CHAPTER II
THEORY AND LITERATURE REVIEW

2.1 Chapter Overview

A competitive electricity market involves multiple suppliers or generators competing to sell their electricity to various customers, including large consumers or retailers who distribute it to smaller end-users. Although electric energy can technically be stored in batteries, doing so on a large scale is economically impractical, rendering electricity a real-time commodity that must be produced and consumed instantly. Electric demand exhibits substantial daily, weekly, and seasonal variations, compounded by a significant random component (Bunn, 2000). The primary commodity traded in these markets is energy; however, additional services such as reserves, reactive power, and automatic generation control (AGC) are essential to maintaining system security (Gjengedal et al., 1998). The AGC is essential for maintaining grid safety and reliability, particularly in regulating frequency deviations and supporting commercial transactions. AGC systems automatically adjust the output of generating units in response to changes in system frequency, ensuring the real-time balance between supply and demand. In deregulated power markets, designing effective mechanisms for procuring and pricing AGC services is a key challenge. AGC services can be secured through negotiations between market operators, generation companies, or specialised auctions. The demand for AGC capacity significantly impacts market outcomes, as generation units in AGC mode automatically adjust their output to correct mismatches between planned production and actual system load. Efficient pricing mechanisms ensure that AGC resources are compensated fairly while maintaining economic efficiency and system security (Zhao et al., 2004). To ensure efficient trading, these ancillary services must be accommodated within the market structure (Singh & Papalexopoulos, 1999). Moreover, the geographical distribution of generators and consumers, coupled with the principles of Kirchhoff's laws, dictates the paths power takes across transmission systems, leading to potential congestion issues. Alleviating such congestion requires adjusting supply (generator outputs) and demand (customer consumption), which can constrain competition (Gedra, 1999). The interdependence of energy, ancillary services, transmission, and real-time stochastic nature of electricity demand presents significant challenges in designing efficient electricity markets.

2.2 Optimal Power Flow

Optimal power flow (OPF) is a fundamental and complex challenge in power system operation, typically characterised by its large-scale, highly constrained, nonlinear, and non-convex nature. This complexity necessitates using sophisticated solution techniques for optimal and reliable system performance. The primary objective of OPF is to minimise the cost of active power generation within an interconnected power system, where controllable variables such as active and reactive power outputs, transformer tap settings, and phase-shift angles are adjusted within the bounds of various operational constraints. The OPF procedure integrates power flow methodologies with economic dispatch strategies, systematically tuning control variables to optimise objective functions like minimising active power generation costs or power losses. Economic dispatch is also constrained by transmission system limits, including MW and MVA flow limits at buses. These limits ensure that the resulting generation dispatch achieves the minimum total generation cost and satisfies the power flow equations at the optimal point. This optimisation process ensures compliance with physical and operational limits imposed on control variables, dependent variables, and their functional relationships. Consequently, OPF is crucial in ensuring the economic efficiency and reliability of power system operations.(Wood & Wollenberg, 2014).

The standard OPF problem aims to minimise the total cost of active power generation across multiple units while satisfying operational constraints. The objective function quantifies the total production cost, considering factors such as fuel expenses and generation efficiency, and is optimised subject to constraints, including generation limits and system balance requirements.

Objective function:

minimise $$\sum_{i=1}^{NG} C_i(P_{G,i}). \quad (2.1)$$

The OPF problem is subject to several constraints that reflect the physical and operational limits of the power system.

Generator limit inequality constraints:

$$P_{G,i}^{\min} \le P_{G,i} \le P_{G,i}^{\max} \quad ,i = 1,...,NG. \quad (2.2)$$

Power balance constraints:

$$\sum_{i=1}^{NG} P_{G,i} = \sum_{j=1}^{ND} P_{L,j} + P_{loss}, \quad (2.3)$$

In OPF solution, AC power flow is used to confirm the steady-state operation of the power system using non-linear equations. These equations relate the voltage magnitudes and angles to the active and reactive power injections at each bus.

AC power flow equations:

$$S_i = V_i \sum_{j=1}^{N} Y_{ij} V_j^*. \quad (2.4)$$

where S_i is the complex power at bus i, which consists of active power P_i and reactive power Q_i, expressed as $S_i = P_i + jQ_i$, V_i is the voltage at bus i, represented as a complex number $V_i = |V_i| \angle \theta_i$, Y_{ij} is the admittance between buses i and j, representing the combined effects of conductance G_{ij} and susceptance B_{ij} of the transmission line, V_j^* denote the complex conjugate of the voltage at bus j. Hence, separate equations for active power P_i and reactive power Q_i:

$$P_i = \sum_{j=1}^{NB} V_i V_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)], \quad i = 1, \ldots, NB, \tag{2.5}$$

$$Q_i = \sum_{j=1}^{NB} V_i V_j [G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)], \quad i = 1, \ldots, NB. \tag{2.6}$$

The AC power flow equations are nonlinear due to the trigonometric functions involved, making them more complex to solve than the linear DC power flow equations. Typically, numerical methods such as Newton-Raphson or Gauss-Seidel are used to solve these equations iteratively. Constraints are as follows:

(1) Power balance constraints (active and reactive power)
(2) Voltage magnitude and phase angle constraints
(3) Generation limits
(4) Line flow limits

2.3 Spot Pricing of Electricity

Spot pricing is the foundation of deregulated electricity markets, facilitating efficient short-term operations and providing crucial signals for long-term investments. By accurately reflecting the balance of supply and demand, spot prices assist in optimising the use of existing resources while leading potential trends that enhance social welfare. The concept of spot pricing in electricity markets was first introduced by Schweppe et al. (1988), who proposed that the optimal electricity price should vary across space and time. This pricing mechanism accounts for the variable costs of electricity production at the time of consumption, adjustments needed to offset transmission losses, delivery costs, and any constraints related to generation or transmission capacity that might affect supply availability. The foundational theory of real-time pricing has since been expanded to address additional considerations.

Over the past decades, this foundational theory has been significantly expanded to include broader considerations, particularly for system security. Caramanis et al. (1987) pioneered integrating system security into the pricing framework, underscoring the necessity of a pricing mechanism that balances economic efficiency with grid reliability. This conceptual advancement laid the groundwork for further refinements in real-time pricing models, which increasingly accounted for the complexities of operational constraints. Alvarado et al. (1991) and Kaye et al. (1995) further enhanced the modelling of security constraints, ensuring that real-time pricing could effectively maintain grid stability while optimizing economic outcomes. Berger and Schweppe (1989) explored the potential of real-time pricing to support load frequency control, demonstrating how dynamic pricing can be a tool for maintaining system stability. Extending the theory's application, Baughman and Siddiqi (1991) addressed the real-time pricing of reactive power, a crucial component in voltage control, while Siddiqi and Baughman (1995) examined the pricing mechanisms for spinning reserves, which are essential for system reliability. Building on these foundational works, Baughman et al. (1997) introduced an advanced pricing theory that integrates these diverse elements into a cohesive framework. By employing Lagrange decomposition, this approach effectively navigates the complexities inherent in modern electricity markets, addressing the additional constraints and requirements imposed by an increasingly interconnected and sophisticated grid.

