CHAPTER VI
CO-OPTIMISED FRAMEWORK FOR COMBINED ELECTRICITY MARKET AND EMISSION MECHANISMS WITH RENEWABLE ENERGY CERTIFICATES AND ANCILLARY SERVICES

6.1 Chapter Overview

Achieving carbon neutrality in the power sector requires market designs that align economic efficiency with environmental sustainability and system security. This chapter proposes a co-optimised framework for combined electricity market-clearing framework that includes the electricity market (EM), the carbon pricing mechanism (CM), the renewable energy market (REM), and the ancillary services market (ASM) procurement, advancing beyond fragmented market approaches that address these objectives separately. The proposed model is applied to a 160-bus equivalent Thai power system, which reflects Thailand's distinctive regulatory structure, rapidly growing electricity demand, and national commitment to carbon neutrality. This application addresses a significant gap in the literature, which has predominantly focused on developed markets while offering limited insights for emerging economies facing unique structural and regulatory challenges.

The chapter makes four principal contributions. First, it develops an integrated market-clearing model that optimises energy dispatch, carbon pricing, renewable energy utilisation, and ancillary service procurement, overcoming the limitations of existing fragmented approaches. Second, it provides a system-specific assessment of the Thai power system, capturing the country's unique operational and regulatory characteristics. Third, the model explicitly incorporates welfare optimisation across multiple stakeholder groups, consumers, producers, government, and renewable energy participants, offering insights into the distributional consequences of multi-dimensional market mechanisms. Finally, the findings provide evidence-based recommendations for Thailand's decarbonisation pathway, with broader implications for countries balancing emission reduction, energy security, and economic competitiveness.

The analysis compares five market mechanism scenarios, revealing that while carbon taxation reduces emissions and generates fiscal revenues, it imposes welfare losses. REC trading enhances producer viability but has limited operational effects, and ancillary service procurement strengthens reliability at added cost. By contrast, the integrated multi-dimensional market reduces emissions by nearly 5%, achieves more equitable welfare distribution among stakeholders, and mitigates the drawbacks of single-policy instruments. Sensitivity analyses confirm that market integration amplifies the environmental effectiveness of carbon pricing and enhances the welfare gains from REC trading. These results demonstrate that coordinated market mechanisms can simultaneously support emission reduction, system adequacy, and fair welfare allocation, providing timely insights for Thailand's energy transition and offering broader lessons for electricity market design in emerging economies pursuing sustainable development pathways. Figure 6.1 illustrates the conceptual framework underpinning this study, where the ISO coordinates energy, renewable, and ancillary service markets alongside carbon pricing mechanisms to achieve transparency, efficiency, and decarbonisation.

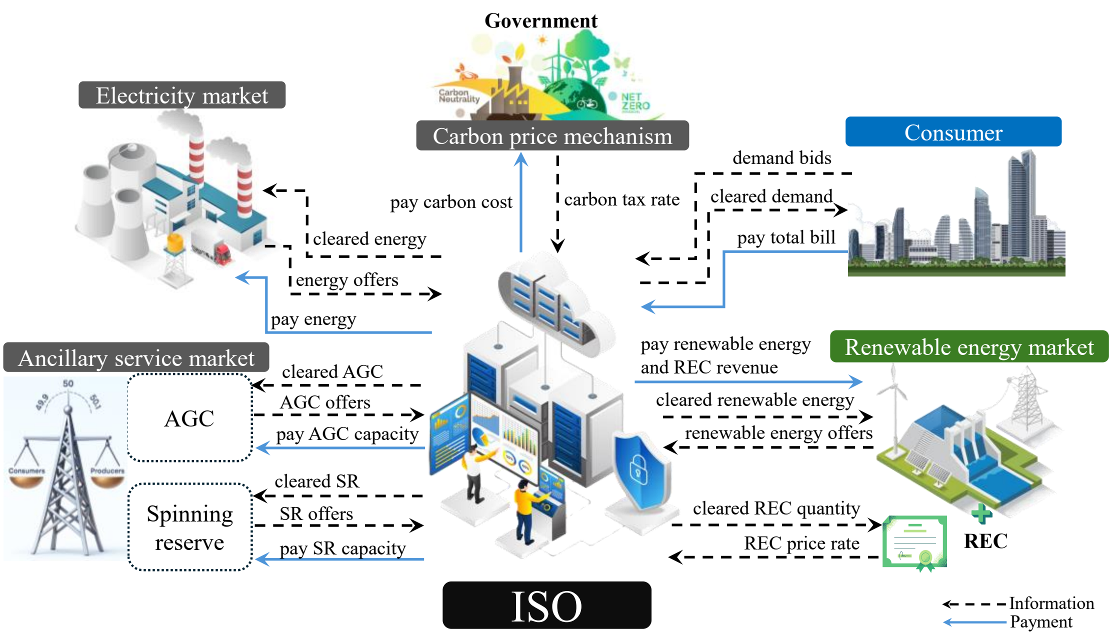

Figure 6.1 Framework of multi-dimensional markets

6.2 Economic and Market Performance Metrics

This section defines the economic and market performance metrics used to evaluate the outcomes of each market study case. These indicators measure the system's overall efficiency, welfare distribution, and the financial implications for key stakeholders. Specifically, the study employs welfare-based and revenue-based metrics to capture the economic interactions among consumers, producers, and the system operator. However, each metric is expressed in mathematical form, which collectively provides economic interpretations rather than purely mathematical constructs. Hence, this section focuses on the quantitative assessment of market efficiency, stakeholder welfare, and financial performance under different policy configurations.

6.2.1 Social Welfare

Social welfare (SW) represents a fundamental measure of market efficiency, capturing the balance between societal benefits from electricity consumption and the total system costs required to supply it. In general terms, SW is defined as the difference between the gross demand benefit, reflecting consumers' willingness to pay, and the aggregate supply costs, including generation costs, carbon emissions, renewable integration, and ancillary reserves. Two variants of social welfare to provide deeper analytical insight are considered in this study:

(1) Economic social welfare reflects the intrinsic efficiency of resource allocation by excluding financial transfers such as carbon tax payments and REC trading. This indicator isolates the pure economic outcome of market optimisation, focusing on the balance between demand benefits and real production costs, as formulated:

$$SW_{eco} = \sum_{j=1}^{ND} B_j(P_{D,j}) - \sum_{i=1}^{NG} CG(P_{G,i}) - \sum_{r=1}^{NRE} CRE(P_{RE,r}) - \sum_{i=1}^{NG} CAGC(P_{G,i}) - \sum_{i=1}^{NG} CSR(P_{G,i}). \tag{6.1}$$

(2) Post-Transfer Social Welfare, in contrast, incorporates monetary transfers arising from policy mechanisms, namely, carbon tax revenues and REC

payments, to capture the effective redistribution of welfare among market participants, including consumers, producers, and the government. This variant, therefore, represents the net financial outcome of all stakeholders after accounting for fiscal and incentive-based instruments, as defined:

$$SW_{post} = \sum_{j=1}^{ND} B_j(P_{D,j}) - \sum_{i=1}^{NG} CG(P_{G,i}) - \sum_{i=1}^{NG} CCE(P_{G,i}) - \sum_{i=1}^{NG} CAGC(P_{G,i}) - \sum_{i=1}^{NG} CSR(P_{G,i})$$
$$-\sum_{r=1}^{NRE} CRE(P_{RE,r}) + \sum_{r=1}^{NRE} RECR(P_{RE,r}), \tag{6.2}$$

where $B_j(P_{D,j})$, $CG(P_{G,i})$, $CCE(P_{G,i})$, $CAGC(P_{G,i})$, $CSR(P_{G,i})$, $CRE(P_{RE,r})$, and $RECR(P_{RE,r})$ are formulated as shown in Equations (3.16), (3.13), (3.15), (5.1), (5.2), (4.1), and (4.2), respectively.

6.2.2 Consumer Surplus

Consumer surplus (CS) measures the economic benefit that consumers receive from purchasing electricity at the market-clearing price, representing the difference between consumers' willingness to pay and the actual payment. This indicator reflects the affordability and efficiency of market outcomes from the consumer's perspective. A higher consumer surplus indicates improved welfare and competitive pricing conditions. The actual expenditures in the market, including payments for energy, reserves, and REC transfers, are defined as:

$$CS = \sum_{j=1}^{ND} B_j(P_{D,j}) - \left[\underbrace{\lambda_{CG} \sum_{j=1}^{ND} P_{D,j}}_{\text{energy revenue}} + \underbrace{\lambda_{AGC} \sum_{i=1}^{NG} AGC_i + \lambda_{SR} \sum_{i=1}^{NG} SR_i}_{\text{ancillary service revenue}} + \underbrace{\sum_{r=1}^{NRE} RECR(P_{RE,r})}_{\text{REC revenue}} \right], \tag{6.3}$$

where λ_{CG} is the energy marginal price obtained from the Lagrange multiplier of the power balance constraint, λ_{AGC} and λ_{SR} are market-clearing prices for AGC and SR, respectively.

