. The efficiency parameter of the battery is represented by ηch,dsh.

$$SOC\left(T_m\right) = \left(SOC\left(T_m - 1\right) - \frac{W_S}{W_{Rated}}\right) \times 100\% \qquad (7)$$

$$SOC(T_m) = SOC(T_m - 1) - \frac{1}{W_{Rated}} \int_0^T \eta_{ch,ds}\, I_T\, dT_m \times 100\% \qquad (8)$$

SOC (Tm-1) refers to the initial charge of the battery. SOC (Tm) represents the remaining battery power at time (Tm). WS represents the amount of power drained by the battery from time 0 to T, and It represents the current, with a positive value indicating discharge. In order to prevent the process of aging and to optimize performance, a certain threshold for the state of charge (SOC) has been established as the safe operational limit, as stated in Eq. (5). Battery aging is facilitated by the depth of discharge [57], whereas overcharging circumstances can lead to deterioration [58].

$$SOC_{\min\_Lmt} \leq SOC(T) \leq SOC_{\max\_Lmt} \qquad (9)$$

4.3 Objective function

The objective function is to minimize the cost of microgrids while optimizing energy utilization and transaction as expressed in Equation (10).

The proposed deregulated energy market system is allowing trading of electricity units between the microgrids and the main grid in the competitive environment in real time with the duration of interval (dTm= 5 minutes).

$$\begin{aligned} C_{net}(T_m) = \sum_{M=1}^{288} & [P_{import\_adj}(T_m) \times C_{MCP}(T_m) \times dT_m \\ & + P_{import\_grid} \times C_{grid}(T_m) \times dT_m] \\ & - [P_{export\_adj}(T_m) \times C_{MCP}(T_m) \times dT_m) \\ & - P_{export\_grid}(T_m) \times C_{FIT}(T_m) \times dT_m] \end{aligned} \qquad (10)$$

Where:

Where **P**local_gen (Tm) is the power from the local generation (renewable & BESS) at time Tm. **P**import_adj (Tm) and **P**export_adj (Tm) is representing the power imported and exported between microgrids at time Tm. CMCP(Tm) is the market clearing price at time Tm. **P**import_grid (Tm) and **P**export_grid is the power imported and exported from the main grid at time Tm. **C**grid(Tm) is the cost of energy from the main grid and CFIT(Tm) is representing the feed in tariff rate for the energy exported to main grid at time Tm. dTm is denoting the time interval duration.

Constraints managed by the deregulated energy market system.

1. Power balance constraint

$$P_{(Local_{gen})}\left(T_m\right) + P_{(import_{adj})}\left(T_m\right) + P_{(import_{grid})}\left(T_m\right) = P_{Demand}\left(T_m\right) \qquad (11)$$

The generating agent of respective microgrid ensures that the total demand is met by local generation, adjacent microgrid imports, and grid imports.

2. Adjacent microgrid priority constraint

$$P_{import\_nbr}(T_m) \leq Available\ power\ from\ adjacent\ microgrid\ (T_m) \qquad (12)$$

3. Grid import constraint

$$P_{import\_adj}(T_m) \leq P_{Demand}(T_m) - [P_{Local\_gen}(T_m) + P_{import\_adj}(T_m)] \qquad (13)$$

The agent prioritize the imports from the adjacent microgrid, making use of available clean power before resorting to grid power.

4. Surplus export constraint

$$P_{export\_adj}(T_m) \leq \ Adjacent\ microgrid\ demand\ (T_m) \quad (14)$$

$$P_{export\_adj}(T_m) = P_{Local\_gen}(T_m) + P_{import\_adj}(T_m) + P_{import\_grid}(T_m) - P_{Demand}(T_m) \quad (15)$$

The agent is managing surplus energy by first offering it to the adjacent microgrid, then exporting any remaining surplus to the main grid.

5. Results and Discussion

5.1 Simulation analysis

The optimization results of proposed grid tied multi-microgrid has been conducted using MATLAB Simulink. The main objective is to minimize the grid electricity cost through demand-side management (DSM), the installation of renewable energy resources, the integration of grid storage system and trading of clean energy among the microgrids under the summer TOU pricing strategy. The simulation of five cases of grid tied multi-microgrid provides the comprehensive insights into the impacts of different strategies on energy management and grid dependency. The analysis covers five distinct cases, each exploring different strategies to achieve the objective.

In the scenario 1, the load demand of Pindorian and Mahfooz Shaheed microgrids in Islamabad region of Pakistan is entirely dependent on main grid without any local generation (wind energy conversion system and PV system), is presented in Figure 5.1(a) and Figure 5.2(a). The simulation results indicate that significant amount of power is being import from the main grid during peak demand tariff, it leads to high energy consumption charges for the consumers within the respective microgrid. Scenario 2 showcases the benefits of integrating renewable energy resources, is displayed in Figure 5.1(b) and Figure 5.2(b). The import power from the main grid is significantly reduced as the local renewable energy sources now contribute to the local demand. It also enhances the sustainability of the microgrid by leveraging clean energy. The unexpected nature of wind and solar power, however, is that their availability follows a stochastic nature, and this requires storage system for managing power fluctuation and supply predictability. In the final scenario, the storage system is installed alongside the main grid. The import power from the main grid is further reduced compared to the scenario 2. The storage system effectively manage the energy supply, balancing the intermittent nature of solar power and wind power. The addition of storage system effectively manage the microgrid's ability to manage energy efficiently. By charging during off-peak hours and discharging during peak demand period, is depicted in Figure 5.1(c) and Figure 5.2(c).

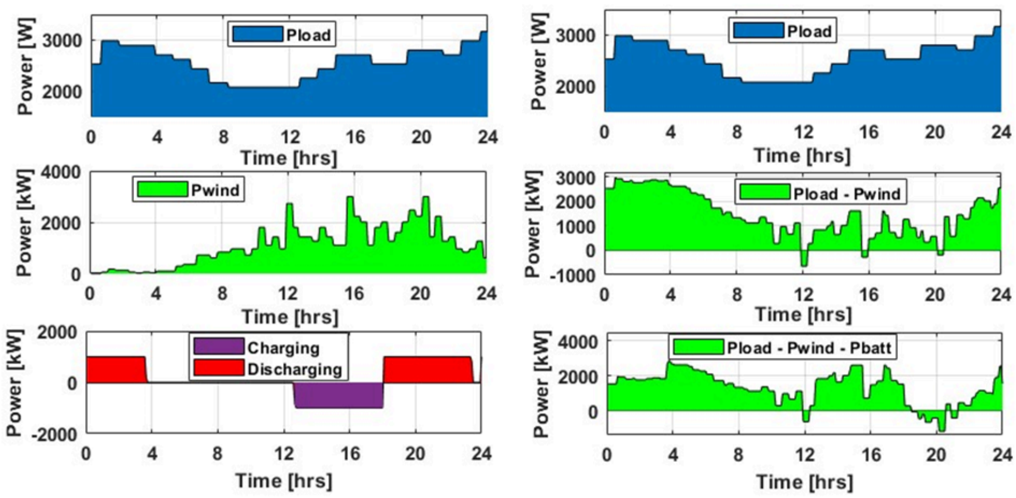


Figure 5.1. *(a) Microgrid-1 load entirely reliant on main grid (b) Load is powered by both wind energy conversion system and the main grid (c) Load is powered by wind energy conversion system, supported by storage system alongside the grid.*

