CHAPTER VII
CONCLUSION AND RECOMMENDATION

7.1 Conclusion

This thesis aimed to develop an integrated optimal power dispatch framework that captures the complex interactions among electricity markets, carbon pricing mechanisms, renewable energy participation, REC revenues, and ancillary service requirements. The findings across Chapters 3 to 6 demonstrate that the research has successfully achieved these aims, offering both methodological advances and practical insights into the design of coordinated low-carbon electricity markets.

The mathematical framework developed in this research provides a unified optimisation structure that brings together elements typically treated in isolation: energy dispatch, carbon costs, renewable incentives, and system security obligations. By embedding these elements within a single clearing mechanism, the model overcomes the limitations of fragmented market structures and reveals the efficiency gains that arise from co-optimisation. The numerical analyses confirm that incorporating carbon emission costs directly into the dispatch process yields lower emissions and reduces overall expenditure, demonstrating the economic and environmental value of carbon-aware market operations.

The integration of renewable energy certificates and demand-side bidding further enriches market interactions. The results show that when renewable incentives and demand flexibility are jointly optimised with conventional generation and carbon pricing, the system achieves substantially higher cost savings and social welfare improvements. This highlights the crucial role of multi-dimensional coordination, across both supply and demand, in shaping efficient and equitable market outcomes.

The extended framework involving ancillary service co-optimisation illustrates the additional reliability and environmental benefits gained when system security requirements are integrated into the broader market mechanism rather than treated as a separate process. Coordinated procurement of reserves, combined with stepwise demand response incentives, enhances operational flexibility and supports deeper emission reductions without compromising system stability.

Applying the model to the 160-bus equivalent Thai power system further demonstrates its practical relevance. The integrated approach consistently outperforms single-policy or sequential mechanisms across economic, environmental, and reliability dimensions, offering clear evidence that coordinated multi-market designs can produce superior system-wide outcomes. Moreover, the hybrid PSO-QP method effectively captures non-convex operational characteristics, producing dispatch solutions that are both technically feasible and economically efficient, an essential requirement for real-world implementation.

The research establishes that unified market-clearing mechanisms, which jointly consider carbon pricing, renewable incentives, ancillary services, and demand-side participation, can deliver significant improvements in efficiency, sustainability, and system security. The integrated optimisation framework and methodological innovations presented in this thesis therefore contribute a robust foundation for advancing low-carbon electricity market reform and support the long-term transition toward a more efficient, resilient, and environmentally responsible power sector.

7.1.1 Comparative Analysis of Single-Sided and Double-Sided Auctions

To further contextualise the implications of the proposed integrated framework, Table 7.1 presents a comparative assessment of Single-Sided Auction (SSA) and Double-Sided Auction (DSA) mechanisms. The comparative summary reveals that the transition from SSA to DSA fundamentally shifts the market paradigm from a supply-driven model to a more holistic, elastic structure. While the SSA is limited by fixed demand and partial welfare representation, the DSA enhances economic efficiency by endogenously reflecting demand elasticity. This shift not only maximises total social welfare but also yields significant environmental and operational dividends, specifically through reduced carbon emissions and lower ancillary service requirements. Ultimately, the DSA framework provides a more robust and responsive mechanism for managing the complexities of a low-carbon power system.

Table 7.1 Comparative summary of single-side auction and double-side auction schemes

Dimension	Single-Sided Auction	Double-Sided Auction
Economic Efficiency	• Demand fixed (inelastic) • Dispatch determined solely by supply bids • Higher reliance on marginal units	• Demand bids introduce elasticity • Improved price responsiveness • More efficient resource allocation
Social Welfare	• Only producer surplus represented • Consumer surplus cannot be measured • Welfare outcome is partial	• Both consumer and producer surplus included • Welfare maximised through joint optimisation • More accurate welfare representation
Carbon Impact	• Higher total dispatch levels • Greater use of high-emission marginal units	• Lower dispatch due to DR elasticity • Reduced reliance on marginal units • Lower carbon emissions
Ancillary Services	• Higher AS requirement • Larger ramping and flexibility needs	• Lower AS requirement • Reduced ramping due to demand-side participation

7.2 Recommendation

Building upon the findings presented in Chapters 3 to 6, several promising directions for future research can be identified as follows:

(1) The integrated market framework could be extended to incorporate uncertainties from renewable energy sources, such as wind and solar generation variability, through stochastic or robust optimisation methods. This would enhance the model's applicability to real-world systems with high renewable penetration.

(2) Future studies should explore the temporal and spatial dynamics of carbon pricing and emission trading, including inter-regional carbon markets and time-varying emission factors. Such extensions would enable a more accurate representation of long-term decarbonisation pathways and the impacts of cross-border electricity trade.

(3) The integration of energy storage systems and flexible loads into the optimisation framework offers a valuable avenue for improving system flexibility, reducing curtailment, and enhancing the reliability of renewable integration. Advanced coordination mechanisms between storage, demand response, and ancillary service markets could further strengthen market efficiency and resilience.

(4) Expanding the framework to include multi-energy systems, such as the coupling of electricity, heat, hydrogen, and gas networks, would provide a holistic view of energy system decarbonisation. This approach could reveal additional synergies among sectors and improve overall energy utilisation efficiency.

(5) Integrating advanced machine learning methods to capture user behaviour, strategic or gaming bidding patterns, and other market dynamics. Such behavioural modelling, when combined with hybrid optimisation algorithms, could further improve market efficiency, robustness, and adaptability under uncertainty.

(6) From a policy perspective, future research could focus on market design under evolving carbon-neutrality targets, assessing how dynamic policy instruments, such as flexible carbon caps, renewable portfolio standards, and demand-side incentives, interact within integrated market frameworks. Pilot-scale implementation studies in actual market environments, such as Thailand's evolving power sector, would provide valuable insights into the feasibility and effectiveness of the proposed models in guiding low-carbon market reforms.

Therefore, advancing these directions will deepen the understanding of integrated market operations, strengthen the connection between policy and technical optimisation, and support the global transition toward sustainable, carbon-neutral power systems.