6.2.3 Total Revenue

Total revenue quantifies the overall income generated from electricity sales and other market components, such as REC trading and ancillary service payments. This metric clearly indicates market liquidity, price signals, and financial performance under varying policy conditions, facilitating comparison across market cases to assess the impact of multi-dimensional integration on revenue generation. The mathematical representation is given by:

$$R_{total} = \underbrace{\lambda_{CG}\sum_{j=1}^{ND} P_{D,j}}_{\text{energy revenue}} + \underbrace{\lambda_{AGC}\sum_{i=1}^{NG} AGC_i + \lambda_{SR}\sum_{i=1}^{NG} SR_i}_{\text{ancillary service revenue}} + \underbrace{\sum_{r=1}^{NRE} RECR(P_{RE,r})}_{\text{REC revenue}} . \tag{6.4}$$

6.2.4 Producer Surplus

Producer surplus (PS) represents the total benefit to generation companies. It is calculated as the difference between market revenues and production costs, serving as a measure of producer profitability and market competitiveness. Changes in producer surplus across scenarios indicate that policy instruments, such as carbon pricing, renewable incentives, or ancillary service payments, affect generator welfare and market incentives. The producer surplus is expressed as:

$$\begin{aligned} PS = R_{total} - \Bigg[& \sum_{i=1}^{NG} CG(P_{G,i}) + \sum_{i=1}^{NG} CCE(P_{G,i}) + \sum_{i=1}^{NG} CAGC(P_{G,i}) + \sum_{i=1}^{NG} CSR(P_{G,i}) \\ & + \sum_{r=1}^{NRE} CRE(P_{RE,r}) \Bigg]. \end{aligned} \tag{6.5}$$

6.3 Objective Function and Study Cases

The proposed model evaluates the implications of different policy instruments within a double-side auction in five market study cases. Each case activates a subset of the available markets, including EM, CM, REM, and ASM, and defines a corresponding welfare-maximising objective function. Table 6.1 summarises market cases under a double-sided auction framework.

6.3.1 Case 6.0: Baseline Case

This case represents a conventional energy-only market, serving as the baseline for evaluating the impacts of subsequent policy interventions. Within the double-sided auction framework, the market-clearing process considers only the electricity market on the supply side, where generation companies submit energy offers while consumers submit demand bids. The corresponding objective function for this case is formulated to maximise the social welfare derived solely from energy transactions, without incorporating carbon pricing, renewable energy incentives, or ancillary service procurement as follows:

$$\text{maximise} \qquad f_{6.0}(x,u) = \left[\sum_{j=1}^{ND} B_j(P_{D,j}) - \sum_{i=1}^{NG} CG(P_{G,i}) \right] + \mu \cdot \left[g(x,u) \right]^2 , \tag{6.6}$$

subject to equality and inequality constraints as in Equations (3.4)-(3.12).

6.3.2 Case 6.1: Carbon Pricing Mechanism

In this case, a carbon tax is introduced to internalise the environmental externalities associated with fossil-fuel-based generation. The carbon pricing mechanism directly influences generation dispatch decisions by adding a cost component proportional to each generator's carbon emission rate. Under the double-sided auction, this tax redistributes welfare through government revenue collection while incentivising cleaner generation choices. The objective function in this scenario includes the carbon cost term within the welfare optimisation problem, thereby reflecting both economic and environmental considerations in the market-clearing process as follows:

$$\text{maximise} \qquad f_{6.1}(x,u) = \left[\sum_{j=1}^{ND} B_j(P_{D,j}) - \sum_{i=1}^{NG} CG(P_{G,i}) - \sum_{i=1}^{NG} CCE(P_{G,i}) \right] + \mu \cdot \left[g(x,u) \right]^2 , \tag{6.7}$$

subject to equality and inequality constraints as in Equations (3.4)-(3.12).

6.3.3 Case 6.2: Renewable Energy Market

Case 6.2 extends the baseline framework to include renewable energy generation and REC trading. The objective of this case is to examine whether renewable incentives alter producer revenues, market equilibrium, and social welfare outcomes. Within the double-sided auction, renewable producers submit bids representing generation costs, while REC prices are endogenously determined based on demand from obligated entities or consumers seeking clean energy participation. The objective function, therefore, integrates REC revenue streams and renewable generation costs, allowing assessment of clean energy policies' effect on market efficiency and the financial viability of renewable producers. So, the objective function is defined as follows:

$$\text{maximise} \quad f_{6.2}(x,u) = \left[\sum_{j=1}^{ND} B_j(P_{D,j}) - \sum_{i=1}^{NG} CG(P_{G,i}) - \sum_{r=1}^{NRE} CRE(P_{RE,r}) + \sum_{r=1}^{NRE} RECR(P_{RE,r}) \right] + \mu \cdot \left[g(x,u) \right]^2 \tag{6.8}$$

subject to equality as in Equations (4.7) and (3.5) and inequality constraints as in Equations (3.6)-(3.12).

6.3.4 Case 6.3: Ancillary Services Market

This case incorporates ancillary service co-optimisation alongside the electricity market to reflect system security requirements. Specifically, the model accounts for AGC and SR obligations. The double-sided auction structure is expanded to include bids for ancillary services from generation companies, with corresponding costs and benefits integrated into the market-clearing process. The objective function maximises social welfare by jointly optimising energy and ancillary service procurement, capturing the trade-offs between security enhancement and increased operational costs, as follows:

$$\text{maximise} \quad f_{6.3}(x,u) = \left[\sum_{j=1}^{ND} B_j(P_{D,j}) - \sum_{i=1}^{NG} CG(P_{G,i}) - \sum_{i=1}^{NG} CAGC(P_{G,i}) - \sum_{i=1}^{NG} CSR(P_{G,i}) \right] + \mu \cdot \left[g(x,u) \right]^2, \tag{6.9}$$

subject to equality as in Equations (5.16) and (3.5) and inequality constraints as in Equations (5.9)-(5.14).

6.3.5 Case 6.4: Multi-Dimensional Market Mechanism

The final case represents the fully integrated market framework, in which all policy instruments, carbon pricing, renewable energy incentives, and ancillary services are co-optimised simultaneously. This configuration captures the interactive effects among environmental, renewable, and security objectives, offering the most comprehensive representation of a real-world multi-dimensional market. Within the double-sided auction, the ISO clears energy, REC, and ancillary service bids concurrently, ensuring consistency in price signals and welfare allocation across all market segments. The objective function combines all relevant cost and benefit components, enabling an integrated optimisation that balances economic efficiency, environmental sustainability, and system security. Hence, the objective function is formulated as follows:

maximise
$$f_{6.4}(x,u)=\left[\sum_{j=1}^{ND}B_j(P_{D,j})-\sum_{i=1}^{NG}CG(P_{G,i})-\sum_{i=1}^{NG}CCE(P_{G,i})-\sum_{i=1}^{NG}CAGC(P_{G,i})\right.$$
$$\left.-\sum_{i=1}^{NG}CSR(P_{G,i})-\sum_{r=1}^{NRE}CRE(P_{RE,r})+\sum_{r=1}^{NRE}RECR(P_{RE,r})\right]+\mu\cdot\left[g(x,u)\right]^2, \quad (6.10)$$

subject to:

$$\sum_{i=1}^{NG}P_{G,i}+\sum_{i=1}^{NG}AGC_i+\sum_{i=1}^{NG}SR_i+\sum_{r=1}^{NRE}P_{RE,r}=\sum_{j=1}^{ND}P_{D,j}\ , \quad (6.11)$$

$$P_{G,i}^{\min}\le P_{G,i}\le P_{G,i}^{\max}\ ,\quad 0\le AGC_i\le AGC_i^{\max},\quad 0\le SR_i\le SR_i^{\max},\quad P_{RE,r}^{\min}\le P_{RE,r}\le P_{RE,r}^{\max},$$
and

$$P_{G,i}+AGC_i+SR_i\le P_{G,i}^{\max},\ i=1,\ldots,NG\ , \quad (6.12)$$

$$\sum_{i=1}^{NG}AGC_i\ge\%AGCR\left(\sum_{i=1}^{NG}P_{G,i}+\sum_{r=1}^{NRE}P_{RE,r}\right), \quad (6.13)$$

$$\sum_{i=1}^{NG}SR_i\ge\%SRR\left(\sum_{i=1}^{NG}P_{G,i}+\sum_{r=1}^{NRE}P_{RE,r}\right), \quad (6.14)$$

Table 6.1 Market study cases under double-side auction framework

Case	Market components	Objective function
Case 6.0	EM	Welfare maximisation with energy cost-benefit only
Case 6.1	EM+CM	Adds carbon cost into the market mechanism to internalise emissions
Case 6.2	EM+REM	Includes REC revenues and renewable energy in the market mechanism
Case 6.3	EM+ASM	Co-optimises AGC and SR procurement with energy market
Case 6.4	EM+CM+REM+ASM	Multi-dimensional framework with environmental, renewable, and security of supply to the market mechanism

6.4 Methodology

This study employs two optimisation approaches, including quadratic programming (QP) and hybrid particle swarm optimisation-quadratic programming (PSO-QP), to determine the optimal market-clearing outcomes under different policy and operational scenarios. The comparative application of these two techniques allows for assessing economic and technical efficiency in the integrated market framework. The QP-based optimisation provides an efficient means for solving the economic dispatch problem, particularly in markets where only real power generation is treated as a control variable. This method is suitable for convex quadratic cost functions and linear or mildly nonlinear constraints, making it computationally efficient and appropriate for initial benchmark studies. However, QP assumes simplified network conditions, typically DC-based formulations, and therefore cannot fully represent the nonlinear power flow and voltage-dependent characteristics of actual AC systems.