This evolution in spot pricing theory has not only built upon the foundational contributions of Schweppe et al. (1988) but has also significantly advanced the practical applicability of these concepts within contemporary electricity markets, ensuring that pricing mechanisms are robust enough to address emerging challenges. Central to this modern theory is the LMP concept, which deconstructs the electricity price at any location into three primary components: marginal energy, congestion, and losses. These components are derived from the least-cost, security-constrained dispatch of system resources, which aims to meet system demand as efficiently as possible. Marginal energy represents the incremental cost of producing electricity at the reference bus, with prices fluctuating based on load distribution across the network. Congestion reflects the additional costs incurred when transmission constraints prevent the delivery of the least-cost energy to all locations. At the same time, marginal losses account for the energy dissipated due to resistance in transmission lines. The integration of these components, marginal energy, congestion, and losses, provides a nuanced and comprehensive framework for understanding energy pricing, highlighting the economic implications of transmission constraints and the overall efficiency of the electricity system.

The LMP is the most widely adopted pricing scheme in contemporary electricity markets. Numerous studies have explored various pricing schemes, emphasising the importance of competitive equilibrium, revenue adequacy, and consumer payment minimisation. For instance, Y. Wang et al. (2023) proposed an optimization-based partial marginal pricing model that introduces discriminatory price components to manage the price coupling among market participants while ensuring both competitive equilibrium and revenue adequacy. This model effectively transforms a bi-level strategic bidding problem into a mixed-integer linear programming problem, enabling a comprehensive analysis of strategic bidding behaviours under different pricing schemes. Additionally, M. Wang et al. (2022) examined the practical experience of foreign electricity markets' settlement mechanisms, specifically investigating the effects of bidding procedures and the fairness of outcomes for both generators and consumers under three different settlement mechanisms: LMP, zonal pricing, and average system pricing. Their study developed a spot market clearing and settlement model to quantitatively assess the impact of zonal settlement mechanisms on the interests of various market participants within China's evolving electric spot market environment, ultimately enhancing market efficiency and fairness.

LMP, by definition, corresponds to the dual multiplier of the nodal active power balance constraint in the OPF model and can be implemented using both AC and DC OPF models. Yang et al. (2017) introduced a linear model for calculating loss-embedded LMP, beginning with an analysis of the Karush-Kuhn-Tucker (KKT) conditions in a general OPF formulation. This analysis provided critical insights into the interrelationships among LMP, reactive power marginal cost, and congestion cost, leading to the development of an iterative algorithm for solving the loss-embedded LMP. In a related study, Liu et al. (2009) explored the use of AC and DC OPF models for deriving LMP, with particular emphasis on the equivalence between full-structured and reduced-form models. They substantiated their theoretical findings with a three-bus system case study, illustrating the practical application of both OPF models and demonstrating that LMP results are consistent across both full-structured and reduced-form DC OPF models. Furthermore, Yang et al. (2021) compared loss factor-based LMP methods using IEEE 5-bus and 39-bus systems. They found that marginal loss factor-based LMP methods produce higher market settlement surpluses but lower generation income. Consequently, the study recommended OPF-based methods for calculating loss factors over PF-based methods, as the latter's larger variations could negatively impact market stability. Table 2.1 presents a summary of selected literature on the spot pricing of electricity, providing a concise overview of key contributions in this field.

Table 2.1 The summary of selected literature on the spot pricing of electricity

Ref.	Method	Description
Schweppe et al. (1988)	DC load flow	• Introduced the concept of spot pricing in electricity markets • Proposed that optimal electricity prices should vary across space and time, accounting for marginal energy, marginal loss, and congestion relaxation
Baughman et al. (1997)	Hamiltonian function (the dynamic equivalent of a Lagrangian)	• Utilizes Lagrangian decomposition to address complex constraints in modern electricity markets • Key Components of Pricing: - Active power, including marginal energy, marginal loss, congestion relaxation, marginal outage cost, and constraint terms - Reactive power, including marginal energy, congestion relaxation, marginal outage cost, voltage security, and constraint terms

Table 2.1 The summary of selected literature on the spot pricing of electricity (Continued)

Ref.	Method	Description
Wang et al. (2023)	Optimization-based partial marginal pricing model	• Introduces an optimization-based partial marginal pricing model with discriminatory price components • Ensures the PMP model maintains competitive equilibrium and revenue adequacy while managing price coupling among market participants • The bi-level strategic bidding problem is transformed into a mixed integer linear programming problem for thorough analysis
Wang et al. (2022)	A multi-agent-based electricity market simulation	• Investigates the effects of bidding procedures and fairness on the generator and consumption sides under three settlement mechanisms: LMP, zonal pricing, and ASP • A multi-agent-based electricity market simulation establishes a spot market clearing and settlement model
Liu et al. (2009)	AC and DC optimal power flow	• AC and DC OPF models to derive LMP. • Full-structured and reduced-form models to understand their equivalence in LMP calculations. • Illustrate the derivation of LMP solutions using a three-bus system • They show the same results, reinforcing the reliability of the models used: the LMP solutions derived from the full-structured and reduced-form DC OPF models

Table 2.1 The summary of selected literature on the spot pricing of electricity (Continued)

Ref.	Method	Description
Yang et al. (2021)	MLF-based LMP methods	• Compared loss factor-based LMP methods in electricity markets • Used IEEE 5-bus and 39-bus systems for testing • Found marginal loss factors-based LMP methods: -Produce higher market settlement surpluses - Lead to lower generation income • Recommended OPF-based methods over PF-based methods for loss factor calculation
Yang et al. (2017)	Optimal Power Flow	• Introduced a linear model for loss-embedded LMP calculation • Analyzed KKT conditions in general OPF formulation • Revealed relationships among LMP, reactive power marginal cost, and congestion cost • Developed an iterative algorithm to solve loss-embedded LMP • Improved accuracy in representing true marginal electricity costs at different network locations

2.4 Ancillary Service

The primary service in power systems is generating and delivering real power. However, ensuring this power is reliable, high-quality, and efficiently produced requires ancillary services. These services are organised by their time scales, ranging from real-power balancing, which demands constant attention and immediate response, to black-start services, which are rarely needed but crucial for system recovery after a blackout (NERC, 1996). Ancillary services provided by the system operator are essential to maintaining grid stability and supporting electricity dispatch, trade, and delivery. While services are critical, exclude activities such as investment in generation and transmission infrastructure, which, although important, are not classified as ancillary services. The specific services offered and definitions can vary across markets. However, market operators typically procure ancillary services from participants in accordance with reliability standards established by the North American Electric Reliability Corporation (NERC) and regional Coordinating Councils, such as the Western Electricity Coordinating Council (WECC).

While energy and ancillary services are procured separately, a generator can receive compensation for both as long as the capacities allocated to each service do not overlap within the same period. This mutual exclusivity ensures that resources are efficiently utilised without double-counting capacity. A significant subset of these ancillary services is procured through market-based mechanisms, notably regulation reserves, spinning reserves, and non-spinning reserves (Zhou et al., 2016).

(1) Regulation services are regarded as essential mechanisms for maintaining the real-time equilibrium between electricity supply and demand by compensating for minor fluctuations. Generation units that provide such services are required to respond to AGC signals issued by the system operator, enabling output adjustments over very short time intervals, typically from one to several seconds. Depending on the market design, regulation services are commonly categorised into regulation-up (capacity available to increase output) and regulation-down (capacity available to reduce production). In some markets, a fast-frequency regulation product has also been introduced, primarily supported by energy storage systems and demand response resources, which can modify their output more rapidly than conventional generators. Within competitive electricity markets, the procurement of AGC services has attracted considerable attention from both researchers and practitioners. These services are generally procured either through direct contractual arrangements between market operators and generating companies or via auction-based mechanisms (Rebours et al., 2007). An optimal dispatch algorithm for AGC was developed by Chen et al. (2007) to address capacity requirements for regulation dispatch under uncertain demand conditions, highlighting the stochastic nature of these requirements.

