CHAPTER I
INTRODUCTION

1.1 Background and Significance of the Research Problem

The power sector significantly contributes to global greenhouse gas (GHG) emissions, accounting for nearly 40% of energy-related carbon dioxide emissions worldwide. To mitigate climate change, governments and energy regulators are implementing strategies to reduce emissions from power generation sources. These strategies include clean energy incentives, carbon pricing mechanisms, renewable energy mandates, and emission standards. Collectively, these measures drive emissions reduction efforts and promote investment in low-carbon technologies (IEA, 2022). In competitive electricity markets, independent system operators (ISOs) play a vital role in managing wholesale energy markets and ensuring a secure power supply (Kirschen & Strbac, 2004). The optimal energy dispatch schedules and locational marginal prices (LMPs) are determined by ISOs, reflecting the real-time cost of meeting additional demand at specific nodes within the transmission network (Litvinov, 2010). Energy trading occurs through various auction mechanisms, including single-sided auctions (SSAs), where electricity is offered by generation companies (GENCOs), and double-sided auctions (DSAs), where bids for electricity demand are submitted by distribution companies (DISCOs) (Fu et al., 2023; Wood & Wollenberg, 2014).

In addition to energy market operations, ISOs procure ancillary services to maintain grid reliability and balance supply and demand in real time (Zhou et al., 2016). Services such as regulation reserves, spinning reserves, and non-spinning reserves ensure system stability, especially as renewable energy integration increases (Banshwar et al., 2017; Reddy et al., 2015). Short-term supply-demand imbalances are managed through regulation reserves, while backup capacity in case of sudden generation or transmission outages is provided by spinning and non-spinning reserves. In power pool markets, energy production is optimised by the ISO, with consumption levels and pricing for producers and consumers determined to pass generation costs to consumers reasonably and efficiently (Yang et al., 2021). The importance of ancillary services has been heightened by the increasing penetration of renewable energy sources (RES), such as wind and solar power. While renewable generation is vital for achieving carbon neutrality, grid stability is challenged by the variability and unpredictability inherent in these sources, requiring more flexible, responsive reserves. However, ancillary services are still procured separately from energy markets in many electricity systems, resulting in inefficiencies, higher costs, and a lack of coordination between energy generation and grid reliability needs (Banshwar et al., 2017). To further incentivise renewable energy adoption, renewable energy certificates (RECs) have been introduced (Tao et al., 2021). Market-based rewards for renewable energy generation are provided through these certificates, similar to carbon trading mechanisms. However, REC trading, carbon pricing, and ancillary services often operate independently of energy market functions, leading to suboptimal market outcomes. Cost reduction, increased renewable energy deployment, and enhanced system reliability could be achieved through market integration, as recent research suggests (Hustveit et al., 2017).

This thesis proposes a comprehensive framework to address market fragmentation challenges through a progressive, multi-stage analysis. The fundamental interaction between the energy market and carbon taxation mechanisms is examined in Chapter 3, using a spot-pricing approach to assess the immediate impact of carbon taxes on system operations and market outcomes. The baseline effects of carbon pricing on generation dispatch and electricity costs are established through this foundational analysis. The analysis is extended in Chapter 4 to incorporate renewable energy sources into the system. This chapter examines how carbon taxation interacts with renewable generation and explores the additional economic benefits from REC trading. The synergistic effects of integrating environmental pricing mechanisms with clean energy deployment are revealed by examining the dual incentive structure of carbon costs and renewable certificates. The framework is advanced further in Chapter 5 by introducing the ancillary services market dimension. This chapter examines the integration of energy markets, carbon pricing mechanisms, and ancillary service procurement, with particular emphasis on incentive-based demand response programmes. A key innovation explored in this chapter involves the dual-use capability of demand response resources, which can provide spinning reserves when not actively engaged in load curtailment. System flexibility and security are thereby enhanced while resource utilisation is optimised.

A co-optimised electricity market-clearing framework that simultaneously coordinates four distinct market components is presented in Chapter 6, including electricity market (EM), carbon pricing mechanism (CM), renewable energy market (REM), and ancillary services market (ASM). This integrated optimisation approach addresses the inherent inefficiencies of fragmented market operations by simultaneously optimising electricity dispatch decisions, carbon costs, renewable incentives, and reliability requirements. The computational framework for this integrated approach is illustrated in Figure 1.1. Superior economic efficiency, enhanced environmental performance, and improved system security can be achieved through market integration, as demonstrated by this progressive analytical structure. The proposed framework provides policymakers and system operators with valuable insights for modernising electricity market structures in the context of ambitious decarbonisation targets and increasing renewable energy penetration.