To overcome these limitations, the hybrid PSO-QP approach is introduced. In this method, PSO is employed to fine-tune nonlinear control variables, which directly influence reactive power flow, transmission losses, and system stability. These Variables significantly affect the feasible operating region of the power system and the resulting market outcomes. The QP algorithm is then embedded as a local solver within the PSO framework to optimise the generation dispatch for each candidate solution proposed by PSO. This hybrid structure enables the model to combine the global exploration capability of PSO with the fast convergence and precision of QP, achieving solutions that are both economically optimal and technically feasible under realistic AC network constraints. As a result, the hybrid PSO-QP framework provides a more accurate representation of system operations in integrated electricity markets that include environmental, renewable, and reliability considerations. The subsequent sections detail the implementation of each method. Section 6.4.1 presents the QP optimisation process, while Section 6.4.2 explains the hybrid PSO-QP approach and its computational procedure.

6.4.1 Quadratic Programming Optimisation

QP optimisation is applied to determine the optimal energy dispatch that maximises total social welfare within a convex optimisation framework. The objective function is quadratic, while all equality and inequality constraints are linear. This structure allows for efficient computation and ensures convergence to a unique global solution. The general quadratic programming structure is given as in Equation (5.24). So, the procedural steps for the QP optimisation are as follows:

(1) Case 6.0: Baseline Case

Step 1: Gather all required system data.

Step 2: Perform a power flow analysis to determine the $P_{G,i}$ and $P_{D,j}$.

Step 3: Define the control variables are $P_{G,i}$ and $P_{D,j}$ as in Equation (5.26) and

$$\mathbf{x}_{P_D} = [P_{D,1}, \ldots, P_{D,ND}] \tag{6.15}$$

Step 4: Minimise the objective function, as in Equation (6.6), using QP as follows:

$$\mathbf{H}_{6.0} = \begin{bmatrix} \mathbf{H}_{P_G} & 0_{ND\times ND} \\ 0_{ND\times ND} & \mathbf{H}_{P_D} \end{bmatrix}_{(NG+ND)\times(NG+ND)}, \tag{6.16}$$

$$\mathbf{f}_{6.0} = [B_{G,1} \ldots B_{G,NG} \;\; S_1 \ldots S_{ND}]^T, \tag{6.17}$$

where:

$$\mathbf{H}_{P_G} = \begin{bmatrix} 2A_{G,1} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 2A_{G,NG} \end{bmatrix}_{NG\times NG}, \tag{6.18}$$

$$\mathbf{H}_{P_D} = \begin{bmatrix} 2T_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 2T_{ND} \end{bmatrix}_{ND\times ND}, \tag{6.19}$$

$$\mathbf{x}_{6.0} = \left[\mathbf{x}_{P_G} \;\; \mathbf{x}_{P_D} \right], \tag{6.20}$$

$$A_{G,i} = a_i ,\; B_{G,i} = b_i ,\; i = 1,\dots,NG , \tag{6.21}$$

$$T_j = d_j ,\; S_j = e_j ,\; j = 1,\dots,ND, \tag{6.22}$$

Step 5: Verify that the optimised values satisfy the power balance constraint, reserve requirements, and operational limits for $P_{G,i}$ and $P_{D,j}$. If any constraints are violated, refine the QP setup and resolve.

(2) Case 6.1: Carbon Pricing Mechanism

Step 1: Gather all required system data.

Step 2: Perform a power flow analysis to determine the $P_{G,i}$ and $P_{D,j}$.

Step 3: Define the control variables are $P_{G,i}$ and $P_{D,j}$ as in Equations (5.26) and (6.15).

Step 4: Minimise the objective function, as in Equation (6.7), using QP as follows:

$$\mathbf{H}_{6.1} = \begin{bmatrix} \mathbf{H}_{5.1a,1} & 0_{ND\times ND} \\ 0_{ND\times ND} & \mathbf{H}_{P_D} \end{bmatrix}_{(NG+ND)\times(NG+ND)}, \tag{6.23}$$

$$\mathbf{f}_{6.1} = [B_1 \dots B_{NG} \;\; S_1 \dots S_{ND}]^T , \tag{6.24}$$

where:

$$\mathbf{x}_{6.1} = \left[\mathbf{x}_{P_G} \;\; \mathbf{x}_{P_D} \right]. \tag{6.25}$$

Step 5: Verify that the optimised values satisfy the power balance constraint, reserve requirements, and operational limits for $P_{G,i}$ and $P_{D,j}$. If any constraints are violated, refine the QP setup and resolve.

(3) Case 6.2: Renewable Energy Market

Step 1: Gather all required system data.

Step 2: Perform a power flow analysis to determine the $P_{G,i}$ and $P_{D,j}$.

Step 3: Define the control variables are $P_{G,i}$, $P_{D,j}$, and $P_{RE,r}$ as in Equations (5.26), (6.15), and

$$\mathbf{x}_{P_{RE}} = [P_{RE,1}, \ldots, P_{RE,NRE}] \tag{6.26}$$

Step 4: Minimise the objective function, as in Equation (6.8), using QP as follows:

$$\mathbf{H}_{6.2} = \begin{bmatrix} \overset{P_G}{\mathbf{H}_{P_G}} & \overbrace{0_{(NRE+1)\times(NRE+1)}}^{P_{RE} \text{ and } REC} & \overbrace{0_{ND\times ND}}^{P_D} \\ 0_{(NRE+1)\times(NRE+1)} & \mathbf{H}_{P_{RE}} & 0_{ND\times ND} \\ 0_{ND\times ND} & 0_{ND\times ND} & \mathbf{H}_{P_D} \end{bmatrix}_{(NG+NRE+1+ND)\times(NG+NRE+1+ND)} \text{,(6.27)}$$

$$\mathbf{f}_{6.2} = [B_{G,1} \ldots B_{G,NG} \;\; K_1 \ldots K_{RE} \;\; RECR \;\; S_1 \ldots S_{ND}]^T, \tag{6.28}$$

where:

$$\mathbf{H}_{P_{RE}} = \begin{bmatrix} \overbrace{\begin{matrix} 2R_1 & \ldots & 0 \end{matrix}}^{P_{RE}} & \overset{REC}{0} \\ \begin{matrix} \vdots & \ddots & \vdots \end{matrix} & \vdots \\ \begin{matrix} 0 & \ldots & 2R_{NRE} \end{matrix} & 0 \\ \begin{matrix} 0 & \ldots & 0 \end{matrix} & 0 \end{bmatrix}_{(NRE+1)\times(NRE+1)} , \tag{6.29}$$

$$\mathbf{x}_{6.2} = \left[\mathbf{x}_{P_G} \;\; \mathbf{x}_{P_{RE}} \;\; \mathbf{x}_{P_D} \right], \; K_r = f_r \,, \; r = 1, \ldots, NRE \,. \tag{6.30}$$

Step 5: Verify that the optimised values satisfy the power balance constraint, reserve requirements, and operational limits for $P_{G,i}$ and $P_{D,j}$. If any constraints are violated, refine the QP setup and resolve.

(4) Case 6.3: Ancillary Services Market

Step 1: Gather all required system data.

Step 2: Perform a power flow analysis to determine the $P_{G,i}$ and $P_{D,j}$.

Step 3: Define the control variables are $P_{G,i}$, AGC_i, SR_i, and $P_{D,j}$, as in Equations (5.26), (5.27), (5.28), and (6.15).