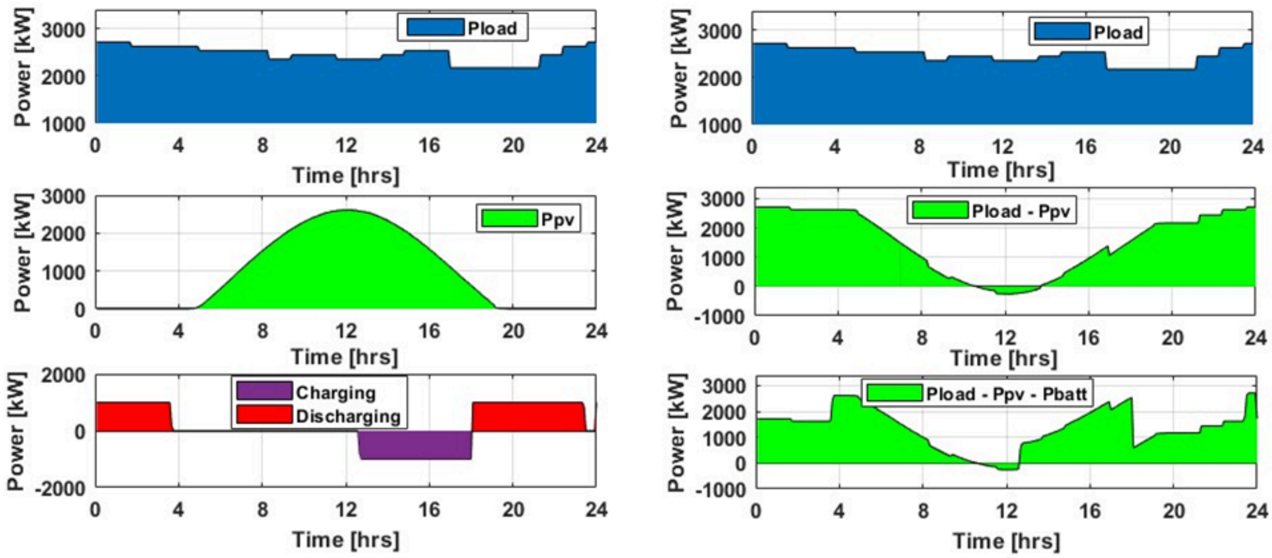


Figure 5.2.. (a) Microgrid-2 load entirely reliant on main grid (b) Load is powered by both PV system and the main grid (c) Load is powered by PV system, supported by storage system alongside the grid.

Initially state of charge of the battery is 60%, load is supplied by the battery from 0 to 3:66 am by the storage system within the microgrid-1 and microgrid-2. In the microgrid-2, when the solar power is not available to meet load demand, the stored energy with initial state of charge of 60% will serve the load in conjunction with the main grid until the battery reaches minimum SOC of 20%. During off-peak tariff period, the storage system will be charged up to 80% SOC. The storage system will then discharge again down to 20% SOC during peak demand tariff period, is shown in Figure 5.3.

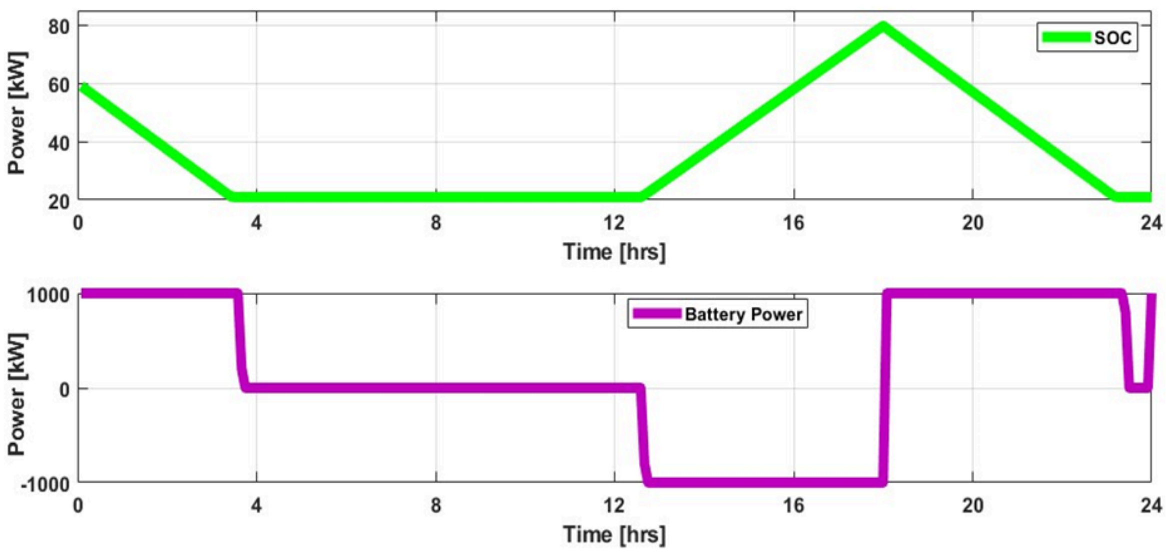


Figure 5.3.. Optimal charging and discharging of battery with respect to grid retail tariff.

5.2 Base Case: Microgrid load solely depend upon the main grid

Base case is demonstrating that load demand in the Pindorian and Mahfooz Shaheed regions of Islamabad, where microgrids are installed, is entirely dependent on main grid during both peak and off-peak demand tariff periods, with no contributions from local generation sources. Procurement of energy by the microgrids from the main grid is discussed in the Table 5.1 and cost associated with the acquisition of energy is detailed in the Table 5.2. As a result, cumulative load of the microgrids is supplied solely by the fossil fuel-based energy generation from the main grid, is presented in Figure 5.4. This reliance leads to elevated electricity grid cost of the microgrids.

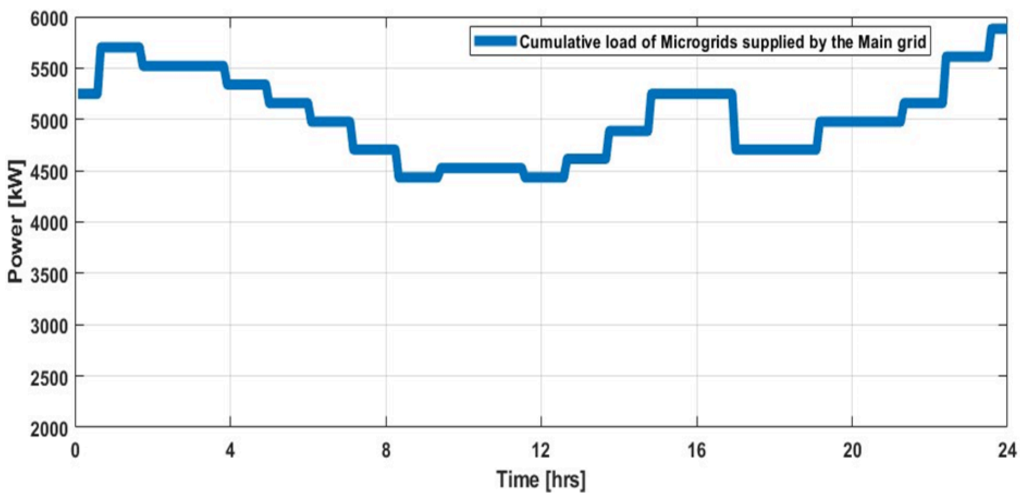


Figure 5.4. *The cumulative load of microgrids supplied by the main grid.*

Table 5.1. *The quantity of energy procured by the microgrids from the grid during a specific tariff period*

Tariff periods	Time	Microgrid-1 import units (kWh)	Microgrid-2 import units (kWh)
Off-Peak Hours	12:00am – 7pm	44700	44950
	11pm – 12am	1321	1132
Peak Hours	7pm – 11pm	15490	12970

***Table 5.2.** The cost associated with the acquisition of energy units by the microgrids from the grid during a specific tariff period..*

Tariff periods	Time	Microgrid-1, import units ($)	Microgrid-2, import units ($)
Off-Peak Hours	12:00am – 7pm	4472	4497
	11pm – 12am	132.2	113.3
Peak Hours	7pm – 11pm	2194	1837

5.3 Case 1: Microgrid load is served by the main grid along with the demand side management

In case 1, it is observed that following the deployment of demand side management (DSM) in the microgrids serving the Pindorian and Mahfooz Shaheed regions, the non-essential load of microgrid is reduced by 10% during peak demand tariff periods, is displayed in Figure 5.5. This reduction is evident in the Table 5.3, which shows a reduced amount of energy imported during peak demand tariffs and cost associated with acquisition of energy during peak hours is expressed in Table 5.4. Prior to the DSM implementation, energy units were imported 15490kWh and 12970kWh from the microgrids in Pindorian and Mahfooz Shaheed, respectively. After the DSM implementation, the energy units imported decreased to 14320kWh and 12000kWh respectively. Consequently, energy charges for consumers in these regions decreased due to reduced import during peak demand periods from the main grid.