(2) Spinning reserves, also referred to as synchronised reserves, are recognised as vital for enabling the power system to respond promptly to forced outages or other

contingency events. These reserves are provided by online generating units that are synchronised to the grid but not operating at full capacity, thereby allowing a rapid increase in generation output when required. Units participating in spinning reserve provision are generally expected to be capable of ramping up their generation within 10 to 15 minutes of receiving instructions. Demand-side resources may also contribute to spinning reserves by curtailing their consumption within the same timeframe.

(3) Non-spinning reserves, also termed supplementary reserves, are intended to facilitate system recovery following unexpected contingencies, serving a function similar to that of spinning reserves. However, these reserves may also be supplied by offline generating units, provided that such units can be started and reach the required output level within a specified period, typically ranging from 10 to 30 minutes, depending on the market. Online units with surplus capacity may likewise contribute to non-spinning reserves. In many cases, the total available non-spinning reserve capacity encompasses surplus capacity from spinning reserves. Both spinning and non-spinning reserves are commonly classified as primary, supplemental, or contingency reserves.

(4) Other Ancillary Servicesare also considered indispensable for the secure and efficient operation of the power system, including black start capability, reactive power support, voltage control, and energy imbalance services. Black-start capability is fundamental for system restoration following a total blackout, typically relying on small diesel generators or energy storage systems to provide the initial energy needed to restart larger generating units. Reactive power provision and voltage control are required to maintain system voltages within acceptable limits and to mitigate transmission congestion caused by reactive power flows, thereby enhancing active power transfer capacity. Jay and Swarup (2021) examined the complexities associated with establishing a reactive power market, with particular attention to uncertainties and the non-convex nature of AC optimal power flow (AC-OPF). Their findings suggest that effective pricing may be achieved by determining nodal prices corresponding to the Lagrangian dual variables of the AC-OPF, thereby incorporating system operating conditions into the pricing mechanism.

Table 2.2 Ancillary services offered by ISO/RTO markets in the United States

	Product	Description
CAISO	• Regulation-up	• Must immediately increase output in response to automated signals • In the Day-Ahead Market and Hour-Ahead Market
	• Regulation-down	• Must immediately decrease output in response to automated signals
	• Regulation Mileage-up/down	• The absolute change in output between four-second set points
	• Spinning Reserves	• Synchronized to the grid • Must respond within 10 minutes • Must run for at least two hours
	• Non-spinning	• Must respond within 10 minutes • Must run for at least two hours
ERCOT	• Regulation-up	• must immediately increase output in response to automated signals
	• Regulation-down	• Must immediately decrease output in response to automated signals
	• Responsive Reserves	• Must respond within “the first few minutes of an event that causes a significant deviation from the standard frequency”
	• Non-spinning Reserves:	• Must respond within 30 minutes; must run for at least one hour
ISO-NE	• Regulation	• Must immediately increase or decrease output in response to automated signals
	• TMSR	• Synchronized to the grid; must respond within 10 minutes
	• TMNSR	• Must respond within 10 minutes
	• TMOR	• Must respond within 30 minutes

Table 2.2 Ancillary services offered by ISO/RTO markets in the United States (Continued)

	Product	Description
MISO	• Regulation	• Must respond fully within five minutes • Online and synchronized with the grid • Able to respond to automated signals
	• Spinning Reserve	• Synchronized to the grid • Must respond within 10 minutes
	• Supplemental Reserve	• Not necessarily synchronized to the grid • Must respond within 10 minutes
NYISO	• Regulation	• Must immediately increase or decrease output in response to automated signals
	• TMSR	• Synchronized to the grid • Must respond within 10 minutes
	• TMNSR	• Must respond within 10 minutes
	• Thirty-minute Spinning Reserves • Thirty-minute Non-synchronized Reserves	• Synchronized to the grid • Must respond within 30 minutes • Must respond within 30 minutes
PJM	• Regulation	• Must immediately increase or decrease output in response to automated signals
	• Synchronized Reserves	• Synchronized to the grid • Must respond within 10 minutes
	• Primary Reserves	• Must respond within 10 minutes • Includes Synchronized Reserves
SPP	• Regulation	• Must immediately increase or decrease output in response to automated signals
	• Spinning Reserves	• Synchronized to the grid • Must respond within 10 minutes
	• Non-spinning Reserves	• Not necessarily synchronized to the grid • Must respond within 10 minutes

Energy imbalance services address mismatches between scheduled and actual energy delivery during a given operational period and may be provided by both supply- and demand-side resources. Although dedicated markets for such services are not operated across most U.S. power systems, resource adequacy is ensured through internal requirements and other procurement mechanisms. In the United States, seven independent power markets administered by ISOs or regional transmission organisations (RTOs) are responsible for managing transmission networks, administering energy and ancillary service markets, and ensuring compliance with reliability standards established by the North American Electric Reliability Corporation (NERC), except for the Electric Reliability Council of Texas (ERCOT), which operates outside the jurisdiction of the Federal Energy Regulatory Commission (FERC). Across these markets, ancillary services are generally organised into the categories of regulation, spinning reserves, and non-spinning reserves. Table 2.2 shows ancillary services offered by ISO/RTO markets in the United States.

The increasing integration of RES into electricity generation has substantially increased demand for ancillary services (AS) to maintain power system stability. This transition has stimulated extensive research into market mechanisms and optimisation strategies aimed at addressing the challenges associated with renewable energy integration, operational reliability, and cost efficiency. Reddy et al. (2015) developed a market-clearing mechanism for wind-thermal power systems to manage the stochastic nature of wind generation. This framework incorporated both thermal and demand-side reserves while accounting for wind volatility within energy and spinning reserve markets. Optimal scheduling was achieved by combining a genetic algorithm with a two-point estimate method for probabilistic real-time OPF. The approach, validated on the IEEE 30-bus system, demonstrated the potential to minimise day-ahead and real-time adjustment costs when benchmarked against Monte Carlo simulations.

Building on this foundation, Banshwar et al. (2017) introduced a market-based approach enabling renewable power producers to participate simultaneously in energy and ancillary service markets within a disaggregated day-ahead framework. The sequential clearing of these markets was performed using AC-OPF techniques, ensuring feasibility under transmission and power flow constraints. The study, which focused on the ten-minute spinning reserve (TMSR) and thirty-minute replacement reserve (TMRR), demonstrated that the joint participation of renewable producers in energy and reserve markets could significantly enhance market efficiency while reducing total operational costs. Similarly, Lin et al. (2021) addressed unit commitment challenges in ancillary service optimisation by integrating Discrete Particle Swarm Optimisation and Sequential Quadratic Programming (DPSO–SQP). This model incorporated AGC and real spinning reserve (RSR), achieving optimal energy supply scheduling while satisfying energy balance and operational constraints. Comparative analyses with Genetic Algorithm (GA), Evolutionary Programming (EP), PSO, and Simulated Annealing (SA) confirmed the robustness of the proposed hybrid method in minimising day-ahead market operating costs.

At the distribution level, the proliferation of distributed energy resources and uncontrollable loads has further amplified the necessity for ancillary services. In response, He et al. (2023) developed a bi-level game-theoretic model for multi-agent load aggregators to participate in ancillary service markets and maximise their respective profits. The model was reformulated as a single-level structure using Karush-Kuhn-Tucker (KKT) conditions and strong duality theory. In contrast, PSO was used to determine the Nash equilibrium arising from non-cooperative interactions among aggregators. This approach underscored the increasing importance of decentralised coordination in distribution-level ancillary service provision. More recently, Lu et al. (2024) introduced a Convex Hull (CH) pricing-based frequency regulation (FR) market aimed at enhancing stability, flexibility, and cost-effectiveness in low-carbon systems. The CH pricing scheme, derived through the sub-gradient surrogate Lagrangian method, enabled efficient joint market clearing while minimising uplift payments. The results demonstrated notable improvements in frequency performance, alongside reductions in total operating costs, uplift payments, and carbon emissions.