Step 4: Minimise the objective function, as in Equation (6.9), using QP as follows:

$$\mathbf{H}_{6.3} = \begin{bmatrix} \overbrace{\mathbf{H}_{P_G}}^{P_G} & \overbrace{0_{ND\times ND}}^{P_D} & \overbrace{0_{NG\times NG}}^{AGC} & \overbrace{0_{NG\times NG}}^{SR} \\ 0_{ND\times ND} & \mathbf{H}_{P_D} & 0_{NG\times NG} & 0_{NG\times NG} \\ 0_{NG\times NG} & 0_{NG\times NG} & 0_{NG\times NG} & 0_{NG\times NG} \\ 0_{NG\times NG} & 0_{NG\times NG} & 0_{NG\times NG} & 0_{NG\times NG} \end{bmatrix}_{(3\cdot NG+ND)\times(3\cdot NG+ND)}, \tag{6.31}$$

$$\mathbf{f}_{6.3} = [B_{G,1} \ldots B_{G,NG} \;\; S_1 \ldots S_{ND} \;\; AGCP_1 \ldots AGCP_{NG} \;\; SRP_1 \ldots SRP_{NG}]^T, \tag{6.32}$$

where:

$$\mathbf{x}_{6.3} = \left[\mathbf{x}_{P_G} \;\; \mathbf{x}_{P_D} \;\; \mathbf{x}_{AGC} \;\; \mathbf{x}_{SR}\right]. \tag{6.33}$$

Step 5: Verify that the optimised values satisfy the power balance constraint, reserve requirements, and operational limits for $P_{G,i}$ and $P_{D,j}$. If any constraints are violated, refine the QP setup and resolve.

(5) Case 6.4: Multi-Dimensional Market Mechanism

Step 1: Gather all required system data.

Step 2: Perform a power flow analysis to determine the $P_{G,i}$ and $P_{D,j}$.

Step 3: Define the control variables are $P_{G,i}$, AGC_i, SR_i, $P_{RE,r}$ and $P_{D,j}$, as in Equations (5.26), (5.27), (5.28), (6.26), and (6.15).

Step 4: Minimise the objective function, as in Equation (6.10), using QP as follows:

$$\mathbf{H}_{6.4} = \begin{bmatrix} \overbrace{\mathbf{H}_{5.1a,1}}^{P_G \text{ and Carbon}} & \overbrace{0_{NG\times NG}}^{AGC} & \overbrace{0_{NG\times NG}}^{SR} & \overbrace{0_{(NRE+1)\times(NRE+1)}}^{P_{RE} \text{ and } REC} & \overbrace{0_{ND\times ND}}^{P_D} \\ 0_{NG\times NG} & 0_{NG\times NG} & 0_{NG\times NG} & 0_{(NRE+1)\times(NRE+1)} & 0_{ND\times ND} \\ 0_{NG\times NG} & 0_{NG\times NG} & 0_{NG\times NG} & 0_{(NRE+1)\times(NRE+1)} & 0_{ND\times ND} \\ 0_{(NRE+1)\times(NRE+1)} & 0_{(NRE+1)\times(NRE+1)} & 0_{(NRE+1)\times(NRE+1)} & \mathbf{H}_{P_{RE}} & 0_{ND\times ND} \\ 0_{ND\times ND} & 0_{ND\times ND} & 0_{ND\times ND} & 0_{ND\times ND} & \mathbf{H}_{P_D} \end{bmatrix}_{(3\cdot NG+(NRE+1)+ND)\times(3\cdot NG+(NRE+1)+ND)}, \tag{6.34}$$

$$\mathbf{f}_{6.4} = [B_1 \dots B_{NG} \;\; AGCP_1 \dots AGCP_{NG} \;\; SRP_1 \dots SRP_{NG} \;\; K_1 \dots K_{RE} \;\; RECR \;\; S_1 \dots S_{ND} \;]^T, \tag{6.35}$$

where:

$$\mathbf{x}_{6.4} = \left[\mathbf{x}_{P_G} \;\; \mathbf{x}_{AGC} \;\; \mathbf{x}_{SR} \;\; \mathbf{x}_{P_{RE}} \;\; \mathbf{x}_{P_D} \right]. \tag{6.36}$$

Step 5: Verify that the optimised values satisfy the power balance constraint, reserve requirements, and operational limits for $P_{G,i}$ and $P_{D,j}$. If any constraints are violated, refine the QP setup and resolve.

6.4.2 Hybrid Particle Swarm Optimisation-Quadratic Programming

The hybrid PSO-QP method integrates the global search capability of PSO with the precision and convergence efficiency of QP. This hybrid structure is designed to overcome the local optimality limitations of conventional QP while maintaining computational robustness in solving complex non-linear optimisation problems. In this approach, the control variables encompass the complete set of parameters from the AC-OPF framework, including generator active power, voltage magnitudes, transformer tap-changing, and reactor reactances. The PSO algorithm first performs a global exploration of the solution space to identify promising candidate solutions, which are then refined using the QP module for local optimisation under precise constraint satisfaction. So, the procedural steps for the Hybrid PSO-QP optimisation are as follows:

Step 1: Gather all required system data. Define upper and lower bounds for all control variables related to network and market optimisation.

Step 2: Specify the optimisation architecture and performance metric, set the PSO parameters, and configure the QP solver settings.

Step 3: Define PSO control variables as follows:

$$\mathbf{x}_{PSO} = \left[V_1, \ldots, V_{NG}, T_1, \ldots, T_{NL}, X_{C,1}, \ldots, X_{C,NC} \right]. \tag{6.37}$$

And define QP control variables for Cases 6.0, 6.1, 6.2, 6.3, and 6.4 are as in Equations (6.20), (6.25), (6.30), (6.33), and (6.36).

Step 4: Formulate the objective function representing social welfare maximisation according to Equations (6.6)-(6.14), integrating all relevant cost and benefit components.

Step 5: Initialise the PSO parameters, including particle positions and velocities, randomly within the specified bounds of V, T, and X_C.

Step 6: Execute the PSO process incorporating power flow analysis. For each particle i at iteration k, apply particle control settings to the network model and perform an AC power flow to update the network admittance and determine system states such as voltage profiles, line flows, and transmission losses.

Step 7: Formulate the QP sub-problem conditional on the current particle's network configuration, representing the inner optimisation for market-clearing variables under given system states.

Step 8: Solve the inner QP to obtain QP control variables. If the solver returns an infeasible solution, apply a penalty or modify constraint limits and attempt a remedial re-solve.

Step 9: Evaluate the fitness function for each particle by computing the financial social welfare from the QP results combined with the particle's network variables. Include penalty terms for any constraint violations.

Step 10: Update each particle's personal best and the global best based on the evaluated fitness. Subsequently, update particle velocities and positions using the standard PSO update equations, ensuring all control variables remain within their respective bounds.

Step 11: Check for constraint violations across the current iteration. If any violation exceeds the defined tolerance, apply adaptive penalties or correction mechanisms and return to Step 6 to re-evaluate the adjusted particle.

Step 12: If iteration count k reaches the maximum iteration or improvement in gbest < tolerance, proceed to final refinement. Otherwise, increment k and repeat Steps 6-11.

Step 13: Fix the best control variables (V, T, and X_C) obtained from PSO and perform a high-precision QP refinement with tightened tolerances to compute the final optimised solution vector. Verify the KKT residuals and solver diagnostics to ensure optimality and feasibility.

Step 14: Conduct a final AC power flow validation using the complete optimised set (P_G, P_D, P_{RE}, AGC, SR, V, T, and X_C). If any constraint is violated, apply targeted and return to Step 13.

Step 15: Record the final optimal results, including total generation, losses, emissions, financial social welfare, and computation time.

6.5 Simulation Results and Discussions

This study evaluates the proposed integrated market framework on the 160-bus equivalent Thai power system, which represents a realistic and complex system suitable for policy-oriented market analysis. The framework integrates energy, carbon, renewable, and ancillary service markets under a double-sided auction mechanism. The following subsections describe the test system and the market scenarios considered in the analysis. The test system comprises 42 conventional generating units, including one reference unit, five dispatchable renewable energy resources, and 59 demand bidding areas, all interconnected through 85 AC transmission lines, 100 on-load tap-changing transformers, and 22 shunt devices that provide local reactive compensation. The system also models ancillary services with requirements for AGC and SR, each set at 5% of total system demand. Policy parameters include a carbon tax rate of 200 THB/tCO_2 and a REC price of 200 THB/REC, ensuring that environmental and renewable incentives are explicitly incorporated into the optimisation process. The characteristics of the test system are summarized in Table 6.2. This analysis employs and compares two distinct optimisation approaches. The simulation results are presented in the subsequent subsections: Section 6.5.1 details the outcomes derived using QP optimisation. In contrast, Section 6.5.2 presents the results from a hybrid PSO-QP algorithm.

