CHAPTER IV

CO-OPTIMISED FRAMEWORK FOR COMBINED ELECTRICITY MARKET AND EMISSION MECHANISMS WITH RENEWABLE ENERGY CERTIFICATES[2]

4.1 Chapter Overview

This chapter introduces a novel integrated energy trading mechanism that unifies the RECs mechanism, CCE, and the conventional electricity market. Traditionally, REC trading has been conducted separately from electricity trading, with limited integration of carbon emissions into the core functions of electricity markets. The proposed approach incorporates an OPF model with a unified market-clearing mechanism that minimises CG, accounts for CE, and captures renewable energy benefits through REC earnings while maintaining system reliability.

By embedding carbon pricing mechanisms, generators can internalise the cost of carbon emissions within their electricity prices, thereby addressing environmental externalities. The framework also merges carbon pricing and REC trading by comparing SSA and DSA mechanisms, enabling generators to submit integrated energy bids that account for CCE and potential REC revenues. Simultaneously, consumers can purchase electricity and RECs based on their valuation of renewable energy's environmental benefits. This double-sided market framework enhances economic efficiency and environmental sustainability by maximising social welfare through the seamless integration of the REC price and CCE, as illustrated in Figure 4.1.

[2] A portion of this chapter has been published in the *Journal of Renewable and Sustainable Energy (Muangkhiew & Chayakulkheeree, 2024).*

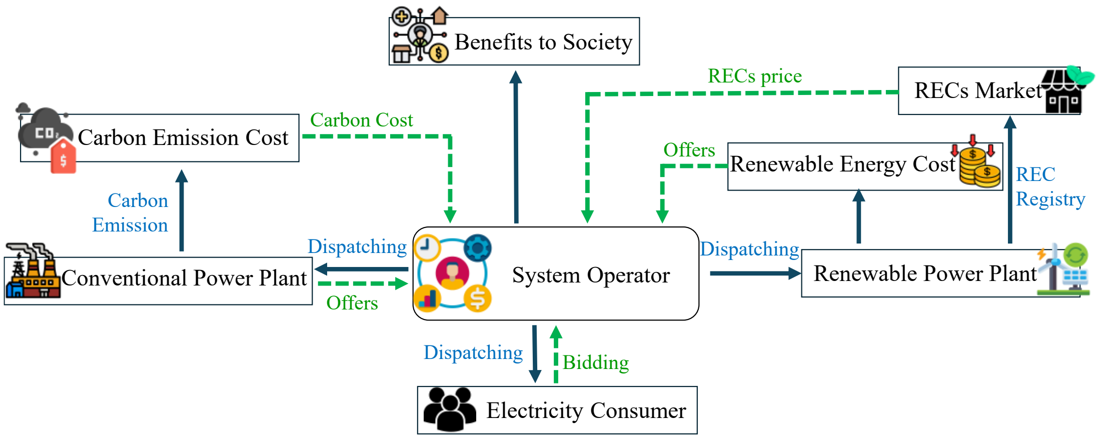

Figure 4.1 The coupling mechanism of the electricity-carbon-REC market

4.2 Mathematical Formulation

The proposed optimisation model minimises the total system operating cost, which includes generation cost (CG), carbon emissions cost (CCE), renewable energy cost (CRE), and renewable energy certificate revenue (RECR). This formulation is subject to equality and inequality constraints. Equations (3.13) and (3.14) define the calculations for CG and CCE, respectively.

4.2.1 Cost of Renewable Energy

In the SSA scheme, control variables x within the PSO population are represented by Equation (3.36). Dispatchable RES are vital for addressing the variability and intermittency of renewable technologies, providing reliable power that aids in reducing fossil fuel dependency. However, integrating renewable energy requires careful consideration of both environmental benefits and economic costs. The cost of renewable energy (CRE), expressed in dollars per hour ($/h), is often linked to power output in megawatts (MW) through a quadratic relationship. This nonlinear cost-power dynamic is crucial for optimising renewable integration and ensuring economic viability within the energy mix. Mathematically, the CRE can be represented as:

$$CRE(P_{RE,r}) = \sum_{r=1}^{NRE} (f_r P_{RE,r}^2 + g_r P_{RE,r} + h_r), \tag{4.1}$$

where $P_{RE,r}$ denotes the active renewable energy power output RE at bus r (MW), f_r, g_r, and h_r are the coefficients that determine the shape of RE the quadratic curve, NRE is the number of renewable energy sources.