Parallel to the development of new optimisation frameworks, contemporary studies have highlighted the growing operational challenges in low-inertia systems. Baig et al. (2021) employed an inertia-dependent stochastic unit commitment (SUC) model to demonstrate that ancillary service costs in Great Britain could increase by up to 165% if inertia levels were not explicitly integrated into market design. The findings emphasised the critical linkage between inertia and frequency response provision, reinforcing the need for restructured ancillary service markets under conditions of reduced synchronous generation. The evolution of market mechanisms and pricing models has also been a central research theme. Zheng and Litvinov (2006) proposed an ex post pricing framework for co-optimised electricity and reserve products in ISO New England’s market, simplifying the pricing process through a decoupled approach that maintained consistency between electricity and reserve prices while avoiding the complexity of conventional heuristic methods. Complementarily, Wang et al. (2005) presented a cost-benefit-based clearing model for operating reserve markets, which simultaneously determined the optimal reserve capacity under both uniform-price and pay-as-bid auction mechanisms. Together, these studies laid the analytical groundwork for modern reserve market structures that balance economic efficiency with system reliability.

Comprehensive reviews of ancillary service market evolution have been conducted. Pollitt and Anaya (2021) traced the transformation of ancillary services from by-products of conventional generation to independent market products increasingly shaped by renewable integration. Meanwhile, Viola et al. (2024) expanded on this perspective through a systematic review of ancillary service markets in the United States and Europe, developing a standard taxonomy of AS products and identifying key design principles to support systems with high shares of variable renewable energy (VRE). The review proposed potential solutions to remaining technical and regulatory challenges, emphasising the importance of adaptive, technology-neutral market frameworks that can maintain reliability in fully decarbonised systems.

Beyond pricing and optimisation, research attention has also focused on zonal coordination, active network participation, and demand-side flexibility. Dutta et al. (2024) examined zonal reserve pricing under transmission congestion and contingency scenarios, revealing that system reliability and market efficiency can be improved through optimised reserve procurement. Jin et al. (2015) explored the participation of active distribution networks (ADNs) in ancillary service provision through a bilevel coordinated dispatch model that captures the interaction between distribution-level decision-making and main-grid market clearing. The results demonstrated that balanced participation between electricity and ancillary service markets could be achieved through decentralised optimisation strategies. The contribution of demand-side participation has been further established as a critical element of ancillary service markets (Rahmani et al., 2024). The research investigated the impact of demand response (DR) programmes on reserve costs, demonstrating that consumption management and load-shifting strategies can significantly reduce generation and reserve costs during peak demand periods. The findings reaffirmed the essential role of consumer flexibility in ensuring economic and operational efficiency in restructured electricity markets.

Advancements in strategic bidding mechanisms have continued to refine the design of the ancillary service market. Maneesha and Swarup (2022) formulated a convex joint double-auction strategy integrating wind power plants, pumped storage hydro plants, and demand response resources within day-ahead electricity and ancillary service markets. By incorporating both upward- and downward-spinning reserves, the model effectively mitigated output imbalances and improved overall market performance. Complementary insights into market behaviour were analysed in heterogeneous consumer responses to ancillary service subscription models. The study demonstrated that subscription-based pricing can enhance market competitiveness while enabling more effective price discrimination among consumers with varying usage patterns and willingness to pay (Wang et al., 2019). The literature consistently emphasises that as renewable integration deepens, ancillary service markets must be restructured to achieve operational resilience, economic efficiency, and equitable participation across both supply and demand sides, thereby ensuring the long-term stability of future low-carbon power systems. So, the summary of selected literature on ancillary services in the energy sector is shown in Table 2.3.

Table 2.3 The selected literature on ancillary services in the energy sector

Ref.	Method	Description
Chen et al. (2007)	The optimal AGC dispatching model	• Focus on the optimal dispatch algorithm for AGC - Capacity requirements for regulation dispatch - Uncertain demand conditions • Objectives of the algorithm: - Minimise opportunity costs - Minimise uplift costs - Minimise regulation costs • Constraints considered: - Operating constraints - AGC capacity requirements - Generator ramping rate limitations - Regulation capacity constraints
Jay and Swarup (2021)	AC-OPF	• Analyze the complexities of implementing a reactive power market, emphasising uncertainty in system conditions and non-convexity of the AC-OPF problem. • Propose that nodal prices, linked to the Lagrangian dual variables of AC-OPF, offer an effective pricing mechanism by incorporating system operating conditions.
Reddy et al. (2015)	• GA - based scheduling • a two-point estimate method - based probabilistic real-time OPF	• Considering generator spinning reserve and demand-side reserve constraints • Propose a market-clearing mechanism for wind-thermal systems • Models wind volatility impact on energy and spinning reserve markets • Validates approach on IEEE 30-bus system • Compares results with Monte Carlo Simulation

Table 2.3 The selected literature on ancillary services in the energy sector (Continued)

Ref.	Method	Description
Banshwar et al. (2017)	AC OPF	• Propose a market-based approach for renewable power producers to participate in energy and ancillary service markets in a disaggregated day-ahead framework. • The method sequentially clears the EM and ASM to optimize costs and ensure feasible solutions. • Focuses on RM, specifically TMSR and TMRR. Demonstrates that RPP participation in EM and RM can lead to cost savings and effective market clearing.
Lin et al. (2021)	DPSO and SQP	• Integrates DPSO and SQP for unit commitment with ancillary services in power market. • Analyze AGC, RSR, and SR for the day-ahead power market cost model. • Comparison with GA, EP, PSO, and SA for effectiveness • Lower costs with ancillary services in power market operations.
He et al. (2023)	Bi-level game model for multi-agent load aggregators Nash equilibrium calculation using particle swarm optimization algorithm	• Proposed a bi-level game model for multi-agent load aggregators • The model aims to participate in the ancillary service market and maximize profit for each aggregator. • The bi-level model was transformed into a single-level model using the KKT condition and strong duality theory. • The non-cooperative game relationship exists between load aggregators • Nash equilibrium of the market calculated using particle swarm optimization algorithm

Table 2.3 The selected literature on ancillary services in the energy sector (Continued)

Ref.	Method	Description
Lu et al. (2024)	Convex Hull (CH) pricing	• Propose a CH pricing-based FR ancillary services market. • The market aims to enhance stability, support, and flexibility, especially from low-carbon sources. • Develop an exact CH pricing scheme using the sub-gradient surrogate Lagrangian method. • Finding improved system frequency performance, Reduced total operation costs, Lower uplift payments, and Decreased carbon emissions
Baig et al. (2021)	Inertia-dependent stochastic unit commitment (SUC) model	• Finding: AS costs in GB could rise 165% if inertia is not explicitly market-integrated. • Emphasised the critical link between inertia and frequency response.
Zheng & Litvinov (2006)	Ex post pricing framework	• Proposed for co-optimised energy and reserve (ISO New England). • Simplified pricing using a decoupled approach.
Wang et al. (2005)	Cost-benefit-based clearing model	• Determined optimal operating reserve capacity. • Assessed uniform-price and pay-as-bid auction mechanisms.
Pollitt & Anaya (2021)	Comprehensive review	• Traced the evolution of ancillary services from by-products to independent market products. • Analysed the impact of renewable integration.
Viola et al. (2024)	Systematic review (US & Europe)	• Developed a standard taxonomy for AS products. • Identified design principles for high VRE systems. • Advocated for adaptive, technology-neutral frameworks.