Table 6.2 The 160-bus equivalent Thai power system data

Parameter	Value	Description
Total generation offers	20,986 MW	Maximum capacity for all conventional units
Total demand bids	22,093 MW	Aggregated demand offers across 59 bidding areas
Dispatchable renewable energy capacity	2,520 MW	Available renewable power from 5 sites
AGC capacity	3,450 MW	Total AGC available from participating generators
SR capacity	3,450 MW	Maximum spinning reserve contribution
AGC requirement	5% of demand	Minimum proportion of demand allocated to AGC
SR requirement	5% of demand	Minimum proportion of demand allocated to SR
Carbon tax rate	200 THB/tCo_2	Cost imposed on generator emissions
REC price	200 THB/REC	Market price for renewable energy certificates

6.5.1 Simulation Results using QP Optimisation

The proposed model presents five market scenarios, as shown in Table 6.3, where dispatch, generation costs, emissions, and policy-related revenues are reported. The results provide a quantitative foundation for understanding which alternative market designs reshape operational efficiency, environmental performance, and welfare distribution. By progressively introducing carbon taxation, renewable incentives, and ancillary service requirements, the scenarios reveal the isolated and combined effects of policy instruments on market outcomes.

The baseline energy-only case (Case 6.0) yields the highest dispatch of 18,792 MW and the highest emissions of 10,774 tCO_2/h, reflecting the absence of environmental regulation and reserve obligations. This benchmark highlights the efficiency of unconstrained operation but also exposes its ecological cost. When a carbon tax is introduced in Case 6.1, dispatch declines marginally to 18,735 MW, accompanied by a modest reduction in emissions of approximately 0.3%. Although the system-wide change is limited, the policy alters welfare allocation by transferring a portion of producer surplus to government revenue, thereby internalising part of the environmental externality.

The addition of renewable incentives in Case 6.2, through REC trading, leaves dispatch and emissions virtually unchanged at 18,730 MW and 10,739 tCO_2/h, respectively. Nevertheless, financial flows are significantly affected, producer surplus and overall welfare increase due to the revenues from REC. This suggests that REC mechanisms primarily operate as financial instruments that enhance welfare distribution without altering the operational merit order. In Case 6.3, the procurement of ancillary services fundamentally changes the allocation of capacity. The total dispatch reduction to 18,204 MW from the generation fleet is reserved for AGC and SR requirements. While this strengthens system reliability, the associated reserve costs reduce consumer and producer surpluses, resulting in a total decline in overall welfare compared to previous scenarios. The multi-dimensional market (Case 6.4) produces the most balanced outcome. Dispatch decreases further to 17,872 MW, while emissions decline by nearly 5% relative to the baseline. At the same time, the joint activation of carbon pricing, REC trading, and ancillary service procurement generates multiple revenue streams, diversifying welfare distribution across stakeholders. Although total costs are higher, the complementarities among policy instruments mitigate adverse distributional effects, yielding a more sustainable welfare configuration.

In terms of welfare decomposition, economic and financial social welfares reveal significant differences across scenarios. In Case 6.0, both coincide at 49.1 billion THB/h, reflecting the absence of policy effects. With carbon taxation in Case 6.1, SW_{eco} declines to 46.9 billion THB/h, while SW_{post} remains stable as fiscal revenues offset efficiency losses. In Case 6.2, REC incentives yield the highest SW_{eco} of 55.9 billion THB/h, though SW_{post} is slightly lower at 55.4 billion THB/h. Ancillary service procurement in Case 6.3 reduces both measures to 46.3 billion THB/h, highlighting the economic burden of reserve requirements. The multi-dimensional design in Case 6.4 restores SW_{eco} to 50.7 billion THB/h and further raises SW_{post} to 52.2 billion THB/h, demonstrating that combined policy instruments balance efficiency trade-offs with financial redistribution.

These comparative results demonstrate the policy relevance of a multi-dimensional market design that incorporates environmental costs, renewable incentives, and reliability services within a unified welfare-maximising framework. The multi-dimensional scenario demonstrates that market structures can be aligned with broader policy objectives rather than focusing solely on efficiency or short-term cost minimisation. Moreover, it illustrates a pathway to balance economic performance with emission reduction and system adequacy. This highlights the potential of multi-dimensional electricity markets to support sustainable energy transitions while ensuring a more even distribution of welfare among stakeholders.

Table 6.3 Simulation results from QP method [Part I]

Case	Total P_G (MW)	CG (THB/h)	CE (tCO_2/h)	CCE (THB/h)	Total P_{RE} (MWh)	CRE (THB/h)	$RECR$ (THB/h)
Case 6.0	18,792.1	18,622,750	10,773.78	0	0	0	0
Case 6.1	18,735.09	18,445,308	10,741.96	2,148,393	0	0	0
Case 6.2	18,730.45	18,431,145	10,739.38	0	2,520	1,514,566	504,000
Case 6.3	18,203.71	17,359,255	10,437.78	0	0	0	0
Case 6.4	17,872	16,655,174	10,248.47	2,049,693	2,520	1,514,566	504,000

Table 6.3 Simulation results from QP method [Part II]

Case	Total AGC (MW)	$CAGC$ (THB/h)	Total SR (MW)	CSR (THB/h)	Total P_D (MW)	B (THB/h)	SW_{eco} (THB/h)	SW_{post} (THB/h)
Case 6.0	0	0	0	0	18,792.1	67,721,650	49,098,900	49,098,900
Case 6.1	0	0	0	0	18,735.09	67,541,027	46,947,326	49,095,719
Case 6.2	0	0	0	0	21,250.45	75,366,381	55,924,670	55,420,670
Case 6.3	910.19	1,115,100	910.19	1,040,730	18,203.71	65,856,992	46,341,907	46,341,907
Case 6.4	1,019.6	1,208,840	1,019.6	1,126,057	20,392	72,746,680	50,696,349	52,242,043

Note: Detailed simulation results are addressed in Table B.2 (Appendix B.2)

(1) Welfare Redistribution and Stakeholder Impacts

An essential dimension of the simulation results concerns the redistribution of welfare among consumers, producers, government, and renewable participants. Figure 6.2 illustrates the decomposition of post-transfer social welfare across scenarios. In the baseline, welfare is derived entirely from consumer and producer surplus. With the introduction of a carbon tax in Case 6.1, government revenue emerges as a new component, while producer surplus declines. In Case 6.2, REC trading increases producer surplus through additional renewable income, leaving consumer surplus largely unaffected. The inclusion of ancillary services in Case 6.3 reallocates part of welfare to reserve providers but reduces the overall level due to higher costs. Case 6.4 illustrates a more balanced configuration that incorporates contributions from consumers, producers, the government, and REC revenues. The incremental effects are more clearly illustrated in Figure 6.3, which compares welfare changes relative to the baseline. Carbon taxation (Case 6.1) reduces overall welfare due to compliance costs, whereas REC incentives (Case 6.2) increase welfare by adding renewable revenues without increasing system costs. Ancillary service procurement (Case 6.3) again reduces welfare, reflecting the cost of reliability requirements. However, the multi-dimensional framework in Case 6.4 yields a net positive effect, confirming that complementarities among instruments can offset their individual drawbacks.

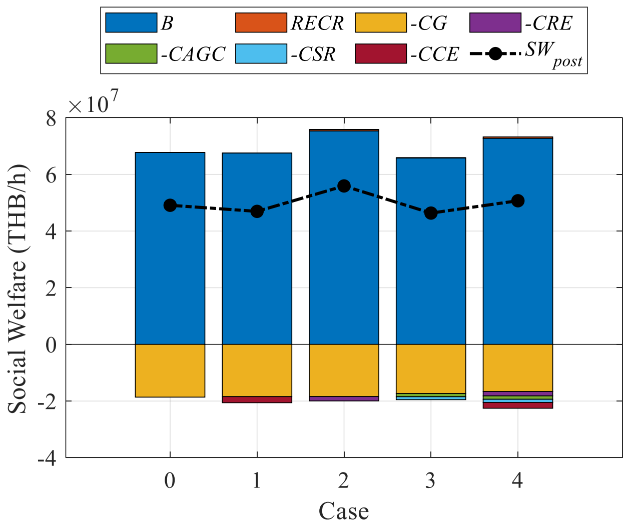

Figure 6.2 Decomposition of post-transfer social welfare

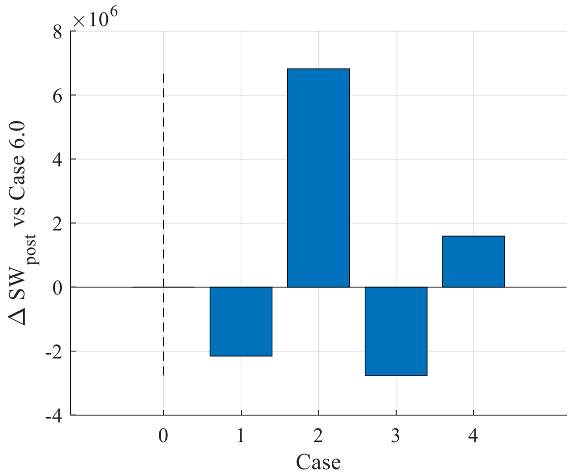

Figure 6.3 Incremental decomposition of post-transfer social welfare across market cases