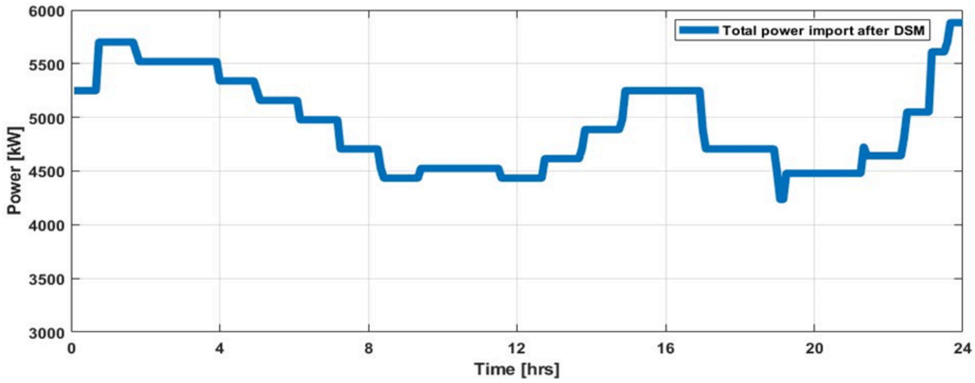


***Figure 5.5.** Reduced amount of power import during peak rate tariff*

Table 5.3. The quantity of energy procured by the microgrids from the grid during a specific tariff period.

Tariff periods	Time	Microgrid-1, import units (kWh)	Microgrid-2, import units (kWh)
Off-Peak Hours	12:00am – 7pm	44700	44950
	11pm – 12am	1321	1132
Peak Hours	7pm – 11pm	14320	12000

Table 5.4. The cost associated with the acquisition of energy units by the microgrids from the grid during a specific tariff period.

Tariff periods	Time	Microgrid-1, import units ($)	Microgrid-2, import units ($)
Off-Peak Hours	12:00am – 7pm	4472	4497
	11pm – 12am	132.2	113.3
Peak Hours	7pm – 11pm	2028	1700

5.4 Case 2: Renewable resources integration to meet MG load requirement along with main grid

In case 2, it is observed that after the installation of renewable resources, micrograids load are being served by both clean energy and the main grid, is shown in Figure 5.6. Specifically, the wind energy conversion system in microgrid-1 (Pindorian) supplies the load demand during both peak and off-peak tariff periods. In contrast, Photovoltaic (PV) source in microgrid-2 (Mahfooz Shaheed) primarily serves the load during off-peak periods, while during peak demand tariff periods most of the power is drawn from the main grid to meet the load demand. The reduced amount of energy procured by the micrograids from the main grid during peak and off-peak hours is detailed in Table 5.5 and cost associated with acquisition of energy is presented Table 5.6.

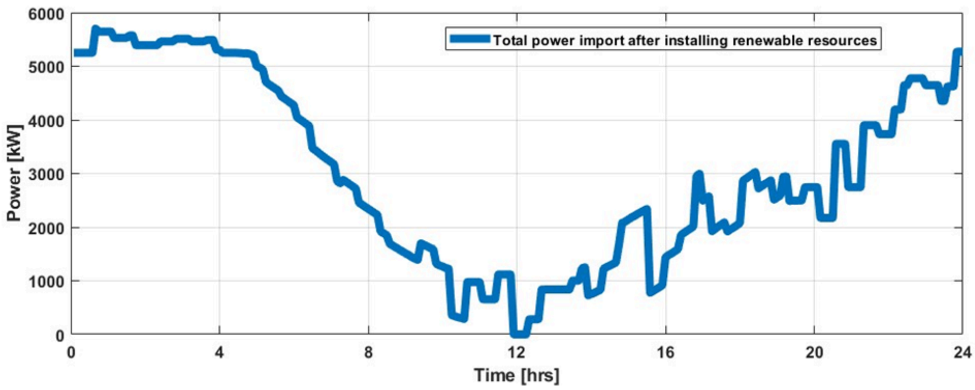


Figure 5.6. *Total amount of power import by the micrograids after the integration of RERs.*

Table 5.5. *The quantity of energy procured by the micrograids from the main grid during a specific tariff period.*

Tariff periods	Time	Microgrid-1 import units (kWh)	Microgrid-2 import units (kWh)
Off-Peak Hours	12:00am – 7pm	28330	23000
	11pm – 12am	932.4	1132
Peak Hours	7pm – 11pm	6303	12570

Table 5.6. The cost associated with the acquisition of energy units by the microgrids from the grid during a specific tariff period.

Tariff periods	Time	Microgrid-1 import bills ($)	Microgrid-2 import bills ($)
Off-Peak Hours	12:00am – 7pm	28330	2301
	11pm – 12am	93.3	113.3
Peak Hours	7pm – 11pm	89.4	1782

5.5 Case 3: Microgrid load served by local generation (renewable and storage system) along with main grid.

In case 3, battery energy storage system (BESS) is integrated with renewable energy resources to meet the load demand of the respective microgrids in Pindorian and Mahfooz Shaheed. BESS is implemented to mitigate the intermittency of the renewable energy resources. Initially the battery, with the 60% state of charge, will supply power to the microgrid load until it reaches the minimum state of charge of 20% during off-peak hours, resulting in a reduced amount of power being imported from the main grid during this period. Subsequently the battery will recharge from the main grid source upto 80% during off-peak hours, allowing it to deliver the power during peak hours to support the main grid and reduce electricity cost, is depicted in Figure 5.7 and Figure 5.8. Figure 5.9 is showing that how much power is imported from main grid prior to the implementation of deregulated market system. Table 5.7 illustrates that amount of power imported during peak demand tariff periods is less compared to previous cases and cost associated with the import of energy is presented in Table 5.8. Table 5.9 shows that surplus clean power from the microgrid-1 is supplied back to the main grid during both peak and off-peak hours, while surplus clean power from the microgrid-2 is fed back to the main grid during off-peak hours and cost associated with export of energy units by the main grid is detailed in Table 5.10. This surplus power is exported at feed in tariff rate.

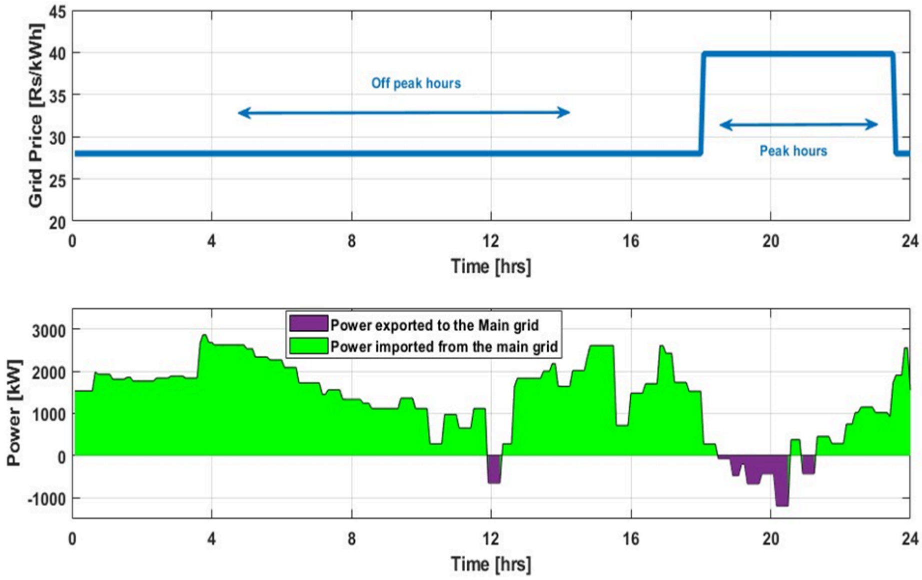


Figure 5.7. Power trading between the microgrid-1 and the main grid during peak and off-peak hours.