Table 2.3 The selected literature on ancillary services in the energy sector (Continued)

Ref.	Method	Description
Dutta et al. (2024)	Analysis of zonal reserve pricing	• Examined pricing under transmission congestion and contingencies. • Showed optimised procurement improves reliability and efficiency.
Jin et al. (2015)	Bilevel coordinated dispatch model	• Explored AS provision from active distribution networks (ADNs). • Demonstrated viability of decentralised optimisation strategies.
Rahmani et al. (2024)	Investigation of demand-side participation	• Assessed the impact of DR programmes on reserve costs. • Finding: Load-shifting strategies significantly reduce generation/reserve costs.
Maneesha & Swarup (2022)	Convex joint double-auction strategy	• Integrated wind, pumped storage, and DR in day-ahead markets. • Mitigated output imbalances by including upward/downward reserves.
Wang et al. (2019)	Analysis of consumer response models	• Studied subscription-based pricing for ancillary services. • Showed it enhances market competitiveness and price discrimination.

2.5 Carbon Pricing Mechanisms

Global climate change is one of the most pressing concerns of our time, prompting international organisations to adopt a range of mitigation policies. In 2015, countries reaffirmed their commitment to the Paris Agreement, which aims to limit the global temperature rise to below 2 degrees Celsius above pre-industrial levels, with efforts to restrict it further to 1.5 degrees Celsius. Despite these commitments, recent developments in social and industrial productivity have led to a continued increase in GHG emissions, exacerbating environmental problems. A significant contributor to this issue is the substantial GHG emissions from the consumption of fossil fuels for electricity generation, which is a primary driver of climate change and a major contributor to a country’s overall carbon footprint.

GHG emissions from organisational activities are categorised into three scopes: Scope 1 includes direct emissions from an organisation’s activities under its control; Scope 2 encompasses indirect emissions associated with the purchase of electricity, steam, heating, or cooling; and Scope 3 covers all other indirect emissions related to the organisation’s activities but originating from sources not owned or controlled by the organisation. In the electricity sector, GHG emissions arise from consumer electricity consumption (Scope 2) and from the burning of fossil fuels to generate electricity (Scope 1). Notably, over 40% of all carbon dioxide emissions from energy are linked to burning fossil fuels for electricity production, making this sector a crucial focus for reducing carbon emissions to meet climate change goals.

To address these challenges, carbon pricing mechanisms, including carbon taxes and cap-and-trade systems, have emerged as prominent policies for reducing GHG emissions. The design of institutions plays a significant role in determining the selection and feasibility of these policy options, as well as the sustainable financing of mitigation measures. Institutions that encourage participation by representatives from emerging industries and technologies can facilitate the transition to low-GHG-emission pathways. However, implementing various policies requires different levels of institutional innovation. For instance, carbon taxation can often leverage existing tax infrastructures, making it administratively simpler to implement than cap-and-trade systems. This may necessitate more complex institutional capabilities, particularly in developing countries.

Several studies have examined integrating carbon-emission costs into the optimal power dispatch framework, exploring their impact on generator schedules, system costs, and emission profiles. It is essential to use it to ensure the electrical grid remains reliable, especially as RESs are added and carbon emissions are reduced. However, these existing studies concentrate on decreasing carbon emissions without integrating carbon pricing mechanisms into single- and multi-objective OPF problems (G. Wang et al., 2022; G. Wang et al., 2023). Several methods have been proposed for an efficient method for optimising control variables in power systems with distributed RESs to minimise carbon emissions (Ilyas et al., 2020; Li et al., 2022).

Carbon pricing mechanisms, including carbon tax and cap-and-trade systems, are two of the most prominent policies for reducing GHG emissions and mitigating global climate change. The design of institutions significantly influences the selection and feasibility of policy options, as well as the sustainable financing of mitigation measures. Institutions that encourage participation by representatives from emerging industries and technologies can facilitate the transition to low-GHG-emissions pathways. The implementation of various policies differs regarding the new institutional capabilities they necessitate. Carbon taxation, for instance, can often leverage existing tax infrastructure, making it administratively simpler to implement than alternatives such as cap-and-trade systems.

Policies GHG emissions have increasingly relied on market-based instruments such as emission trading schemes (ETS) and carbon taxation, both of which aim to internalise the external costs of carbon emissions and promote cost-effective mitigation. In the power sector, these mechanisms have been widely adopted to encourage low-carbon generation and to influence investment decisions towards cleaner technologies. Under assumptions of rational market behaviour and complete markets, GHG pricing instruments are theoretically capable of achieving emission reduction targets at minimal economic cost. Carbon taxes are particularly valued for their administrative simplicity and broad applicability across sectors, as they can be levied upstream at production or import points, ensuring comprehensive coverage of carbon-intensive fuels. In most cases, such taxes are imposed on power generators, with the resulting cost burden subsequently reflected in higher wholesale electricity prices.

Empirical analyses have provided substantial evidence of the effectiveness of carbon taxation in reducing emissions within the power sector. Gugler et al. (2023) employed a regression discontinuity-in-time approach to evaluate the causal impact of the United Kingdom’s carbon tax, revealing a substantial decline in power-sector emissions between 2012 and 2016, with approximately 60% of the reduction directly attributable to the tax. Comparable outcomes were reported in Sweden, where a similar carbon pricing policy achieved significant emission abatement (Andersson, 2019). Complementing this evidence, Fang et al. (2012) developed an economic dispatch model that integrated wind power uncertainty and carbon taxation in the Australian power system. The framework minimised total operational costs, including fuel and emission expenses, while satisfying power balance and system constraints. Subsequent studies, such as that by Xuan et al. (2023), extended this line of research by incorporating carbon price uncertainty and varying carbon tax levels into investment planning for carbon capture, utilisation, and storage (CCUS) technologies. The findings revealed that increased carbon taxation levels, combined with moderate carbon price signals, can incentivise greater investment in decarbonisation technologies and accelerate emission reduction pathways.

The broader implications of carbon taxation have also been examined in the context of energy efficiency and sustainable energy system design. Zeng et al. (2019) proposed an integrated framework that combines combined cooling, heating, and power (CHP) systems with ground-source heat pumps (GSHPs), utilising carbon taxation as an incentive to enhance energy efficiency and reduce emissions. The proposed system demonstrated significant potential to align energy consumption with environmental targets. Similarly, Deng et al. (2024) investigated the integration of carbon taxation with dynamic electricity pricing mechanisms, illustrating how the coordination of economic and regulatory instruments can facilitate low-carbon transitions in the power sector. While carbon taxes provide strong and predictable price signals, ETS have emerged as flexible market-based tools that cap total emissions while allowing trading among emitters. Lin and Jia (2019) employed a dynamic recursive computable general equilibrium model to analyse the effects of ETS price levels on China’s economy and energy consumption. The results indicated that higher ETS prices can lead to deeper emission reductions but impose significant economic costs, particularly on energy-intensive industries. The analysis suggested that maintaining ETS prices between $10 and $20 would achieve meaningful emission reduction without undermining economic stability, especially when complemented by subsidies for renewable generation.