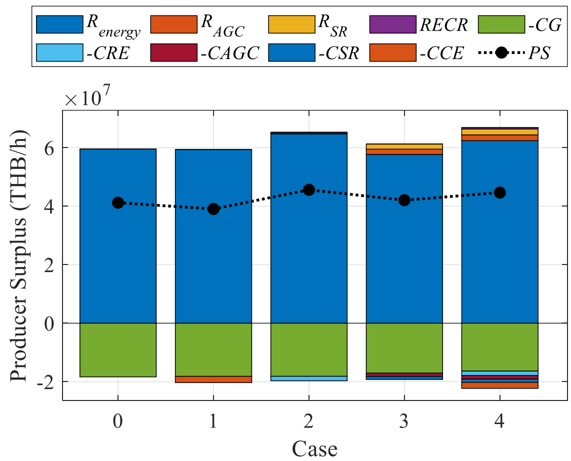

Figure 6.4 Producer surplus across market cases

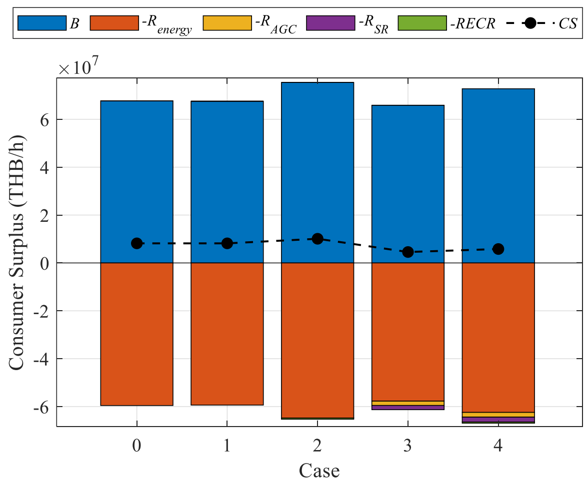

Figure 6.5 Consumer surplus across market cases

Producer surplus, shown in Figure 6.4, declines in Case 6.1 as carbon costs erode profitability, but increases sharply in Case 6.2 owing to REC revenues. It decreases again in Case 6.3 due to reserve obligations, while Case 6.4 recovers part of the loss, yielding a moderate but more stable outcome. Figure 6.5 illustrates that consumer surplus remains relatively unchanged between Cases 6.0 and 6.1, as the burden of carbon taxation is absorbed mainly by producers. In Case 6.2, it reaches its maximum level, reflecting efficiency gains from renewable incentives; however, it decreases in Case 6.3 as ancillary service costs are partially passed through to consumers. Case 6.4 achieves a positive but moderate surplus, striking a balance between consumer benefits, environmental objectives, and reliability. The fiscal implications of carbon pricing are captured in Figure 6.6, where government revenue increases substantially under Cases 6.1 and 6.4. This revenue source could be recycled to support renewable investment or grid modernisation, underscoring its policy relevance. Figure 6.7 extends the analysis to total market revenue, which remains stable between Cases 6.0 and 6.1, increases with the introduction of REC transactions in Case 6.2, and further shifts upward when ancillary services are procured in Case 6.3. The multi-dimensional market achieves the highest revenue, reflecting the simultaneous internalisation of energy, environmental, and reliability payments. Furthermore, Figure 6.8 highlights the evolution of market share in social welfare. In the baseline, producers dominate distribution, while consumers hold a smaller share, and government revenue is absent. Carbon taxation reallocates part of producer surplus to the state, REC trading strengthens producer positions, and ancillary services reduce the shares of both consumers and producers. The multi-dimensional scenario results in a more diversified structure, reducing concentration and promoting a more equitable distribution of welfare across stakeholders.

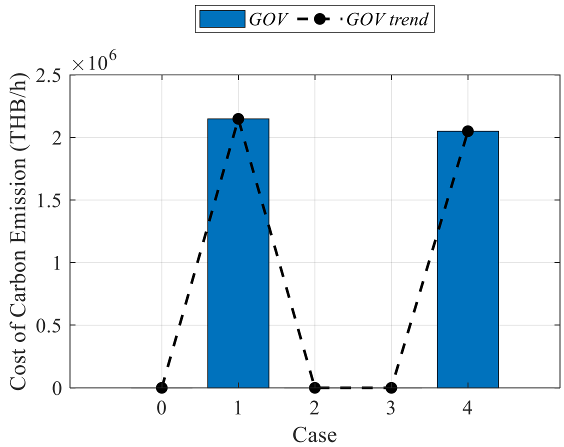

Figure 6.6 Government revenue

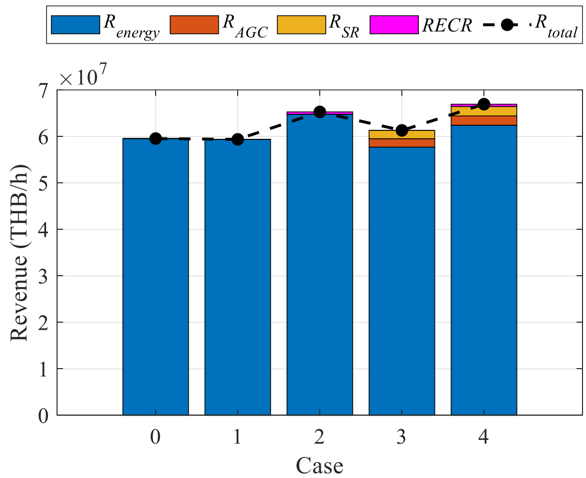

Figure 6.7 Total revenue across market cases

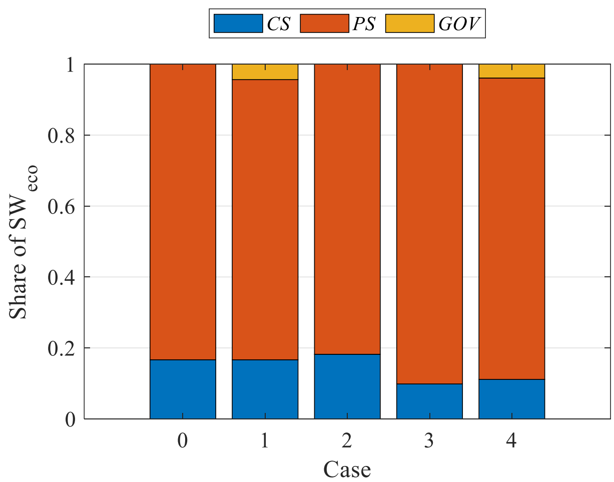

Figure 6.8 Market share of social welfare across cases

(2) Sensitivity Analysis of Carbon Tax

Sensitivity analyses were conducted to assess the influence of variations in carbon tax and REC prices on system operation and welfare outcomes. Tables 6.4 and 6.5 present the detailed results for Cases 6.1 and 6.2, respectively. Figures 6.10 to 6.13 extend the analysis by contrasting these results with those of Case 6.4, thereby illustrating the relative performance of single-instrument and multi-dimensional policy frameworks. Table 6.4 presents the carbon tax sensitivity in Case 6.1. As the tax rate increases from 0 to 1,000 THB/tCO_2, dispatch declines modestly from 18,792 MW to 18,507 MW, while emissions decrease from 10,774 to 10,615 tCO_2/h. Government revenue rises almost linearly, surpassing 10.6 million THB/h at the highest rate, but social welfare decreases from 49.1 to 38.4 billion THB/h. These results confirm that carbon pricing is effective in reducing emissions and generating fiscal revenues, although it imposes significant welfare losses.

Table 6.4 Sensitivity analysis of carbon tax rate

Carbon tax rate (THB/tCO_2)	*Dispatch (MW)*	*CE (tCO_2/h)*	*GOV(THB/h)*	SW_{post} *(THB/h)*
0	18,792.10	10,773.78	0	49,098,899.81
100	18,763.60	10,757.87	1,075,787.04	48,022,317.50
200	18,735.09	10,741.96	2,148,392.99	46,947,325.74
300	18,706.59	10,726.06	3,217,817.86	45,873,924.51
400	18,678.09	10,710.15	4,284,061.65	44,802,113.83
500	18,649.58	10,694.25	5,347,124.35	43,731,893.69
600	18,621.08	10,678.34	6,407,005.98	42,663,264.09
700	18,592.57	10,662.44	7,463,706.52	41,596,225.03
800	18,564.07	10,646.53	8,517,225.98	40,530,776.51
900	18,535.56	10,630.63	9,567,564.36	39,466,918.54
1000	18,507.06	10,614.72	10,614,721.65	38,404,651.10