4.2.2 Renewable Energy Certificate Revenue

In the SSA scheme, control variables x within the PSO population are represented by Equation (3.35). Renewable energy projects can generate additional income through the sale of RECs, which represent their certified clean energy production. Each REC corresponds to the generation of one megawatt-hour (MWh) of electricity from a renewable source, making it a tradable asset in the electricity market. The REC revenue (RECR), therefore, reflects the economic value of this certified renewable energy. Mathematically, the REC revenue can be expressed as the product of the REC price (RECP), measured in dollars per hour, and the corresponding RE output, as follows:

$$RECR(P_{RE,r}) = RECP \times \sum_{r=1}^{NRE} P_{RE,r} \ , \tag{4.2}$$

where $RECP$ denotes renewable energy certificate price ($/MWh).

4.3 Objective Function and Study Cases

This chapter investigates two different auction schemes: single-sided auction (SSA) and double-sided auction (DSA).

4.3.1 Scheme 1: Single-Side Auction Scheme

In the SSA scheme, control variables x within the PSO population are represented by Equation (3.36) as follows:

$$\mathbf{x} = [P_{G,2},\ldots,P_{G,NG},\ V_{G,1},\ldots,V_{G,NG},\ T_1,\ldots,T_{NT},\ X_{C,1},\ldots,X_{C,NC},\ P_{RE,1},\ldots,P_{RE,NRE}]. \tag{4.3}$$

<u>Case 4.1a</u>: Competitive Electricity Price Scheme (CEPS)

This scheme dispatches the generation power of GENCOs by minimising the CG offered by GENCOs, regardless of the CCE from power generation, CRE, RECR, and DSB. Then, the CE and CCE are obtained and included in the total operating cost to compute the carbon accounted for electricity, including the RECR from RE. Hence, the objective function is to be described as:

minimise $$f_{4.1\mathrm{a}}(x,u)=\sum_{i=1}^{NG}CG(P_{G,i})+\mu\cdot\left[g(x,u)\right]^{2}, \tag{4.4}$$

subject to equality and inequality constraints as in Equations (3.4)-(3.12), where $CG(P_{G,i})$ is formulated as shown in Equation (3.13).

Case 4.1b: Competitive Electricity-Carbon Prices Scheme (CECPS)

This scheme dispatches the power from GENCOs by minimising the total cost offered by GENCOs, considering the CCE from power generation as a resultant aggregated supply curve without CRE, RECR, and DSB. As a result, this scheme's total operating cost incorporates electricity and carbon prices. The objective function is formulated:

minimise $$f_{4.1b}(x,u)=\left[\sum_{i=1}^{NG}CG(P_{G,i})+\sum_{i=1}^{NG}CCE(P_{G,i})\right]+\mu\cdot\left[g(x,u)\right]^{2}, \tag{4.5}$$

subject to equality and inequality constraints as in Equations (3.4)-(3.12), where $CCE(P_{G,i})$ is formulated as shown in Equation (3.15).

Case 4.1c: Competitive Electricity-Carbon-REC Prices Scheme (CECRPS)

This scheme dispatches the power from GENCOs by minimising the total cost offered by GENCOs, considering the CCE from power generation, CRE, and RECR, in an aggregated supply curve without DSB. This scheme's total operational cost includes electricity, CCE, CRE, and RECR. The objective function is formulated:

minimise $$f_{4.1\mathrm{c}}(x,u)=\left[\sum_{i=1}^{NG}CG(P_{G,i})+\sum_{i=1}^{NG}CCE(P_{G,i})+\sum_{r=1}^{NRE}CRE(P_{RE,r})-\sum_{r=1}^{NRE}RECR(P_{RE,r})\right]$$
$$+\mu\cdot\left[g(x,u)\right]^{2}, \tag{4.6}$$

subject to:

$$\sum_{i=1}^{NG} P_{G,i} + \sum_{r=1}^{NRE} P_{RE,r} = \sum_{j=1}^{ND} P_{D,j} \ , \tag{4.7}$$

$$P_{RE,r}^{\min} \le P_{RE,r} \le P_{RE,r}^{\max}, \tag{4.8}$$

and as in Equation (3.5). Moreover, inequality constraints are as in Equations (3.6)-(3.12), where $CRE(P_{RE,r})$ and $RECR(P_{RE,r})$ are formulated as shown in Equations (4.1) and (4.2), respectively.