Analyses of the socio-economic implications of carbon pricing have emphasised its distributional and welfare effects across income groups and regions. Using a meta-analytical approach covering 53 empirical studies in 39 countries, Ohlendorf et al. (2021) demonstrated that progressive distributional outcomes are more likely in low-income countries and in the transport sector, particularly when indirect effects and consumer demand adjustments are incorporated into the modelling. Similarly, Dorband et al. (2019) assessed carbon pricing incidence across 87 low- and middle-income countries, revealing that moderate carbon prices can exhibit progressive characteristics in economies with per capita incomes below $15,000. These findings suggest that carbon pricing can simultaneously achieve emission mitigation, revenue generation, and inequality reduction when accompanied by appropriate fiscal frameworks.

Chen and Nie (2016) provided an economic theoretical perspective on carbon taxation by constructing a social welfare model under oligopolistic electricity market conditions. The results indicated that imposing a modest carbon tax on production links enhances social welfare, whereas taxes applied to consumption and redistribution stages can diminish welfare outcomes. The analysis underscored the need for carefully designed carbon tax structures that consider sectoral characteristics and redistribution effects. Aggarwal et al. (2025) further examined the short-term welfare implications of carbon pricing in Uganda, employing a consumer demand system for food and energy commodities. The analysis showed that a carbon price of $40 per tonne of CO_2 would reduce household welfare by 0.2-12% of total expenditure, primarily through higher electricity and fuel prices. However, the study highlighted that complementary social protection measures, such as targeted cash transfers, could mitigate adverse effects on low-income households and enhance policy acceptability. Beyond fiscal and welfare considerations, the role of carbon pricing in shaping low-carbon transition pathways has been explored through integrated modelling approaches. Yang et al. (2025) developed a cyber-physical-social system framework that co-optimises carbon reduction and carbon sequestration strategies in China’s power sector. The study employed clustering and optimisation methods to construct and evaluate diverse carbon neutrality pathways, identifying co-optimised strategies that minimise cumulative economic costs by leveraging spatiotemporal complementarities between renewable substitution and carbon capture retrofitting.

Earlier works have also addressed the broader policy and institutional challenges of carbon market design. Wang et al. (2017) examined China's carbon market mechanisms in the context of renewable energy applications in building projects, proposing a programmatic clean development mechanism (CDM) framework to facilitate the inclusion of building portfolios in carbon trading. The study identified modified volume verification as a core methodological adaptation, which enables building projects to participate effectively in carbon markets. Khastar et al. (2020) conducted an evaluative study of Finland's carbon tax policy using a computable general equilibrium model, concluding that although the tax effectively reduced emissions, it negatively affected social welfare, thereby emphasising the importance of setting an optimal carbon price that balances environmental and social objectives.

Cap-and-trade, also known as emissions trading, is a market-based mechanism for pricing greenhouse gas emissions. In this system, the government establishes an emissions cap, requiring emitters to purchase allowances for each ton of carbon dioxide equivalent released. Entities are allocated specific allowances, each representing one ton of emissions over a set period. Those exceeding their limit can purchase additional allowances from entities that emit less, creating a trading system among participants. Allowance prices are determined by market supply and demand, analogous to stock trading. This approach ensures cost-effective emissions reductions while providing certainty over the total reductions achieved. The cap-and-trade scheme thus incentivises emissions reductions and promotes economically efficient ways to meet environmental goals, balancing ecological concerns with economic considerations.

In recent literature, various models and strategies have been proposed to address the challenges of carbon pricing and its impact on economic and environmental outcomes. Lou (2023) introduced pricing models that explore how the collection ratio and carbon cap influence a manufacturer's decision-making, emphasising profit optimisation within the complexities of carbon emissions and trading mechanisms. In addition, Ouyang et al. (2024) also developed a low-carbon economic dispatch strategy for integrated power systems, leveraging the substitution effects of carbon taxes and carbon trading to enhance economic and environmental benefits. In a comparative analysis, Chen et al. (2020) evaluated carbon tax and cap-and-trade systems concerning their effectiveness, efficiency, and environmental impact. Their findings suggest that while a carbon tax is more effective in reducing emissions, a cap-and-trade system offers higher economic efficiency. This body of work collectively underscores the nuanced trade-offs between different carbon pricing mechanisms and their implications for policy and practice.

2.6 Renewable Energy Certificates

Renewable energy certificates (RECs) have emerged as a pivotal element in market-based strategies to combat climate change, gaining substantial momentum since the early 2000s. Each REC certifies that one megawatt-hour (MWh) of electricity has been generated from renewable sources and supplied to the power grid, effectively decoupling the environmental attributes of clean energy from the physical electricity produced. Ownership of a REC enables entities to claim these environmental benefits, such as reduced carbon footprint, supporting their sustainability objectives regardless of the actual energy sources used in their operations.

The REC system functions through certification by approved authorities, ensuring credibility for both electricity generators and consumers in declaring their production and usage of renewable energy. This mechanism not only facilitates the transition to sustainable energy infrastructure by converting renewable sources into tradable assets but also provides additional revenue streams for renewable energy projects through the sale of these certificates. The trading process initiates when a buyer expresses intent to purchase RECs from a seller (registrant), followed by verification and certification from an authorised REC issuer. A standardised registry system transfers the REC to the buyer upon validation, and the seller receives payment commensurate with the REC’s value, as illustrated in Figures 2.1 and 2.2.

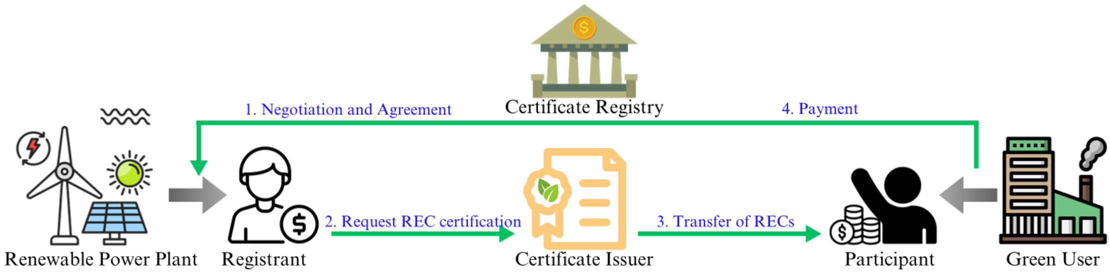

Figure 2.1 Schematic diagram of RECs trading process

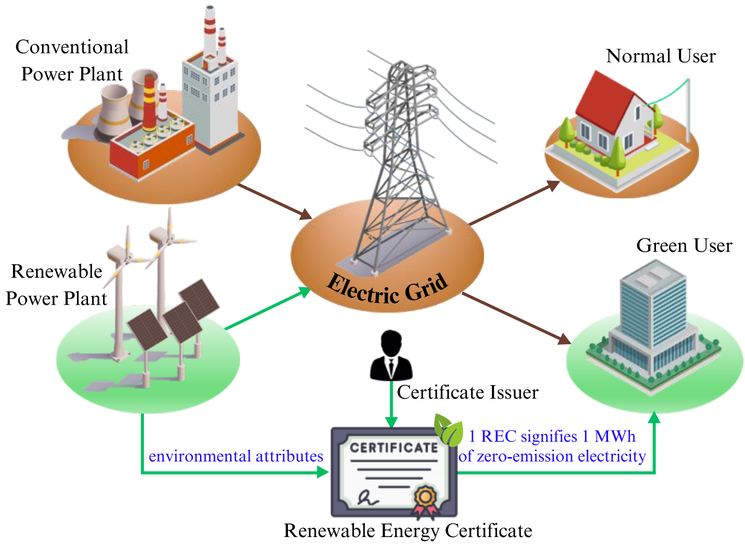

Figure 2.2 Schematic diagram of RECs trading process in the power system

The current REC issuance and tracking system is centralised, highly regulated, and operationally expensive. Further research has explored the institutional and policy dimensions of carbon markets. Ying and Xin-gang (2021) developed a system dynamics model to evaluate the interaction between renewable portfolio standards (RPS), electricity market reform, and carbon emission trading (CET) in China. The findings demonstrated that electricity market liberalisation enhances trading activity and demand for emission allowances, while the introduction of RPS may reduce the demand for emission rights and power generation from carbon-intensive sources. Yu et al. (2021) examined the integration of the tradable green certificate (TGC) market with CET in the Chinese power sector, concluding that combined implementation of these mechanisms supports emission control, optimises the generation mix, and enhances national progress toward carbon neutrality. Similarly, Tan et al. (2021)