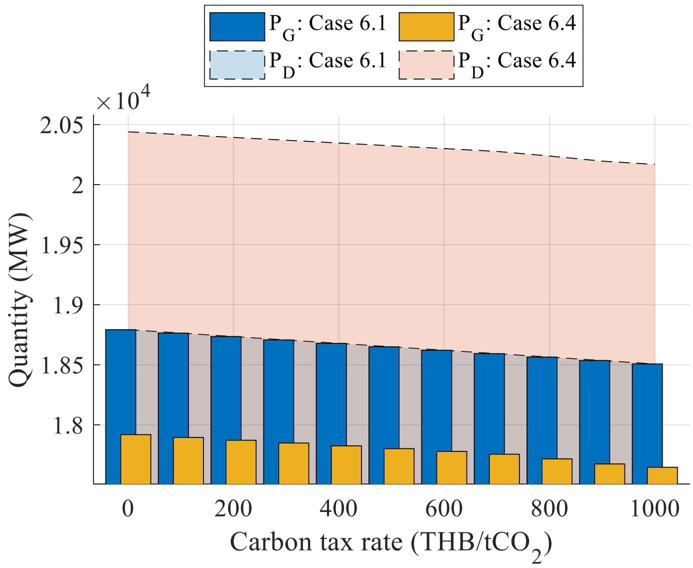

Figure 6.9 Sensitivity of carbon tax rate compared with power generation and power demand

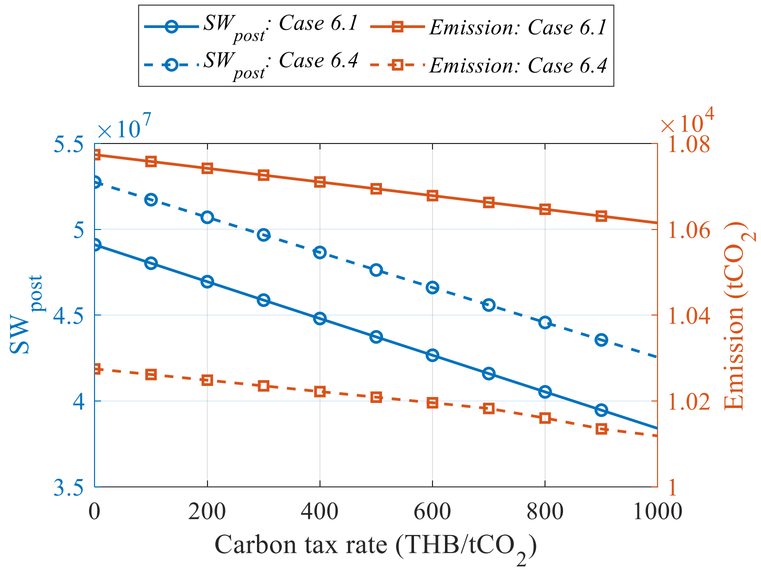

Figure 6.10 Sensitivity of carbon tax rate compared with post-transfer social welfare and emissions

Figure 6.9 compares the results, contrasting Cases 6.1 and 6.4. In both cases, dispatch decreases as the carbon tax rises, but the decline is sharper in Case 6.4, where the integration of renewable and ancillary markets amplifies the operational response to taxation. Demand remains relatively stable across both cases, indicating limited demand-side bidding. Figure 6.10 confirms that emissions decrease with higher carbon taxes in both scenarios. At the same time, welfare declines more steeply in Cases 6.1 and 6.4 as REC and ancillary revenues mitigate part of the welfare loss.

(3) Sensitivity Analysis of REC price

The REC price sensitivity in Case 6.2 is demonstrated in Table 6.5. Across the full range of REC prices, dispatch and emissions remain unchanged at 18,730 MW and 10,739 tCO_2/h, respectively. Nevertheless, producer surplus increases steadily from 44.8 to 47.3 billion THB/h, while total social welfare rises from 55.4 to 57.9 billion THB/h. This suggests that REC trading primarily functions as a financial redistribution mechanism, enhancing producer revenues and overall welfare without altering system operation or environmental outcomes.

Table 6.5 Sensitivity analysis of REC price

REC price (THB/REC)	*Dispatch (MW)*	*CE (tCO_2/h)*	*PS (THB/h)*	SW_{post} *(THB/h)*
0	18,730.45	10,739.38	44,820,442.34	55,420,669.55
100	18,730.45	10,739.38	45,072,442.34	55,672,669.55
200	18,730.45	10,739.38	45,324,442.34	55,924,669.55
300	18,730.45	10,739.38	45,576,442.34	56,176,669.55
400	18,730.45	10,739.38	45,828,442.34	56,428,669.55
500	18,730.45	10,739.38	46,080,442.34	56,680,669.55
600	18,730.45	10,739.38	46,332,442.34	56,932,669.55
700	18,730.45	10,739.38	46,584,442.34	57,184,669.55
800	18,730.45	10,739.38	46,836,442.34	57,436,669.55
900	18,730.45	10,739.38	47,088,442.34	57,688,669.55
1000	18,730.45	10,739.38	47,340,442.34	57,940,669.55

Figure 6.11 compares the outcomes of Cases 6.2 and 6.4. In Case 6.2, rising REC prices translate directly into higher producer revenues, while renewable dispatch remains constant. In the multi-dimensional framework, however, revenues are consistently higher across all REC price levels due to the complementary

contributions of carbon and ancillary service markets. Figure 6.12 confirms the same pattern for social welfare. Although both scenarios show steady increases with higher REC prices, the gains are markedly greater in Case 6.4, reflecting the synergistic effect of combining REC incentives with carbon pricing and ancillary revenues. This demonstrates that while REC trading alone supports producer viability, its welfare-enhancing potential is significantly amplified under market integration.

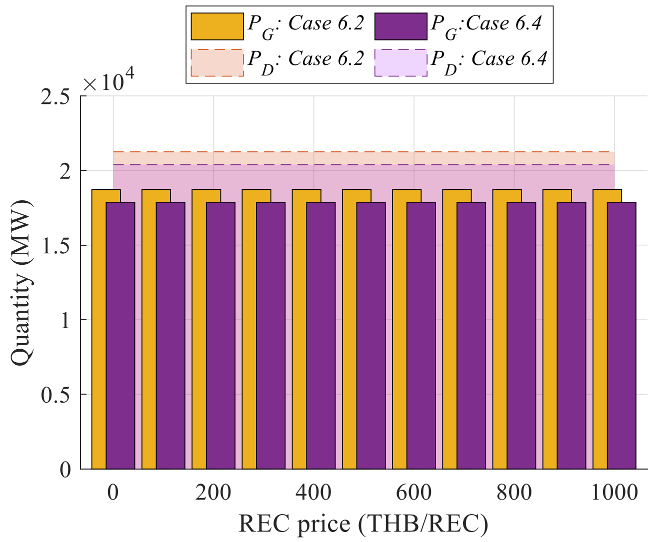

Figure 6.11 Sensitivity of REC price compared with quantity

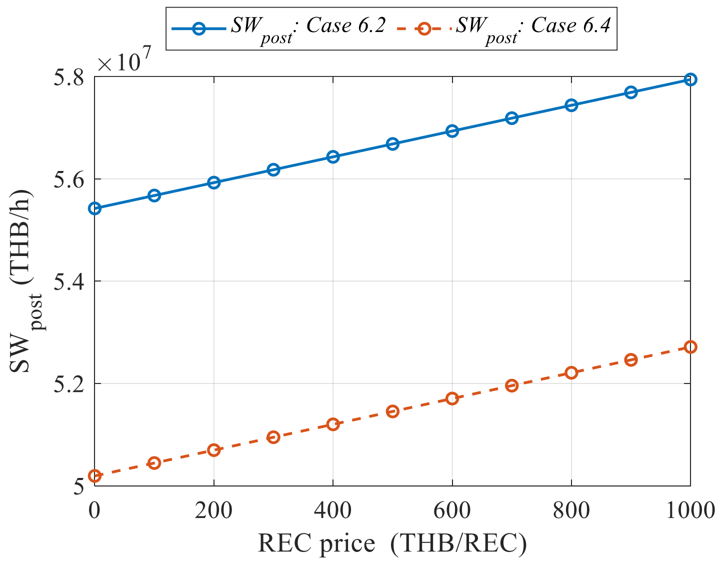

Figure 6.12 Sensitivity of REC rate compared with post-transfer social welfare

As a result, the sensitivity analyses reveal the distinct complementary functions of the two instruments. Carbon pricing delivers measurable emission reductions and fiscal revenues, but reduces short-term welfare. In contrast, REC trading improves financial redistribution and strengthens producer incentives without operational effects. Multi-dimensional market mechanisms interact to mitigate individual shortcomings, achieving a more balanced alignment of efficiency, sustainability, and equity.