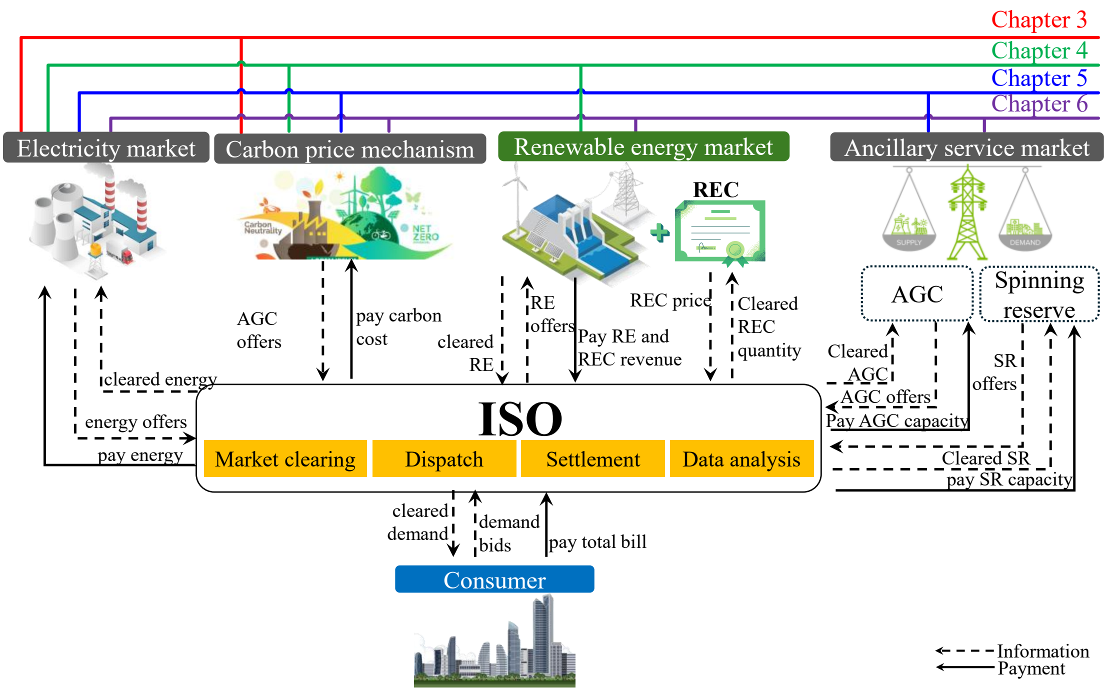

Figure 1.1 The coupling mechanism of the co-optimised market mechanism

1.2 Research Objectives

The main objective of this research is to develop an integrated optimal power dispatch framework that simultaneously considers the interactions among the electricity market, the carbon pricing mechanism, renewable energy sources, renewable energy certificate revenue, and ancillary service markets. The overall aim is to improve market efficiency, environmental performance, and system security through coordinated market clearing. So, to achieve this objective, the study pursues the following specific objectives:

(1) To formulate a co-optimised mathematical optimisation model that coordinates electricity market operations with carbon emission costs, renewable energy certificate revenue, and ancillary service requirements, thereby addressing the inefficiencies inherent in fragmented market structures.

(2) To minimise total system operational costs under a single-sided auction framework where generation companies submit supply offers, with explicit consideration of carbon tax implications, renewable energy certificate revenues, and ancillary service capacity constraints.

(3) To maximise social welfare under a double-sided auction framework where both generation companies and distribution companies participate as market agents, while simultaneously accounting for carbon emission externalities, renewable energy incentives, and system security requirements through ancillary service provision.

(4) To evaluate and compare the economic efficiency, environmental performance, and system security outcomes across different market structures and integration scenarios, providing quantitative evidence for the benefits of multi-dimensional market coordination.

These objectives aim to demonstrate that co-optimised market-clearing mechanisms can achieve superior outcomes in economic efficiency, environmental sustainability, and grid reliability compared to conventional segregated market approaches, thereby providing practical insights for electricity market design and regulatory policy development.

1.3 Scope and Limitations

The scope and limitations of this research are defined as follows:

(1) This research develops an OPF model that integrates the electricity market, carbon pricing mechanism, renewable energy generation, renewable energy certificate trading, and ancillary service requirements within a unified optimisation framework.

(2) The research considers only the carbon tax scheme as the carbon pricing mechanism. Other approaches, such as cap-and-trade systems or emission permit trading, are beyond the scope of this research.

(3) Renewable energy sources are modelled as dispatchable generation units, with analysis focused exclusively on the actual dispatched output quantities. Variability and intermittency associated with renewable generation are not explicitly modelled.

(4) Renewable energy certificate revenues are calculated based on the actual dispatched renewable energy generation, with the assumption that all dispatched renewable energy output is eligible for REC sales.