analysed the combined effects of carbon trading and RPS within China’s multi-energy dispatching systems, demonstrating that carbon trading is more effective in emission reduction when the share of renewable generation is high, while RPS contributes more substantially to energy saving.

Zuo (2022) proposed a blockchain-based, decentralised platform for REC issuance and trading that would allow greater traceability and transparency in transactions and reduce the operational costs of REC exchanges. Additionally, Tao et al. (2021) emphasised the importance of a quantitative, balanced approach to designing REC multipliers, suggesting that such an approach can effectively support renewable energy goals by considering economic and social factors. This strategy is particularly relevant for fostering more stable and consistent energy policies, as demonstrated in the context of South Korea. Further research has also been directed towards improving the low-carbon efficiency of integrated energy systems by leveraging carbon markets and green certificate markets. Tian et al. (2023) proposed an integrated energy trading strategy incorporating the interaction between carbon emissions and green certificates. This approach has been shown to effectively reduce both operating costs and carbon emissions within an integrated energy system. Hence, the summary of the selected literature on carbon pricing mechanism and renewable energy certificates are shown in Table 2.4.

Table 2.4 The selected literature on carbon pricing mechanisms and renewable energy certificates

Ref.	Objective	Method	Description
G. Wang et al. (2022)	• Minimise generation cost • Minimise active power loss • Minimise carbon emissions	• NSGA2 algorithm • TOPSIS	• AC-OPF with carbon emissions reduction using NSGA2 algorithm • TOPSIS method for obtaining optimal solutions in multi-objective optimisation • Tested on IEEE 14-bus system
G. Wang et al. (2023)	• Minimise generation cost • Minimise active power loss • Minimise carbon emissions	• AC-OPF • NSGA-III algorithm	• Constructed OPF calculation model considering carbon emission intensity • Tested on modified IEEE 39-bus system
Ilyas et al., (2020)	• Minimise generation cost • Minimise active power loss • Minimise carbon emissions	• AC-OPF • PSO	• Integration of renewable energy sources in power flow optimisation • Use of fuzzy membership function for compromise solution extraction • Penalty function approach for constraint satisfaction • Tested on Modified IEEE 30-bus system
Li et al. (2022)	• Minimise generation cost • Minimise active power loss • Minimise voltage deviation • Minimise carbon emissions	• AC-OPF • Adaptive crossover non-dominated sorting differential evolution	• Enhances renewable energy integration in power systems • Improves decision-making for multi-objective optimal power flow • Tested on Modified IEEE 30-bus and IEEE 57-bus systems

Table 2.4 The selected literature on carbon pricing mechanisms and renewable energy certificates (Continued)

Ref.	Objective	Method	Description
Gugler et al. (2023)	• Estimate the causal effects of Britain's carbon tax on emissions in the power sector	• Regression discontinuities in time • Causal evidence for carbon tax effects	• Carbon tax led to a significant emissions decline in the British power sector • Coal was replaced by gas due to the impact of carbon pricing
Andersson (2019)	• Analyse the impact of carbon taxes on CO2 emissions in Sweden	• A synthetic control method for comparison	• Establish a causal relationship between implementing a carbon tax and the observed decline in emissions • Evaluate the effectiveness of carbon taxes relative to price elasticities
Fang et al. (2012)	• Minimise generation cost • Minimise carbon emission cost	• Quantum-Inspired Particle Swarm Optimization	• Integrates wind power uncertainty and carbon tax in economic dispatch • Carbon tax reduces emissions and impacts fossil-based generation enterprises.
Xuan et al. (2023)	• Minimise costs associated with CCUS, including investment, operational, carbon capture and storage costs, carbon taxes, and revenues from carbon pricing	• Piecewise Linearisation Method	• Considered carbon price uncertainty and varying carbon tax levels • Rising carbon taxes resulting in increased investment in technologies increases • Tested on a modified IEEE 24-bus system

Table 2.4 The selected literature on carbon pricing mechanisms and renewable energy certificates (Continued)

Ref.	Objective	Method	Description
Zeng et al. (2019)	• Minimise generation cost • Minimise carbon emission cost	• PSO combined with fish swarm algorithm	• Energy consumption, environmental pollution, and operation expense reduction • The coupling CHP-GSHP system outperforms the reference system in energy, cost, and emissions • Flexible energy output provided by the coupled system
Deng et al. (2024)	• Maximise social welfare by integrating a carbon tax	• Differential evolution algorithm combined with CPLEX solver	• Integrated energy prices with a carbon tax. • Tested on an industrial park in northern China
Lin and Jia (2019)	• To analyse the impact of different ETS price levels on the economy, energy consumption, and CO_2 emissions.	• Computable General Equilibrium (CGE) model	• Analyzes the impact of ETS price levels. • Findings: Higher prices reduce GDP and emissions; current pilot prices are too low ($10-$20 suggested) • Tested on China's ETS.
Ohlendorf et al. (2021)	• To determine the sources of variation in the distributional impacts of carbon pricing.	• Ordered Probit Meta-analysis	• Analyzes distributional impacts of carbon pricing. • Findings: Progressive outcomes are more likely in lower-income countries, the transport sector, and when indirect effects are included.

Table 2.4 The selected literature on carbon pricing mechanisms and renewable energy certificates (Continued)

Ref.	Objective	Method	Description
Dorband et al. (2019)	• To assess the distributional incidence of carbon pricing across income groups.	• Incidence Assessment and Decomposition Technique.	• Assesses distributional effects in low/middle-income countries.
Chen and Nie (2016)	• Maximise social welfare	• Classification method	• Evaluates social welfare effects of carbon in China. • Finding: A small tax on the production link raises social welfare.
Aggarwal et al. (2025)	• Maximise social welfare	• Exact Affine Stone Index demand system	• Assesses welfare and demand impacts of a \$40/tCO_2 carbon price in Uganda. • Findings: Significant welfare losses, adverse nutritional impacts, and shifts in consumption. • Recommends complementary social protection.
Yang et al. (2025)	• Minimise economic costs	• Co-optimisation framework (CPSSE & WRT)	• Develops a pathway for power sector carbon neutrality. • Focus: Co-optimisation of carbon reduction (RE) and carbon sequestration (CCS) to minimise economic costs.
Wang et al. (2017)	• To establish a feasible mechanism for RE in building projects to participate in the carbon market.	• Volume verifying method	• Focus: Integrating RE in Chinese building projects into the carbon trading market. • Recommends Programmatic CDM with a modified verification method.