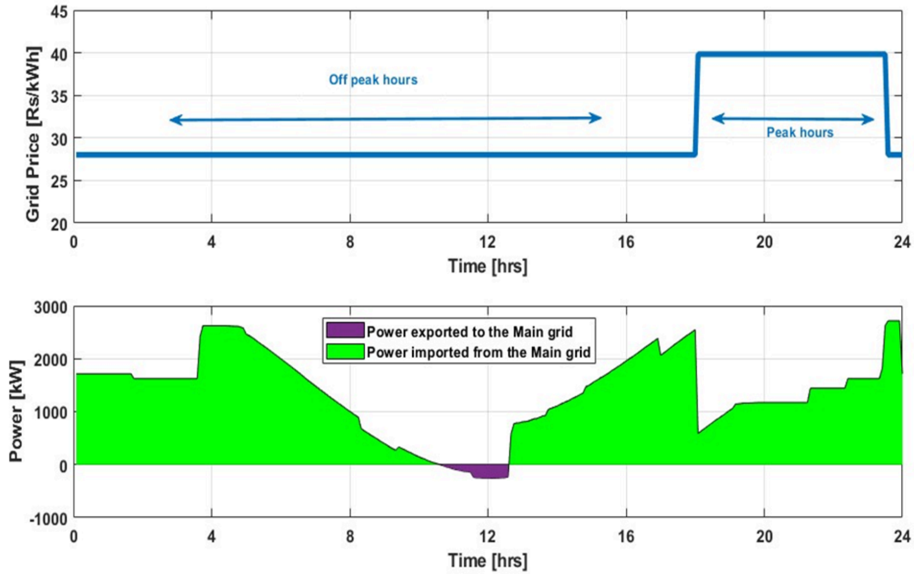


Figure 5.8. Power trading between the microgrid-2 and the main grid during peak and off-peak hours

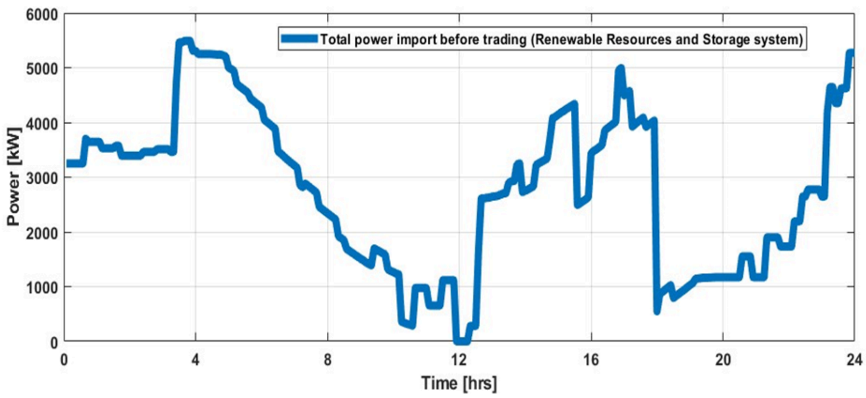


Figure 5.9. Total amount of power import prior to the implementation of deregulated market system

Table 5.7. *The quantity of energy procured by the microgrids from the main grid during a specific tariff period.*

Tariff periods	Time	Microgrid-1 import units (kWh)	Microgrid-2 import units (kWh)
Off-Peak Hours	12:00 am – 07:00 pm	30180	24770
	11:00 pm – 12:00 am	932.4	1132
Peak Hours	07:00pm – 11:00 pm	2336	7379

Table 5.8. *The cost associated with the acquisition of energy units by the microgrids from the main grid during a specific tariff period.*

Tariff periods	Time	Microgrid-1 import bills ($)	Microgrid-2 import bills ($)
Off-Peak Hours	12:00 am – 07:00 pm	3019	2478
	11:00 pm – 12:00 am	93.3	113.3
Peak Hours	07:00 pm – 11:00 pm	332.1	1048

Table 5.9. *The quantity of energy exported by the microgrids to the main grid during a specific tariff period.*

Tariff periods	Time	Microgrid-1 export units (kWh)	Microgrid-2 export units (kWh)
Off-Peak Hours	12:00 am – 07:00 pm	190.6	343.3
	11:00 pm – 12:00 am	0	0
Peak Hours	07:00 pm – 11:00 pm	954.8	0

Table 5.10. *The cost associated with the export of energy units by the microgrids to the main grid during a specific tariff period.*

Tariff periods	Time	Microgrid-1 export bills ($)	Microgrid-2 export bills ($)
Off-Peak Hours	12:00 am – 07:00 pm	19.07	34.3
	11:00 pm – 12:00 am	0	0
Peak Hours	07:00 pm – 11:00 pm	135.3	0

5.6 Case 4: Microgrid load served by local generation (renewable and storage system) along with main grid and adjacent MG through deregulated market system.

In case 4, a deregulated market system is implemented for the trading of clean energy between the microgrids at market clearing price (MCP). The MCP clearing price is decided by the market operator by taking into account the retail grid price and feed in tariff rate. Microgrid as a seller is selling the energy to adjacent microgrid at higher rate as compared to the selling the energy to the main grid at feed in tariff rate. Conversely, Microgrid as a buyer is buying the energy from the adjacent microgrid at lower rate as compared to the buying the energy from the main grid through the deregulated energy market system is illustrated in Table 5.11 and Table 5.12. This approach reduces the fossil fuel-based energy import from the main grid because microgrid prioritize purchasing clean energy when it is available in the adjacent microgrid instead of fossil fuel-based energy. Total power import by the microgrids from main grid after the implementation of deregulated market system is displayed in Figure 5.10. The rates at which energy is being import and export is depicted in Figure 5.11. As shown in the Table 5.13, power import by the microgrid-1 during off-peak hours and by the microgrid-2 during peak hours from the main grid is reduced compared to the case 3 and cost associated with the acquisition of energy from the main grid is illustrated in Table 5.14.

The Pindorian and Mahfooz Shaheed microgrids in Pakistan demonstrate that DSM and renewable energy resources can be incorporated to reduce dependence on the main grid's fossil fuel-based electricity and reduce electricity costs. Furthermore, local energy exchange between microgrids enhances the energy consumption and cost which is helpful for the sustainable energy systems in Islamabad.

