Chapter 8

Conclusions and Future Scope

8.1 Conclusions

In the era of emerging active distribution systems and escalating energy demands, the model of the energy management system is transforming and shifting towards decentralisation and peer-to-peer interactions. This transformation is not just a technological advancement but also marked as an elemental restructuring of the energy ecosystem where the consumers are active contributors instead of passive recipients. This thesis explores existing P2P frameworks and proposes comprehensive frameworks for P2P energy transactions. The goal is to develop an adaptable framework with the help of innovative market mechanisms to address the multifaceted challenges of modern energy management systems. The first two chapters of this thesis give the background of the P2P energy management system with the help of literature reviews and introduce the research gaps and objectives of this thesis. Along with this, the basic types of the P2P energy trading models and the preliminary methodology used in future chapters have also been clearly explained in these chapters. The remaining chapters in this thesis address and investigate the P2P energy-sharing framework.

- **Chapter 3:** A probabilistic energy management framework has been proposed to address uncertainties in renewable energy generation, specifically solar and wind energy. The framework utilizes the Nash Bargaining method within a cooperative game setting, incorporating buildings as participants along with a Community Battery Energy Storage System (CBESS). To manage renewable energy fluctuations, Hong's 2m point estimate method has been employed to develop a stochastic energy management model. A comparative analysis of different energy-sharing pricing mechanisms reveals that the incentive method is more efficient due to its reduced execution time, making it preferable for real-time applications. This framework establishes a B2B energy-sharing model within a community of buildings while ensuring computational efficiency.

- **Chapter 4:** A novel decentralized energy management framework has been introduced for virtual communities consisting of buildings equipped with Renewable Energy Sources (RESs) and load-shifting systems. The formation of virtual communities enhances system scalability by reducing the number of transactions and improving computational efficiency. The proposed energy management scheme includes B2B, B2C, and C2C energy trading models while optimizing Battery Energy Storage System (BESS) scheduling and demand-side management. A non-cooperative game-theoretic approach has been implemented in a decentralized manner, allowing participants to act as buyers, sellers, or both, based on their energy needs and availability. The framework ensures secure energy transactions while maintaining grid stability.

- **Chapter 5:** A cost-saving energy management scheme has been developed for virtual communities integrating a shareable BESS. The proposed Locational Marginal Pricing (LMP)-based energy-sharing framework achieves significant cost reductions for all participating buildings while adhering to network constraints. By leveraging the diversity in load patterns across buildings, the scheme enhances the utilization of renewable energy and minimizes reliance on the utility grid. The study demonstrates that, compared to the base case, the proposed framework achieves net cost reductions of 18.3%, 64.9%, and 11.9% in different case scenarios. Furthermore, it effectively manages uncertainties associated with RESs while ensuring optimal energy distribution.

- **Chapter 6:** A P2P energy-sharing framework has been proposed for a distribution system that actively involves Distributed Generators (DGs) and prosumers. The framework enables the Distribution System Operator (DSO) to manage market clearing and supplementary operations with the support of DGs. A cloud-based mechanism is introduced to ensure secure communication, preventing unauthorized data sharing between the DSO and prosumers. The LMP-based energy-sharing model not only reduces energy costs for participating buildings but also enhances the profitability of DGs. The application of the KS bargaining method ensures an equitable distribution of savings among participants while maintaining network constraints. Additionally, the integration of shareable BESS and strategies to address RES uncertainties improves the system's overall resilience and operational efficiency.

- **Chapter 7:** A cost-saving framework for buildings grouped under Virtual Communities (VCs) has been developed to improve scalability and reduce transaction complexities. By leveraging the load diversity among buildings, the framework effectively minimizes power exchange with the utility while optimizing energy-sharing processes. The model integrates both day-ahead and real-time energy market strategies while ensuring compliance with network constraints. The feasibility and effectiveness of the proposed framework have been validated using Real-Time Digital Simulation (RTDS), demonstrating its practical applicability and benefits.