(5) The study examines two distinct market-clearing schemes: single-sided auctions, where only generation companies submit supply offers, and double-sided auctions, where both generation companies and distribution companies participate as active bidders. The analyses of these auction schemes are conducted to evaluate their impacts on market efficiency and social welfare.

(6) Ancillary services are limited to AGC for frequency regulation and spinning reserve (SR) for contingency response. The analysis focuses solely on the procurement quantities and market-clearing prices of these services. The operational control mechanisms, real-time deployment strategies, and dynamic performance characteristics of ancillary services are beyond the scope of this study. Other ancillary services, such as black-start capability, reactive power support, voltage control, and energy imbalance services, are excluded, as these are typically procured through long-term bilateral contracts and allocated to consumers based on proportional energy consumption.

(7) The research performs a comparative evaluation between separated market mechanisms and the proposed integrated market-clearing framework that combines energy, carbon pricing mechanisms, RES, REC revenue, and ancillary services.

(8) Numerical simulations and validation are conducted using two power system models, including the IEEE 30-bus test system for fundamental analysis and algorithm verification and the 160-bus equivalent Thai power system for practical application.

(9) The research investigates and compares four optimisation algorithms, including particle swarm optimisation (PSO), black widow optimisation (BWO), grey wolf optimiser (GWO), and whale optimisation algorithm (WOA).

These scope definitions ensure focused research development while acknowledging the boundaries within which the proposed framework operates and the simplifying assumptions adopted for tractable mathematical formulation and computational implementation.

1.4 Research Benefit

This study offers several key benefits:

(1) The research develops a novel mathematical framework for simultaneous market-clearing across multiple dimensions, including electricity dispatch, carbon pricing mechanism, renewable energy certificate revenue, and ancillary service procurement. This integrated optimisation approach addresses the theoretical gap in coordinating interdependent market mechanisms that have traditionally operated in isolation and provides a foundation for future research in multi-dimensional electricity market design.

(2) The research demonstrates quantifiable reductions in total system operational costs through the formulation of an integrated optimisation model under single-sided auction structures. By explicitly incorporating carbon tax obligations, renewable energy certificate revenues, and ancillary service requirements within the dispatch optimisation, the proposed mechanism enables system operators to identify cost-effective generation schedules that simultaneously satisfy energy demands, emission constraints, renewable energy targets, and reliability standards. The findings provide practical guidance for independent system operators seeking to enhance economic efficiency whilst managing increasingly complex operational requirements.

(3) The research establishes an integrated market-clearing mechanism for double-sided auction environments that maximises social welfare, defined as the sum of consumer surplus and producer surplus. By coordinating electricity market transactions with carbon pricing, renewable incentives, and ancillary service procurement, the proposed framework ensures that market outcomes reflect the actual economic value and environmental externalities of electricity generation. This approach promotes allocative efficiency and equitable distribution of benefits between supply-side and demand-side market participants, offering valuable insights for regulatory authorities designing competitive electricity markets.

(4) Validation using both the IEEE 30-bus test system and the 160-bus equivalent Thai power system confirms the framework's scalability and practical applicability, offering a methodological reference for real-world implementation in systems with diverse operating conditions. In particular, Thailand's power sector currently functions through segregated mechanisms for electricity dispatch, carbon pricing, renewable incentives, and ancillary service procurement. The proposed integrated market-clearing framework demonstrates that unified coordination across these mechanisms can significantly enhance economic efficiency, reduce operational costs, and improve environmental performance. These results provide evidence-based insights for Thai regulatory authorities seeking to advance market integration reforms amid ongoing electricity transition, decarbonisation, and renewable expansion efforts.

1.5 Thesis Outline

This thesis is organised into six chapters, as shown in Figure 1.2. Chapter 1 introduces the research background, motivation, objectives, and scope of the study, highlighting the necessity of integrating multiple market mechanisms, namely electricity market, carbon pricing mechanism, renewable energy certificates, and ancillary services, within a unified optimisation framework. Chapter 2 presents the theoretical background and literature review relevant to optimal power flow, spot electricity pricing, ancillary service management, carbon pricing mechanisms, and renewable energy certificates. The review establishes the conceptual foundation for developing integrated market-clearing mechanisms and identifies key research gaps addressed in the subsequent chapters.

Chapters 3 to 6 constitute the simulation and analysis components of the study, each addressing a specific aspect of the proposed integrated electricity market framework and its optimisation methodologies. Chapter 3 focuses on integrating the electricity market with a carbon pricing mechanism under both single-sided and double-sided auction schemes. The models are tested on the IEEE 30-bus test system, and optimisation is performed using four stochastic algorithms. Chapter 4 extends the framework by incorporating renewable energy sources and revenue from renewable energy certificates into the joint EM-CM structure. Both single-sided and double-sided auction mechanisms are analysed to examine the influence of renewable participation and REC revenue on market equilibrium. The IEEE 30-bus test system is again employed, and optimisation is performed using the PSO algorithm to determine the optimal dispatch under multiple market configurations.