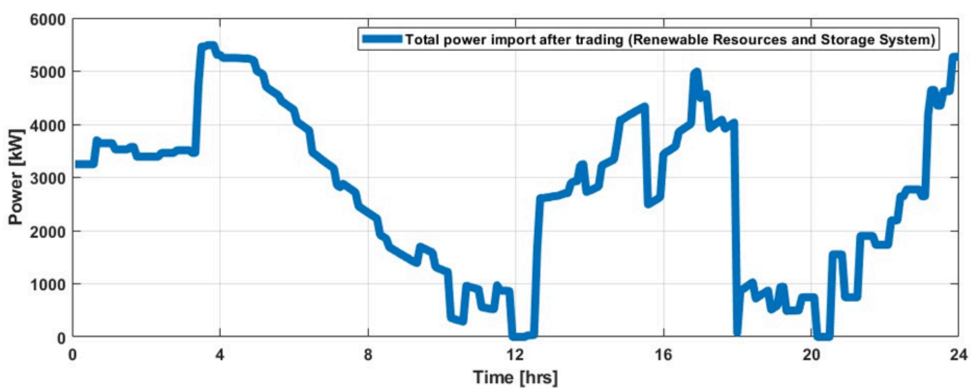


Figure 5.10. *Total amount of power import after the implementation of deregulated market system.*

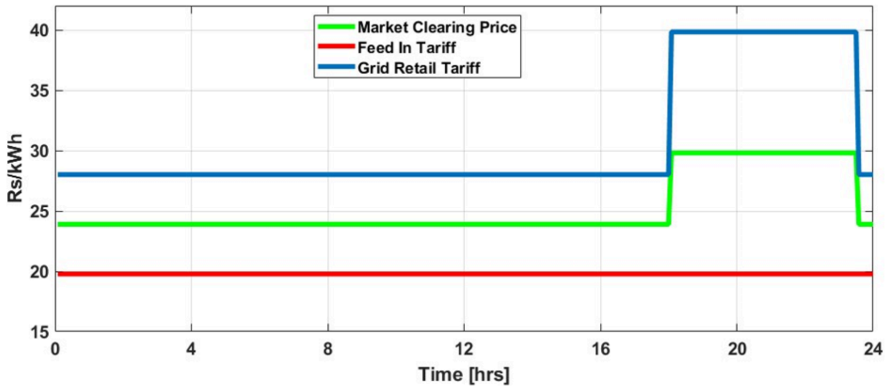


Figure 5.11. The rates at which energy is being import and export.

Table 5.11. The import and export of units between the microgrids and main grid.

Microgrids	Units imported from adjacent MG (kWh)	Units imported from Main grid (kWh)	Units exported to adjacent MG (kWh)	Units exported to Main grid (kWh)
Microgrid-1	232.5	33220	1278	248.5
Microgrid-2	1278	32000	232.5	110.8

Table 5.12. The costs associated with importing and exporting units to and from the main grid and adjacent MG.

Microgrids	Units bought from adjacent MG ($)	Units bought from Main grid ($)	Units sold to adjacent MG ($)	Units sold to Main grid ($)
Microgrid-1	19.84	3422	135.8	17.55
Microgrid-2	135.8	3458	19.84	7.825

Table 5.13. The quantity of energy procured by the microgrids from the main grid during a specific tariff period.

Tariff periods	Time	Microgrid-1 import units (kWh)	Microgrid-2 importunits (kWh)
Off-Peak Hours	12:00 am – 07:00 pm	29950	24770
	11:00 pm – 12:00 am	932.4	1132
Peak Hours	07:00 pm – 11:00 pm	2336	6102

Table 5.14. The cost associated with the acquisition of energy units by the microgrids from the main grid during a specific tariff period.

Tariff periods	Time	Microgrid-1 import bills ($)	Microgrid-2 import bills ($)
Off-Peak Hours	12:00 am – 07:00 pm	2996	2478
	11:00 pm – 12:00 am	93.3	113.3
Peak Hours	07:00 pm – 11:00 pm	332.1	866.4

As shown in the comparison table, fossil fuel-based energy import from the grid is reduced during peak demand tariff period. However, in case 3, energy import is higher during off-peak hours compared to case 2 because battery is being charged using grid power.

In Pakistan, 61% of electricity generated by the thermal power plants. Consequently, the carbon emission factor of 0.61 $kgCO_2/kWh$ is utilized in analyses aimed at assessing carbon emission reduction for environmental benefits.

Table 5.15. *The comparison of energy (kWh) imports by the microgrids from the main grid for the respective cases.*

Tariff periods	Time	Base case	Case 1	Case 2	Case 3	Case 4
Off-Peak Hours	12:00 am – 07:00 pm	89650	89650	51330	54950	54720
	11:00 pm – 12:00 am	2453	2453	2064.4	2064.4	2064.4
Peak Hours	07:00 pm – 11:00 pm	28460	26320	18873	9715	8438

Table 5.16. *Carbon emission factor of 0.61 $kgCO_2/kWh$ is utilized in analyses aimed at assessing carbon emission reduction for environmental benefits.*

Tariff periods	Time	Base case ($kgCO_2$)	Case 4 ($kgCO_2$)	Carbon emission reduction in %age
Off-Peak Hours	12:00 am – 07:00 pm	54686.5	33379.2	38.9
	11:00 pm – 12:00 am	1496.3	1259.28	15.8
Peak Hours	07:00 pm – 11:00 pm	17360.6	5147.18	70.3

These results demonstrate the effectiveness of case-4 in reducing carbon emissions and highlight the potential environmental benefits of utilizing a deregulated market system for cleaner energy trading between the microgrids. When the microgrid require power, it prioritizes acquiring clean power from the neighbouring microgrid instead of fossil fuel based-power from the main grid. If renewable power is not available from the neighbouring microgrid during specified time period, the market operator will then fulfil the microgrid's demand by procuring power from the main grid at higher rate. Conversely, when the microgrid has surplus power, it will sell to the market at high rate. The microgrid-1 imported the power from the microgrid-2 through the deregulated market system during the intervals from time 10.66 to 11.83 and 12.33 to 12.55, while microgrid-2 exported power during these periods. Conversely, microgrid-2 imported the power from the microgrid-1 at 18:00 for 5-minute interval, and from 18.5 to 20.5 and 20.916 to 21.25, during which microgrid-1 power exported. Outside of these specified periods, the microgrids does not have enough power for trading, they will resort to importing from and exporting to the main grid is shown in Figure 5.12 and Figure 5.13.

5.6.1. MG-1

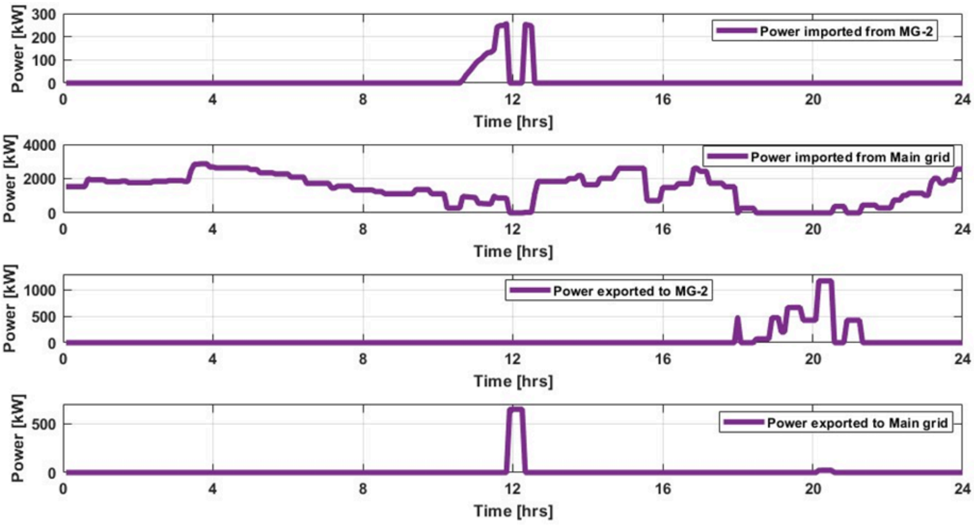


Figure 5.12. *The import and export of power by Microgrid-1 to the Microgrid-2 and Main grid through deregulated Market.*