6.5.2 Simulation Results using Hybrid PSO-QP Optimisation

The simulation results obtained from the hybrid PSO-QP optimisation, summarised in Tables 6.6 and 6.7, demonstrate the effectiveness of the proposed multi-dimensional market framework in improving both economic and environmental performance across different market configurations. A comparative analysis of Cases 6.0 - 6.4 reveals the progressive impacts of integrating carbon pricing, renewable incentives, and ancillary service co-optimisation as illustrated in Table 6.6. The baseline case (Case 6.0), representing a conventional energy-only market, yields a total generation output of 15,799.96 MW with a post-transfer social welfare of THB 51.87 million/h. When a carbon pricing mechanism is introduced in Case 6.1, total emissions decline from 9,104.16 tCO_2/MWh to 9,068.40 tCO_2/MWh, demonstrating effective internalisation of environmental externalities. However, this emission reduction is accompanied by a decrease in post-transfer welfare to THB 50.06 million/h, primarily due to the redistributive effect of carbon tax payments.

The inclusion of renewable generation and REC trading in Case 6.2 enhances producer revenues and overall market performance, improving post-transfer welfare to THB 58.71 million/h. This result highlights the contribution of renewable incentives in stimulating clean energy investment and increasing producer participation. In contrast, Case 6.3, which incorporates ancillary service co-optimisation, yields a lower total generation of 18,203.71 MWh but provides significant reliability benefits, as indicated by the allocation of 910.19 MW of spinning reserve and 1,115,099.94 THB/h of reserve payments. Despite slightly reduced welfare, the inclusion of ancillary services strengthens system adequacy and operational stability. Case 6.4, which co-optimises all policy instruments, achieves the most balanced and realistic outcome. Total generation is reduced to 14,872.03 MW, while emissions reach their lowest level of 8,574.48

tCO_2/MWh, representing a substantial improvement in environmental performance. Post-transfer social welfare attains a value of THB 53.82 million/h, outperforming all single-policy cases. The combined implementation also secures 1,019.6 MW of reserve capacity with an associated reserve cost of 1,208,840 THB/h, maintaining high system security at a reasonable cost.

Thirty independent trials of Case 6.4 were conducted to ensure robustness and consistency of the optimisation results, as shown in Table 6.7. The statistical outcomes show negligible variation among trials, with a standard deviation of only 288.66 THB/h, confirming the stability and convergence reliability of the hybrid PSO-QP approach. The average computation time of approximately 3,356 seconds indicates that the method achieves an acceptable balance between computational burden and optimisation precision for a large-scale system. Moreover, Figure 6.13 shows the distribution of post-transfer social welfare values across the 30 trial solutions for Case 6.4.

The comparison between QP and hybrid PSO-QP optimisation highlights apparent differences in technical representation and welfare outcomes. The hybrid PSO-QP method produces a slightly lower total dispatched generation compared with the QP approach, primarily because the PSO component optimises voltage magnitudes, transformer tap-changing, and compensator reactances, non-convex control variables that directly affect network losses, voltage profiles, and reactive power flows. Simultaneously, the QP module determines active generation, renewable output, AGC, SR, and demand, ensuring coordinated optimisation between market and system variables. The lower dispatch level obtained by the hybrid method reflects a more realistic and physically feasible operating condition, as it accounts for actual AC network losses and voltage-dependent constraints often neglected in conventional QP formulations. Despite this, the hybrid PSO-QP approach achieves a higher post-transfer social welfare, indicating more efficient resource utilisation once technical effects are integrated into the optimisation. By jointly considering economic objectives and system conditions, the hybrid framework delivers solutions that are both economically optimal and technically consistent, offering a more accurate representation of real-world power system operations under integrated market mechanisms.

Table 6.6 Simulation results from hybrid PSO-QP method [Part I]

Case	Total P_G (MW)	CG (THB/h)	CE (tCO_2/MWh)	CCE (THB/h)	Total P_{RE} (MWh)	CRE (THB/h)	$RECR$ (THB/h)
Case 6.0	15,799.96	15,873,916.70	9,104.16	0	0	0	0
Case 6.1	15,735.87	15,689,998.18	9,068.40	1,813,679.83	0	0	0
Case 6.2	15,734.68	15,678,992.26	9,067.73	0	2,520	1,514,566	504,000
Case 6.3	15,206.44	14,605,737.15	8,765.31	0	0	0	0
Case 6.4	14,872.03	13,899,177.02	8,574.48	1,714,896.35	2,520	1,514,566	504,000

Table 6.6 Simulation results from hybrid PSO-QP method [Part II]

Case	Total AGC (MW)	$CAGC$ (THB/h)	Total SR (MW)	CSR (THB/h)	Total P_D (MW)	B (THB/h)	SW_{post} (THB/h)
Case 6.0	0	0	0	0	18,792.10	67,746,643.91	51,872,727.20
Case 6.1	0	0	0	0	18,735.09	67,565,832.49	50,062,154.48
Case 6.2	0	0	0	0	21,250.45	75,398,412.41	58,708,854.15
Case 6.3	910.19	1,115,099.94	910.19	1,040,730	18,203.71	65,880,858.07	49,119,290.60
Case 6.4	1,019.6	1,208,840.19	1,019.6	1,126,057	20,392.00	72,777,612.46	53,818,075.82

Note: Detailed simulation results are addressed in Table B.3 (Appendix B.2)

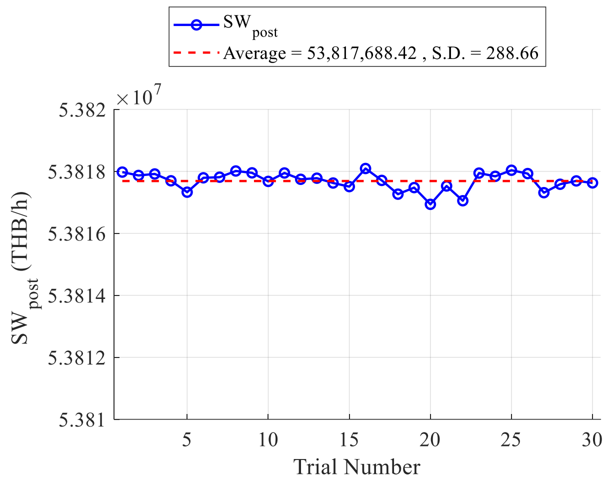

Figure 6.13 The solution with 30 trials of the hybrid PSO-QP method run for Case 6.4

Table 6.7 The best, worst, average, median and standard deviation of post-transfer social welfare and average computation times from 30 trial solutions of Case 6.4

The proposed multi-dimensional market mechanism (Case 6.4)					
	Best	*Worst*	*Average*	*Median*	*S.D.*
SW_{post} (THB/h)	53,818,090.37	53,816,936.9	53,817,688.42	53,817,726.42	288.66
Average time (s)			3,356.0939		

6.6 Conclusion

This research examined a multi-dimensional electricity market framework for the 160-bus equivalent Thai power system, incorporating carbon pricing, renewable incentives, and ancillary service procurement. The results demonstrate that single-policy instruments, including carbon taxation, REC, and ancillary services, exert distinct effects on operational efficiency, emissions, and welfare distribution. While carbon taxation reduces emissions and generates government revenue at the expense of economic efficiency, REC trading primarily serves as a financial mechanism that strengthens producer viability without significantly altering system dispatch. Ancillary service procurement enhances security but imposes additional costs that lower social welfare. By contrast, the multi-dimensional market design reveals strong complementarities. The combined implementation of carbon pricing, renewable incentives, and ancillary service procurement reduces emissions by nearly 5% relative to the baseline, diversifies welfare allocation across stakeholders, and mitigates the adverse impacts of individual policies. Sensitivity analyses further highlight that integration amplifies the environmental effectiveness of carbon taxation while enhancing the welfare gains from REC trading. These results underscore the policy relevance of multi-dimensional electricity markets as a tool for aligning efficiency, sustainability, and reliability objectives.

Furthermore, the hybrid PSO-QP optimisation method demonstrates superior computational performance compared with conventional QP optimisation. By jointly optimising non-convex network control variables with market-clearing variables, the hybrid approach yields more realistic, technically feasible dispatch solutions that explicitly account for power losses and voltage-dependent system constraints. Although the resulting total generation is slightly lower than that obtained by the QP method, the hybrid PSO-QP achieves higher post-transfer social welfare, reflecting improved resource utilisation and system efficiency once physical network effects are considered. This integrated computational framework bridges the gap between economic optimisation and technical feasibility, enhancing the accuracy and policy relevance of market-based decision-making in complex power systems.

From a policy perspective, these findings offer actionable insights for Thailand's carbon neutrality roadmap. The research indicates that carbon pricing alone may not suffice to achieve ambitious climate targets without imposing substantial welfare losses. However, integrated with renewable incentives, ancillary services, and technically consistent optimisation through the hybrid PSO-QP approach, the electricity market can simultaneously deliver emission reductions, ensure system adequacy, and maintain equitable welfare distribution. This multi-dimensional and technically grounded framework offers a pragmatic pathway for Thailand to reconcile short-run operational efficiency with long-term sustainability goals, thereby supporting the country's transition toward a carbon-neutral power sector.