For Cases 4.1a to 4.1c, the study compares the total cost (TC) to society, including electricity production and environmental costs, which are computed as follows:

$$TC = \sum_{i=1}^{NG} CG(P_{G,i}) + \sum_{i=1}^{NG} CCE(P_{G,i}) + \sum_{r=1}^{NRE} CRE(P_{RE,r}) - \sum_{r=1}^{NRE} RECR(P_{RE,r}) \ . \tag{4.9}$$

4.3.2 Scheme 2: Double-Side Auction Scheme

In the DSA scheme, the control variables x within the PSO population are represented by Equation (3.36), as follows:

$$\mathbf{x} = [P_{G,2},\ldots,P_{G,NG},V_{G,1},\ldots,V_{G,NG},T_1,\ldots,T_{NT},X_{C,1},\ldots,X_{C,NC},P_{RE,1},\ldots,P_{RE,NRE},P_{D,1},\ldots,P_{D,ND}] \tag{4.10}$$

<u>Case 4.2a</u>: Market-Based Electricity Price Scheme (MBEPS)

This scheme aims to maximise social welfare for market participants by considering electricity offer prices and DSB; however, it disregards the CCE, CRE, and RECR. After that, the CCE, CRE, and RECR are calculated and coupled with all operating expenses to determine the MBEPS. The objective function is thus:

$$\text{maximise} \qquad f_{4.2\text{a}}(x,u) = \left[\sum_{j=1}^{ND} B_j(P_{D,j}) - \sum_{i=1}^{NG} CG(P_{G,i}) \right] + \mu \cdot \left[g(x,u) \right]^2 , \tag{4.11}$$

subject to equality and inequality constraints as in Equations (3.4)-(3.12), where $B_j(P_{D,j})$ is formulated as shown in Equation (3.16).

Case 4.2b: Market-Based Electricity-Carbon Prices Scheme (MBECPS)

This scheme aims to maximise the overall welfare of market participants, in which electricity offer prices consider CCE (as a resulting aggregated supply curve) and DSB without considering the CRE and RECR. Thus, all this scheme’s benefits and operating costs are considered in terms of carbon and electricity prices. Hence, the objective function provides the following description:

$$\text{maximise} \quad f_{4.2\text{b}}(x,u)=\left[\sum_{j=1}^{ND}B_j(P_{D,j})-\sum_{i=1}^{NG}CG(P_{G,i})-\sum_{i=1}^{NG}CCE(P_{G,i})\right]+\mu\cdot\left[g(x,u)\right]^2 \quad (4.12)$$

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

Case 4.2c: Market-Based Electricity-Carbon-REC Prices Scheme (MBECRPS)

This scheme aims to maximise market participants’ overall welfare, where electricity prices consider CCE, CRE, RECR (as defined by the aggregated supply curve), and DSB. Thus, this scheme's operating costs, integrated CCE, CRE, and benefits regarding RECR are assessed. So, the objective function explains:

$$\text{maximise} \quad f_{4.2c}(x,u)=\left[\sum_{j=1}^{ND}B_j(P_{D,j})-\sum_{i=1}^{NG}CG(P_{G,i})-\sum_{i=1}^{NG}CCE(P_{G,i})-\sum_{r=1}^{NRE}CRE(P_{RE,r}) +\sum_{r=1}^{NRE}RECR(P_{RE,r})\right]+\mu\cdot\left[g(x,u)\right]^2, \quad (4.13)$$

subject to equality and inequality constraints as in Equations (4.7)-(4.8), (3.5)-(3.12).

For Cases 4.2a to 4.2c, the comparison of the overall SW that incorporates economic and environmental aspects is investigated by the following equation:

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

(4.14)