5.6.2. MG-2

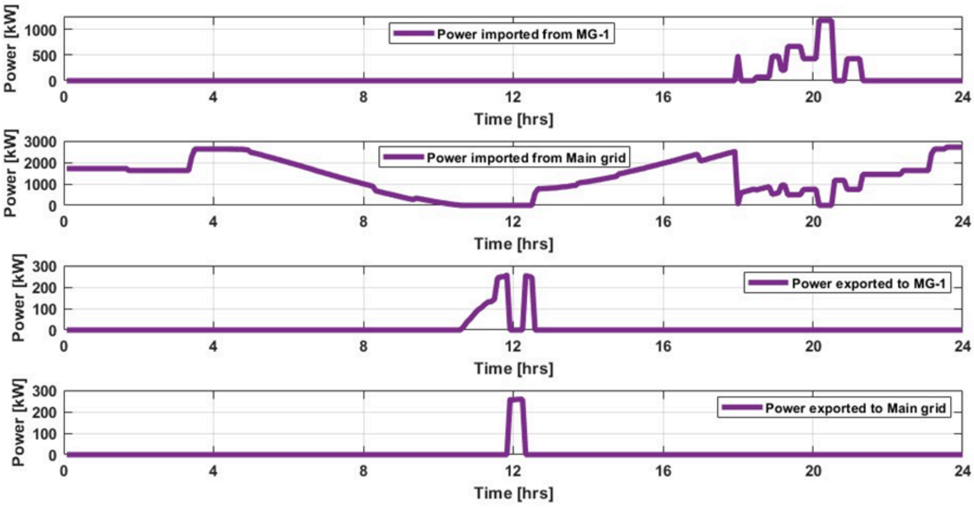


Figure 5.13. *The import and export of power by Microgrid-2 to the Microgrid-1 and Main grid through deregulated Market.*

6. Conclusion and Future work

The implementation of multi-microgrid in Pakistan, as demonstrated in this study, presents a revolutionary solution to the energy issues in the country. This study uses a dynamic simulation model created in MATLAB Simulink to analyse microgrid components such as renewable energy sources, battery energy storage systems, and energy transactions through system and market operations. The study results show that microgrids can play a crucial role in improving energy management, decreasing expenses, and increasing the sustainability of Pakistan's power sector.

The use of renewable energy sources like solar and wind power in microgrids is a feasible solution to the problem of excessive use of fossil fuels in Pakistan and its consequences on the economy and the environment. The use of these renewable resources together with battery energy storage systems not only balances the supply of clean energy but also minimizes the dependence on the grid, thus lowering fuel imports and easing foreign exchange constraints. Microgrids help in reducing the consumer consumption costs and increase energy sustainability by minimizing the reliance on the main grid during peak demand hours.

The multi-agent system used in this study also enhances the microgrid operation by managing energy generation, utilization, and storage in real-time. The system achieves optimal use of resources, cost reduction, and improved reliability by means of Load, Storage, and Generating Agents. This level of optimal management of energy is especially important in the context of Pakistan, where energy demand is increasing rapidly, and the existing infrastructure is insufficient to meet these needs. The results indicate that the proposed approach results in a reduction of the power import from the main grid and CO_2 emissions in all the scenarios and demonstrate the effectiveness of different measures in enhancing energy efficiency and sustainability. In off-peak hours, Case 2 is able to attain a 42.73% reduction in energy imports, Case 3 achieves 38.69%, and Case 4 achieves 38.92%. During peak hours, Case 4 has minimized the importation of power by 70.3%. It significantly lowers carbon emissions by 70.3% during peak periods, contributing to reduce the impact on the environment. These findings demonstrate how optimized energy management can help decrease the use of fossil fuels and decrease carbon emissions, thus supporting SDG 7 on affordable, reliable, sustainable, and clean energy in Pakistan's power sector. This study contributes to SDG 9 by improving microgrid systems through technology in renewable energy and demand response programs. Besides, it contributes to the achievement of SDG 11 by enhancing the resilience of energy systems and encouraging sustainable community development. Furthermore, the study shows that the market structure is crucial in enabling efficient energy trading between the microgrids and the main grid. This market flexibility allows microgrids to sell excess energy at market price, which can generate more revenues than the traditional Feed-in Tariff (FIT) schemes, and to buy clean energy at a cheaper price than the utility grid. The proposed framework of energy management and competitive energy market can effectively address the major issues of Pakistan's power sector and contribute to economic development and environmental sustainability. The results highlight the need for the adoption of advanced technologies to develop a robust and sustainable energy system that will help Pakistan to achieve a sustainable and cost-effective energy future.

Future studies should focus on the improvement of microgrid performance through the use of advanced algorithms and machine learning to improve energy management. The research on the applicability of blockchain technology for secure and transparent transactions will be another focus area.

7. Policy Recommendations

Considering the results of this study and the existing problems in the power sector of Pakistan, the following policy recommendations are suggested to manage the deregulated market system and enhance the microgrid performance. These recommendations are intended to solve some of the most pressing problems, including generation capacity, fossil fuel dependence, foreign exchange drain, monopolistic structure, circular debt, and the lack of competitive bidding, which will lead to a more efficient, sustainable, and robust energy system.

7.1 System operation policy

7.1.1 Ensuring Adequate Generation Capacity:

In order to tackle generation capacity issues, it is suggested that a capacity mechanism should be incorporated into the power system. This mechanism would guarantee that adequate generation resources are available to cater for seasonal and peak demand fluctuations thereby minimizing the supply demand gap. This policy could help maintain economic stability and foster national economic growth by reducing the reliance on capacity payments.

7.1.2 Enhancing grid reliability:

The use of multi-microgrid systems and multi-agent systems is essential for enhancing the reliability of the grid. These technologies will enable the incorporation of renewable energy sources, efficient load management, and decreased dependence on fossil fuel-based generation. Therefore, this approach will reduce the foreign exchange drain on fuel imports and help in the shift to a more sustainable energy source.

7.1.3 Balancing supply and demand:

An efficient forecasting and scheduling system should be put in place to forecast the load demand and supply from different sources of energy such as renewable energy and conventional energy. Through better demand forecasting and supply chain management, this system will assist in the reduction of load shedding and the need to buy power from the main grid in the emergency, thus making the energy supply more stable.

7.2. Market operation policy

7.2.1 Promoting competition in the deregulated market system:

The structure of the deregulated market system should be such that it allows independent power producers to compete in the electricity market through bidding processes. This policy will limit the direct involvement of government agencies like the Central Power Purchasing Agency (CPPA) in power procurement, which will lead to competitive pricing, lower cost of electricity for consumers, and improved market efficiency.

7.2.2 Addressing the circular debt problem:

For avoiding the circular debt problem, it is crucial to develop structures in the context of the deregulated market structure that can facilitate the timely payments between the market players. Adopting strict financial management and promoting timely financial operations will improve the financial situation of the energy sector and create a more stable and transparent market environment.

7.2.3 Efficient Auction process:

The structure of the deregulated market system should encourage the integration of renewable energy projects through a proper auction system. These auctions should focus on projects that can provide cost-competitive and dispatchable renewable energy, which will help to advance the deployment of cheap renewable power into the grid. This policy will help to develop a more diverse and reliable energy mix by promoting investment in low-cost renewable projects.

The structure of the deregulated market system should promote the integration of renewable energy projects through a proper auction system. These auctions should be geared towards projects that can offer cheap renewable energy that is also dispatchable, which will assist in the integration of cheap renewable power into the grid. This policy will assist in the creation of a more diverse and reliable energy mix by encouraging investment in low cost renewable projects.