Table 2.4 The selected literature on carbon pricing mechanisms and renewable energy certificates (Continued)

Ref.	Objective	Method	Description
Khastar et al. (2020)	• Maximise social welfare	• Computable General Equilibrium (CGE) Model	• To analyse the impact of Finland's carbon tax on social welfare and emission reduction. • Assesses carbon tax impacts in Finland. • Findings: The tax successfully reduced emissions but had negative effects on social welfare.
Lou (2023)	• Maximise social welfare considering production costs, demand, and carbon trading implications	• Stackelberg game model	• Analyses carbon cap-and-trade impacts on decision-making • Higher collection ratio potentially reduces emissions • A lower ratio may incentivise new product manufacturing, increasing emissions • Demonstrates interplay between remanufacturing practices and environmental outcomes
Ouyang et al. (2024)	• Minimise generation cost • Minimise carbon emission	• Monte Carlo method • Grey Wolf Optimization	• Carbon trading and renewable energy generation involve inherent uncertainties • Monte Carlo method used to analyse carbon trading price uncertainty • Long Short-Term Memory method forecasts renewable energy power and electricity load

Table 2.4 The selected literature on carbon pricing mechanisms and renewable energy certificates (Continued)

Ref.	Objective	Method	Description
Chen et al. (2020)	• Compare carbon tax and cap-and-trade systems	-	• Finding carbon tax more effective in reducing emissions than cap-and-trade. • A cap-and-trade system leads to higher economic efficiency than a carbon tax.
Ying and Xin-gang (2021)	• To simulate and evaluate the impact of RPS and electricity marketisation on CET.	• System Dynamics (SD) evaluation model	• Simulates the impact of RPS on China's CET. • Findings: Marketisation is positive for CET; RPS implementation harms CET demand.
Yu et al. (2021)	• To analyse the integrated impact of TGC and CET on the power industry.	• SD Simulation Model	• Analyses the integrated impact of TGC and CET in China's power industry. • Findings: Both mechanisms control emissions; RE investment is profitable.
Tan et al. (2021)	• To evaluate the impact mechanism of CET and RPS on a multi-energy power-dispatching system.	• Cost-accounting Models	• Compares CET and RPS. • Findings: CET is more effective with high RE; RPS is better for energy saving.

Table 2.4 The selected literature on carbon pricing mechanisms and renewable energy certificates (Continued)

Ref.	Objective	Method	Description
Zuo (2022)	• Developing a blockchain-based system for managing and trading renewable energy certificates	• Blockchain Technology	• Implementing a blockchain-based system is anticipated to lower the operational costs of REC issuance and trading
Tao et al. (2021)	• optimal REC multipliers	• LCOE-integrated AHP model	• Develop an LCOE-integrated AHP model for REC multiplier analysis • Focuses on cost-effectiveness and social concerns in determining REC multipliers • Revised REC multipliers in Korean market
Tian et al. (2023)	• Minimise generation cost	• Mixed integer linear programming problem	• Integrated energy trading strategy based on carbon emissions/green certificates • The simulation results indicate a significant reduction in operating costs and carbon emissions

2.6 Conclusion

The literature review encompasses several critical topics for studying power systems and electricity markets. It begins with exploring OPF, a fundamental concept aimed at optimising the operation of electrical power systems to minimise costs while satisfying operational constraints. This is followed by examining the spot pricing of electricity, which addresses the dynamic pricing mechanisms that reflect real-time supply and demand conditions in electricity markets. The review then examines the role of ancillary services, which are crucial for maintaining grid stability and reliability.

Furthermore, the review explores market-based emission strategies to reduce carbon emissions within the energy sector. These strategies are categorised into three main areas: carbon tax, a fiscal approach that imposes a fee on carbon emissions to incentivise lower emissions; emission trading, also known as cap-and-trade, which allows companies to buy and sell emission allowances under a capped total limit; and RECs, which provide a market-based instrument to promote renewable energy generation. These strategies are increasingly relevant in global efforts to mitigate climate change. An overview of existing literature review topics is presented in Table 2.5.

Table 2.5 The summary of selected research

Ref.	EM	CM	RES	ASM	Contribution
Schweppe et al. (1988)	✓				Spot pricing
Baughman et al. (1997)	✓				Spot pricing
Wang et al. (2023)	✓				Spot pricing
Wang et al. (2022)	✓				Spot pricing
Liu et al. (2009)	✓				Spot pricing
Yang et al. (2021)	✓				Spot pricing
Yang et al. (2017)	✓				Spot pricing
Jay and Swarup (2021)	✓			✓	Reactive power market
Chen et al. (2007)	✓			✓	AGC
Reddy et al. (2015)	✓		✓	✓	Spinning reserve
Banshwar et al. (2017)	✓		✓	✓	TMSR and TMRR
Lin et al. (2021)	✓			✓	AGC, RSR, and SR
Lu et al. (2024)	✓			✓	Frequency regulation
He et al. (2023)	✓			✓	Ancillary service market
Baig et al. (2021)	✓		✓	✓	Inertia-dependent SUC/AS costs
Zheng et al. (2006)	✓			✓	Ex-post pricing for co-optimised
Wang et al. (2005)				✓	Cost-benefit clearing for reserve
Pollitt & Anaya (2021)			✓	✓	Review of AS evolution with RE
Viola et al. (2024)			✓	✓	AS taxonomy for high-VRE systems
Dutta et al. (2024)				✓	Zonal reserve pricing
Jin et al. (2015)	✓		✓	✓	Bilevel AS dispatch from ADNs
Rahmani et al. (2024)	✓			✓	DR impact on reserve costs
Maneesha et al. (2022)	✓		✓	✓	Joint auction with wind/storage/DR
Wang et al. (2019)				✓	Subscription-based AS pricing
G. Wang et al. (2023)	✓	✓			Carbon emissions reduction
Ilyas et al. (2020)	✓	✓	✓		Carbon emissions
Li et al. (2022)	✓	✓	✓		Carbon emissions

Table 2.5 The summary of selected research (Continued)

Ref.	EM	CM	RES	ASM	Contribution
Gugler et al. (2023)	✓	✓			Carbon tax
Andersson (2019)	✓	✓			Carbon tax
Fang et al. (2012)	✓	✓			Carbon tax
Xuan et al. (2023)	✓	✓			Carbon tax
Zeng et al. (2019)	✓	✓			Carbon tax
Deng et al. (2024)	✓	✓			Carbon tax
Lin and Jia (2019)	✓		✓		CGE analysis of ETS price levels
Ohlendorf et al. (2021)	✓				Meta-analysis of carbon price distribution
Dorband et al. (2019)	✓				Distributional effects of carbon price
Chen and Nie (2016)	✓				SW model for carbon tax
Aggarwal et al. (2025)	✓				SW impact of carbon price
Yang et al. (2025)	✓		✓		Co-optimisation of RE and CCS
Wang et al. (2017)	✓		✓		Programmatic CDM for RE
Khastar et al. (2020)					CGE analysis of carbon tax
Lou (2023)	✓	✓			Carbon cap-and-trade
Ouyang et al. (2024)	✓	✓	✓		Carbon trading and RES
Chen et al. (2020)	✓	✓			Carbon tax and carbon trading
Zuo (2022)		✓	✓		REC trading Blockchain
Tao et al. (2021)	✓	✓	✓		REC
Ying et al. (2021)	✓		✓		Impact of RPS on CET market
Yu et al. (2021)	✓		✓		Integrated impact of TGC and CET
Tian et al. (2023)	✓	✓	✓		REC
Proposed method	✓	✓	✓	✓	Maximise social welfare for integrated EM, CM, REC, and ASM