The important conclusions form these chapters can be summarised as shown below.

- A decentralized P2P energy-sharing framework integrating BESS has been successfully designed and implemented, ensuring privacy and security in energy transactions.
- The concept of virtual communities has been effectively employed to reduce computational complexity and improve the feasibility of large-scale energy-sharing models.
- Game-theoretic methods, including cooperative and non-cooperative game approaches, have been utilized to optimize energy trading, ensuring fair pricing and efficient network constraint handling.
- The proposed LMP-based energy-sharing framework has demonstrated substantial cost savings for buildings while improving renewable energy utilization and minimizing reliance on the utility grid.
- Security and privacy concerns in P2P energy trading have been addressed using cloud-based communication frameworks, ensuring safe interactions between prosumers and the DSO.
- The integration of real-time and day-ahead market mechanisms has further enhanced the adaptability and effectiveness of the proposed framework, making it suitable for large-scale implementation in smart grids.

- The feasibility and effectiveness of the developed models have been validated using RTDS, confirming their practical applicability and contribution to future energy management systems.

This research successfully achieves its objectives by developing a secure and cost-effective P2P energy-sharing framework that integrates BESS and virtual communities. The findings provide a strong foundation for future studies and practical implementations in smart grid energy management.

8.2 Future Scope

Implementing the proposed framework in real-world scenarios presents several key challenges such as the following.

- Data Availability and Accuracy – The effectiveness of the framework depends on the availability and accuracy of real-time and day-ahead data, including load forecasts, generation schedules, and network conditions. Any inaccuracies can impact the efficiency of peer-to-peer (P2P) trading and network utilization charges (NUC).

- Communication and Coordination – Reliable communication among prosumers, communities, and the Distribution System Operator (DSO) is essential. However, ensuring seamless data exchange in real-time while maintaining cybersecurity and privacy remains a significant challenge.

- Regulatory and Market Constraints – The integration of P2P energy trading into existing regulatory frameworks may require policy modifications. Establishing standardized rules for NUC implementation and cost allocation is necessary to facilitate fair participation.

- Computational Complexity – The iterative process of adjusting NUC, re-evaluating Optimal Power Flow (OPF), and conducting real-time scheduling requires significant computational resources. Large-scale implementation may necessitate advanced optimization techniques and high-performance computing. To reduce this complexity to some extent, the concept of virtual communities has been used in this work. However, in real-world scenarios, these virtual communities should be aggregation of buildings having different load patterns to achieve the goal of reducing the grid dependency. This is, again, a challenge in implementation in a given demographic location.

- Consumer Participation and Acceptance – Encouraging active community participation in P2P trading requires awareness, trust, and suitable incentives. Resistance to new pricing mechanisms and uncertainty regarding economic benefits could hinder adoption.

Overcoming these challenges requires technological advancements, regulatory support, and strong collaboration among stakeholders to ensure the successful deployment of the proposed framework.

The work presented in this thesis aims to study P2P energy trading among buildings effectively to incorporate it in real life. It lays the foundation for a decentralized energy management system using the concept of virtual communities through various game theoretic concepts. However, there are certain areas that can be explored in future.

- The implementation of the proposed work may need regulatory changes. Further work could include investigating the legal and policy framework needed to adopt the proposed framework.

- The proposed framework uses a cloud-based platform. Investigating cyber security protocols could be a valuable direction for future work that may include using Blockchain-based platforms.

- The major focus of the proposed work is cost-savings for each participant. Future studies may include multi-objective optimization that balances other related factors, such as improving the power quality, allocating the losses, and minimizing the harmonics due to the presence of virtual communities.

- A more robust computational structure can be developed for trading in real-time, handling the uncertain and irrational behaviour of prosumers, managing different market players including electric vehicles and multiple DSOs, and investigating the different tariff structures present in the system.

By exploring these areas, a secure, efficient and sustainable energy management system can be developed for future energy markets.