References

[1] The world bank, "Expanding Renewable Energy in Pakistan's Electricity Mix," FEATURE STORY, 2020. [Online]. Available: https://www.worldbank.org/en/news/feature/2020/11/09/a-renewable-energy-future-for-pakistans-power-system
[2] The world bank, "Pakistan - Rural Electrification Project," 2023. [Online]. Available: https://documents.worldbank.org/pt/publication/documents-reports/documentdetail/790771468287760752/pakistan-rural-electrification-project
[3] N. U. Rehman and H. Farazaneh, "Techno-Economic Analysis of on Grid PV Power System for Vocational Training Institute in Baluchistan Pakistan to Reduce the Cost of Energy," Int. Exch. Innov. Conf. Eng. Sci., no. February, pp. 13–18, 2022, doi: 10.5109/5909056.
[4] W. Amin et al., "P2P Energy Trading: An Optimal Solution for Energy Shortage in Pakistan," IEEE Access, vol. 10, no. July, pp. 89614–89633, 2022, doi: 10.1109/ACCESS.2022.3200484.
[5] N. P. C. Centre and N. T. and D. C. Limited, "Indicative Generation Capacity Expansion Plan IGCEP 2024," 2024.
[6] Y. Guo, M. Pan, and Y. Fang, "Optimal power management of residential customers in the smart grid," IEEE Trans. Parallel Distrib. Syst., vol. 23, no. 9, pp. 1593–1606, 2012, doi: 10.1109/TPDS.2012.25.
[7] U. Asgher et al., "Smart energy optimization using heuristic algorithm in smart grid with integration of solar energy sources," Energies, vol. 11, no. 12, pp. 1–26, 2018, doi: 10.3390/en11123494.
[8] S. Ali et al., "Energy Management in High RER Multi-Microgrid System via Energy Trading and Storage Optimization," IEEE Access, vol. 10, pp. 6541–6554, 2022, doi: 10.1109/ACCESS.2021.3132505.
[9] C. Lupangu and R. C. Bansal, "A review of technical issues on the development of solar photovoltaic systems," Renew. Sustain. Energy Rev., vol. 73, no. November 2016, pp. 950–965, 2017, doi: 10.1016/j.rser.2017.02.003.
[10] J. K. Kaldellis, Stand-alone and hybrid wind energy systems. 2010. doi: 10.1533/9781845699628.
[11] IEEE Std 1547, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. 2018.
[12] H. Shayeghi, E. Shahryari, M. Moradzadeh, and P. Siano, "A survey on microgrid energy management considering flexible energy sources," Energies, vol. 12, no. 11, p. 2156, 2019.
[13] Y. Liu et al., "Distributed Robust Energy Management of a Multimicrogrid System in the Real-Time Energy Market," IEEE Trans. Sustain. Energy, vol. 10, no. 1, pp. 396–406, 2019, doi: 10.1109/TSTE.2017.2779827.
[14] G. Weiss, Multiagent systems: a modern approach to distributed artificial intelligence. MIT press, 1999.
[15] K. P. Sycara, "Systems," vol. 19, no. 2, pp. 79–92, 1998.
[16] A. S. Nair et al., "Multi-Agent Systems for Resource Allocation and Scheduling in a Smart Grid," Technol. Econ. Smart Grids Sustain. Energy, vol. 3, no. 1, p. 15, 2018, doi: 10.1007/s40866-018-0052-y.
[17] A. Kantamneni, L. E. Brown, G. Parker, and W. W. Weaver, "Survey of multi-agent systems for microgrid control," Eng. Appl. Artif. Intell., vol. 45, no. October, pp. 192–203, 2015, doi: 10.1016/j.engappai.2015.07.005.
[18] A. Ahmad et al., "An optimized home energy management system with integrated renewable energy and storage resources," Energies, vol. 10, no. 4, pp. 1–35, 2017, doi: 10.3390/en10040549.
[19] Z. Wang, K. Yang, and X. Wang, "Privacy-preserving energy scheduling in microgrid systems," IEEE Trans. Smart Grid, vol. 4, no. 4, pp. 1810–1820, 2013, doi: 10.1109/TSG.2013.2274466.
[20] Y. Zahraoui, T. Korõtko, A. Rosin, and H. Agabus, "Market Mechanisms and Trading in Microgrid Local Electricity Markets: A Comprehensive Review," Energies, vol. 16, no. 5, pp. 1–52, 2023, doi: 10.3390/en16052145.
[21] H. S. V. S. K. Nunna and S. Doolla, "Demand response in smart distribution system with multiple microgrids," IEEE Trans. Smart Grid, vol. 3, no. 4, pp. 1641–1649, 2012, doi: 10.1109/TSG.2012.2208658.
[22] S. Groh, V. J. Karplus, and C. von Hirschhausen, "Decentral Electrification, Network Interconnection, and Local Power Markets—An Introduction," Econ. Energy Environ. Policy, vol. 11, no. 1, pp. 1–4, 2021.
[23] F. Lezama, J. Soares, P. Hernandez-Leal, M. Kaisers, T. Pinto, and Z. Vale, "Local Energy Markets: Paving the Path Toward Fully Transactive Energy Systems," IEEE Trans. Power Syst., vol. 34, no. 5, pp. 4081–4088, 2019, doi: 10.1109/TPWRS.2018.2833959.
[24] A. Lüth, J. M. Zepter, P. Crespo del Granado, and R. Egging, "Local electricity market designs for peer-to-peer trading: The role of battery flexibility," Appl. Energy, vol. 229, no. July, pp. 1233–1243, 2018, doi: 10.1016/j.apenergy.2018.08.004.