Chapter 5 introduces ancillary services into the market framework, with a particular emphasis on incentive-based demand response schemes. Two operational approaches, sequential and co-optimised, are modelled under scenarios with and without DR participation. The IEEE 30-bus test system is utilised for simulation, and solutions are derived using quadratic programming and a combined QP-LP approach. Finally, Chapter 6 presents the comprehensive multi-dimensional market-clearing framework under a double-sided auction scheme. The model is applied to the 160-bus equivalent Thai power system to assess real-world applicability. Comparative analyses are performed using deterministic and hybrid PSO-QP optimisation approaches to evaluate performance across economic, environmental, and reliability dimensions.

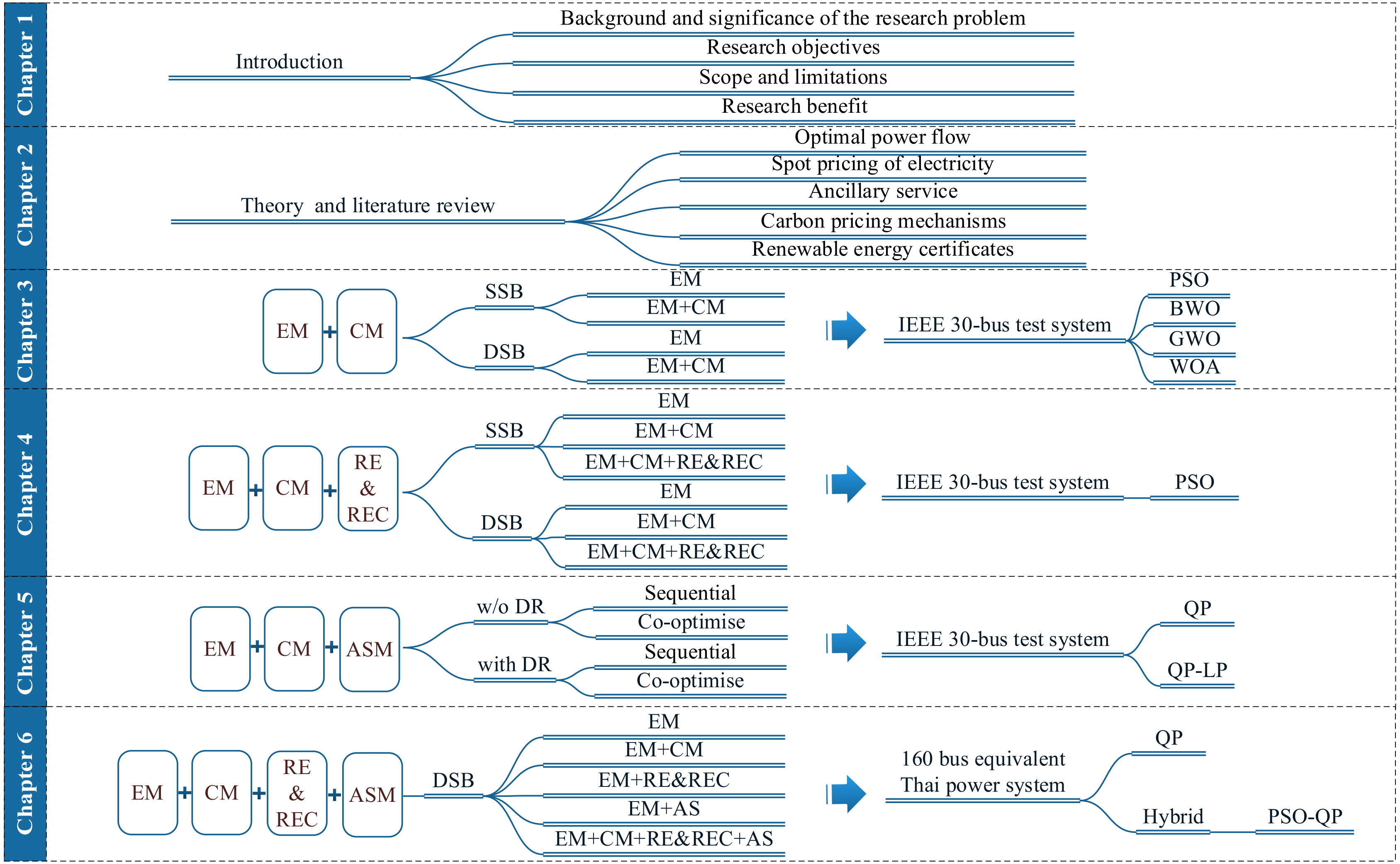

Figure 1.2 Outline of Thesis