[25] M. Z. Malik et al., "Power Supply to Local Communities through Wind Energy Integration: An Opportunity through China-Pakistan Economic Corridor (CPEC)," IEEE Access, vol. 9, no. Ren 21, pp. 66751–66768, 2021, doi: 10.1109/ACCESS.2021.3076181.
[26] V. V. S. N. Murty and A. Kumar, "RETRACTED ARTICLE: Multi-objective energy management in microgrids with hybrid energy sources and battery energy storage systems," Prot. Control Mod. Power Syst., vol. 5, no. 1, p. 2, 2020, doi: 10.1186/s41601-019-0147-z.
[27] M. S. Hussain, S. A. A. Kazmi, Z. A. Khan, M. Alghassab, and A. Altamimi, "Hierarchical Energy Management System with a Local Competitive Power Market for Inter-Connected Multi-Smart Buildings," IEEE Access, vol. 10, pp. 19493–19506, 2022, doi: 10.1109/ACCESS.2022.3150327.
[28] X. Tong, C. Hu, C. Zheng, T. Rui, B. Wang, and W. Shen, "Energy market management for distribution network with a multi-microgrid system: A dynamic game approach," Appl. Sci., vol. 9, no. 24, 2019, doi: 10.3390/app9245436.
[29] M. Vahid-Ghavidel, M. Sadegh Javadi, M. Gough, S. F. Santos, M. Shafie-Khah, and J. P. S. Catalão, "Demand response programs in multi-energy systems: A review," Energies, vol. 13, no. 17, pp. 1–17, 2020, doi: 10.3390/en13174332.
[30] T. Chen, S. Bu, X. Liu, J. Kang, F. R. Yu, and Z. Han, "Peer-to-Peer Energy Trading and Energy Conversion in Interconnected Multi-Energy Microgrids Using Multi-Agent Deep Reinforcement Learning," IEEE Trans. Smart Grid, vol. 13, no. 1, pp. 715–727, 2022, doi: 10.1109/TSG.2021.3124465.
[31] Z. Wang, B. Chen, J. Wang, and J. Kim, "Decentralized Energy Management System for Networked Microgrids in Grid-Connected and Islanded Modes," IEEE Trans. Smart Grid, vol. 7, no. 2, pp. 1097–1105, 2016, doi: 10.1109/TSG.2015.2427371.
[32] V. H. Bui, A. Hussain, and H. M. Kim, "A multiagent-based hierarchical energy management strategy for multi-microgrids considering adjustable power and demand response," IEEE Trans. Smart Grid, vol. 9, no. 2, pp. 1323–1333, 2018, doi: 10.1109/TSG.2016.2585671.
[33] C. Ceja-Espinosa, M. Pirnia, and C. A. Cañizares, "A Privacy-Preserving Energy Management System for Cooperative Multi-Microgrid Networks," no. Irep, pp. 1–9, 2022, [Online]. Available: http://arxiv.org/abs/2207.04359
[34] T. Logenthiran, D. Srinivasan, and A. M. Khambadkone, "Multi-agent system for energy resource scheduling of integrated microgrids in a distributed system," Electr. Power Syst. Res., vol. 81, no. 1, pp. 138–148, 2011, doi: 10.1016/j.epsr.2010.07.019.
[35] J. Lagorse, D. Paire, and A. Miraoui, "A multi-agent system for energy management of distributed power sources," Renew. Energy, vol. 35, no. 1, pp. 174–182, 2010, doi: 10.1016/j.renene.2009.02.029.
[36] M. Haseeb, S. A. A. Kazmi, M. M. Malik, S. Ali, S. B. A. Bukhari, and D. R. Shin, "Multi Objective Based Framework for Energy Management of Smart Micro-Grid," IEEE Access, vol. 8, no. December 2020, pp. 220302–220319, 2020, doi: 10.1109/ACCESS.2020.3041473.
[37] H. S. V. S. Kumar Nunna and S. Doolla, "Energy management in microgrids using demand response and distributed storage - A multiagent approach," IEEE Trans. Power Deliv., vol. 28, no. 2, pp. 939–947, 2013, doi: 10.1109/TPWRD.2013.2239665.
[38] E. Karfopoulos et al., "A multi-agent system providing demand response services from residential consumers," Electr. Power Syst. Res., vol. 120, pp. 163–176, 2015, doi: 10.1016/j.epsr.2014.06.001.
[39] R. K. Bonthu, H. Pham, R. P. Aguilera, and Q. P. Ha, "Minimization of building energy cost by optimally managing PV and battery energy storage systems," 2017 20th Int. Conf. Electr. Mach. Syst. ICEMS 2017, 2017, doi: 10.1109/ICEMS.2017.8056442.
[40] J. Kaur, Y. R. Sood, and R. Shrivastava, "Optimal Resource Utilization in a Multi-Microgrid Network for Tamil Nadu State in India," IETE J. Res., vol. 68, no. 1, pp. 183–193, 2022, doi: 10.1080/03772063.2019.1595182.
[41] Z. Wang, A. Negash, and D. S. Kirschen, "Optimal scheduling of energy storage under forecast uncertainties," IET Gener. Transm. Distrib., vol. 11, no. 17, pp. 4220–4226, 2017, doi: 10.1049/iet-gtd.2017.0037.
[42] Z. Yi, Y. Xu, W. Gu, and W. Wu, "A Multi-Time-Scale Economic Scheduling Strategy for Virtual Power Plant Based on Deferrable Loads Aggregation and Disaggregation," IEEE Trans. Sustain. Energy, vol. 11, no. 3, pp. 1332–1346, 2020, doi: 10.1109/TSTE.2019.2924936.
[43] Y. Luo, S. Itaya, S. Nakamura, and P. Davis, "Autonomous cooperative energy trading between prosumers for microgrid systems," 39th Annu. IEEE Conf. Local Comput. Networks Work., pp. 693–696, 2014, doi: 10.1109/LCNW.2014.6927722.
[44] D. Ilic, P. G. Da Silva, S. Karnouskos, and M. Griesemer, "An energy market for trading electricity in smart grid neighbourhoods," IEEE Int. Conf. Digit. Ecosyst. Technol., 2012, doi: 10.1109/DEST.2012.6227918.
[45] F. Bandeiras, Á. Gomes, M. Gomes, and P. Coelho, "Exploring Energy Trading Markets in Smart Grid and Microgrid Systems and Their Implications for Sustainability in Smart Cities," Energies, vol. 16, no. 2, 2023, doi: 10.3390/en16020801.

[46] N. Javaid et al., "An Intelligent Load Management System with Renewable Energy Integration for Smart Homes," IEEE Access, vol. 5, pp. 13587–13600, 2017, doi: 10.1109/ACCESS.2017.2715225.
[47] M. A. A. Pedrasa, T. D. Spooner, and I. F. MacGill, "Coordinated scheduling of residential distributed energy resources to optimize smart home energy services," IEEE Trans. Smart Grid, vol. 1, no. 2, pp. 134–143, 2010, doi: 10.1109/TSG.2010.2053053.
[48] A. Ahmad et al., "An optimized home energy management system with integrated renewable energy and storage resources," Energies, vol. 10, no. 4, p. 549, 2017.
[49] H. Elkhorchani and K. Grayaa, "Novel home energy management system using wireless communication technologies for carbon emission reduction within a smart grid," J. Clean. Prod., vol. 135, pp. 950–962, 2016, doi: 10.1016/j.jclepro.2016.06.179.
[50] C. B. Ndeke, M. Adonis, and A. Almaktoof, "Energy management strategy for a hybrid micro-grid system using renewable energy," Discov. Energy, vol. 4, no. 1, 2024, doi: 10.1007/s43937-024-00025-9.
[51] T. Adefarati et al., "Design and techno-economic assessment of a standalone photovoltaic-diesel-battery hybrid energy system for electrification of rural areas: A step towards sustainable development," Renew. Energy, vol. 227, no. October 2023, p. 120556, 2024, doi: 10.1016/j.renene.2024.120556.
[52] M. Moradi, M. Parsa Moghaddam, R. Zamani, and M. K. Sheikh-El-Eslami, "A novel community-based local electricity market for multiple communities with joint energy trading considering the risk of participation," IET Gener. Transm. Distrib., vol. 17, no. 5, pp. 1148–1165, 2023, doi: 10.1049/gtd2.12723.
[53] C. Giotitsas, A. Pazaitis, and V. Kostakis, "A peer-to-peer approach to energy production," Technol. Soc., vol. 42, pp. 28–38, 2015, doi: 10.1016/j.techsoc.2015.02.002.
[54] A. De Filippo, M. Lombardi, and M. Milano, "User-aware electricity price optimization for the competitive market," Energies, vol. 10, no. 9, pp. 1–23, 2017, doi: 10.3390/en10091378.
[55] D. of the A. in the matter ofrequest flied byIESCO For and A. of T. the FY2024-25, "National Electric Power Regulatory Authority Islamic Republic of Pakistan," 2024.
[56] X. Zhang, J. Hou, Z. Wang, and Y. Jiang, "Study of SOC Estimation by the Ampere-Hour Integral Method with Capacity Correction Based on LSTM," Batteries, vol. 8, no. 10, 2022, doi: 10.3390/batteries8100170.
[57] A. Zeh, M. Müller, M. Naumann, H. C. Hesse, A. Jossen, and R. Witzmann, "Fundamentals of using battery energy storage systems to provide primary control reserves in germany," Batteries, vol. 2, no. 3, pp. 1–21, 2016, doi: 10.3390/batteries2030029.
[58] B. Weißhar and W. G. Bessler, "Model-based lifetime prediction of an LFP/graphite lithium-ion battery in a stationary photovoltaic battery system," J. Energy Storage, vol. 14, pp. 179–191, 2017, doi: 10.1016/j.est.2017.10.002.

NUST
Defining futures

OUR PARTNERS

Pakistan Renewable Energy Coalition
Together for a Renewables Powered Pakistan

SDPI
Sustainable Development Policy Institute

RE
RENEWABLES FIRST

PRIED
Policy Research Institute for Equitable Development

Indus Consortium
Humanitarian Environment and Development Initiatives

PAKISTAN
ENVIRONMENT TRUST

Private Power & Infrastructure Board
Ministry of Energy (Power Division)
Government of Pakistan

https://uspcase.nust.edu.pk

ilo@uspcase.nust.edu.pk

USPCAS-E Building, NUST Sector H-12,
Islamabad, 44000 Pakistan