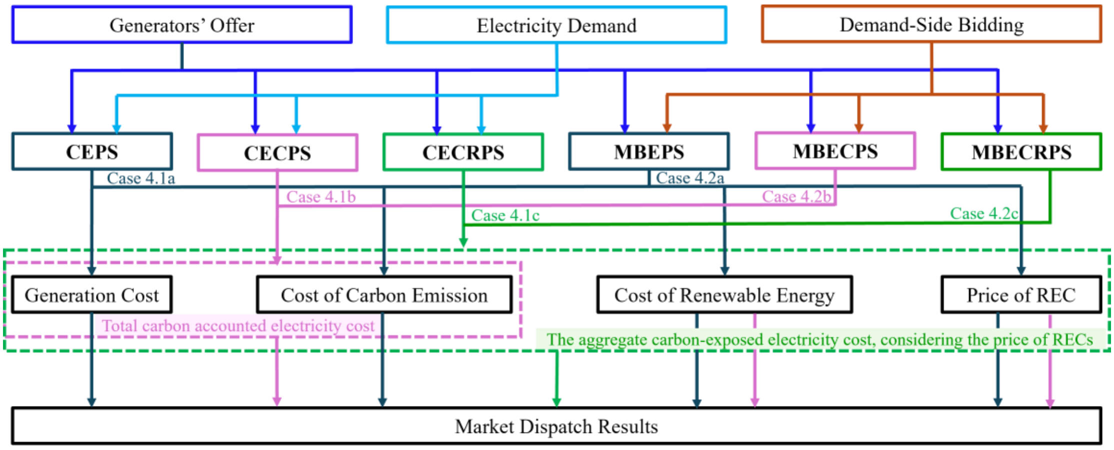

Figure 4.2 Summary of the case study schematic diagram

Figure 4.2 depicts a schematic diagram summarising various pricing mechanisms (cases) for electricity generation and DSBs, considering carbon accounting, CRE, and RECR. Case 4.1a (CEPS) shows that the traditional power pricing system is based purely on CG. Case 4.1b (CECPS) adds CCE to CG to calculate the carbon-accounted electricity cost. Case 4.1c (CECRPS) adds the CG and CCE to CRE and RECR. Regarding demand, Case 4.2a (MBEPS) represents the market-based electricity pricing scheme. In the context of DSB, Case 4.2b (MBECPS) incorporates CCE. In contrast, Case 4.2c (MECRPS) considers CRE and corresponding RECR. The lower row illustrates the market dispatch results, indicating the most significant societal benefit that incorporates the relevant cost elements derived from the various pricing methods described in the scenarios above.

4.4 Methodology

This chapter details the proposed framework for achieving an optimal and efficient clearing of the electricity market, utilising a metaheuristic approach, specifically PSO algorithm. PSO is selected for its proven robustness and efficiency in navigating complex search spaces to find a near-global optimum solution. The computational procedure is structured as follows:

Inputs: Power system data and PSO parameters.

Outputs: Optimal power dispatch, total cost to society, and social welfare.

Step 1: Initialise the PSO parameters.

Step 2: Initialise the particle positions and velocities randomly within the search space, considering the system operating constraints.

Step 3: Formulate the PSO populations for the SSA and DSA schemes defined by Equations (4.3) and (4.10), respectively.

Step 4: Run power flow for all populations and compute the objective function value.

Step 5: Check for constraint violations in the population.

Step 6: Compute the objective function for SSA by Equations (4.4)-(4.6) and DSA by Equations (4.11)-(4.13), incorporating the relevant terms and constraints.

Step 7: Initialise $pbest$ position and fitness for each particle and $gbest$ position and fitness across the entire swarm.

Step 8: Update the particle's velocity and particle's position for SSA and DSA schemes.

Step 9: Check for convergence. If convergence is reached or the maximum number of iterations is completed, proceed to step 10. Otherwise, return to step 4.

Step 10: Designate the global best position as the optimal power dispatch solution.

Step 11: Calculate the carbon emissions associated with the optimal power dispatch using the OPF model.

Step 12: Determine the TC and SW based on the optimal power dispatch and carbon emissions for SSA and DSA, respectively.

4.5 Simulation Results and Discussions

The simulation is on a modified version of the IEEE 30-bus system designed for this study. The generation cost and carbon emission coefficients are shown in Table A.1. The system includes six generators, four tap-changeable transformers, and two static VAR compensators. Moreover, this simulation involves two RES connected to buses 7 and 21, which are the buses connected with high demands as shown in Figure

4.3. The study defines CRE generation as aligning with the lowest price observed for fossil fuel-based generators. Also, the proposed method includes RECR, which is assessed at providing a spending of \$1.7 per MWh. In addition, it considers the economic impacts of greenhouse gas emissions, with a carbon tax (C_{tax}) of \$31 per ton. This analysis demonstrates the importance of environmental and financial factors in the research.

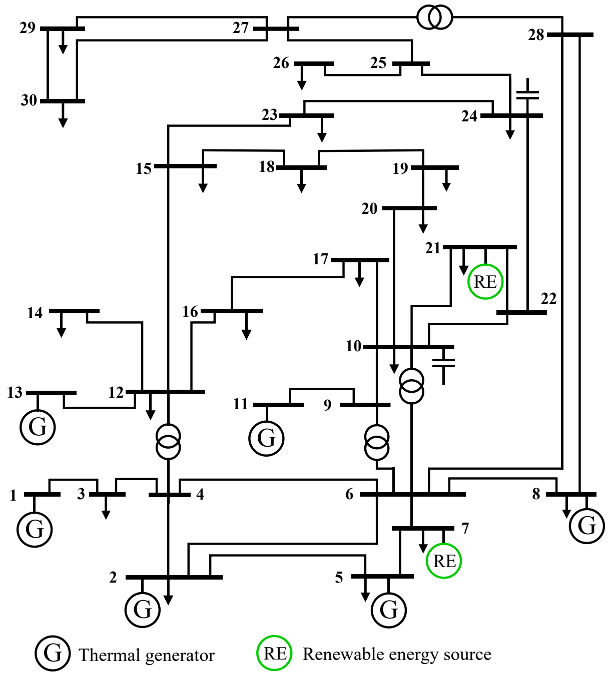

Figure 4.3 Schematic of the modified IEEE 30-bus system

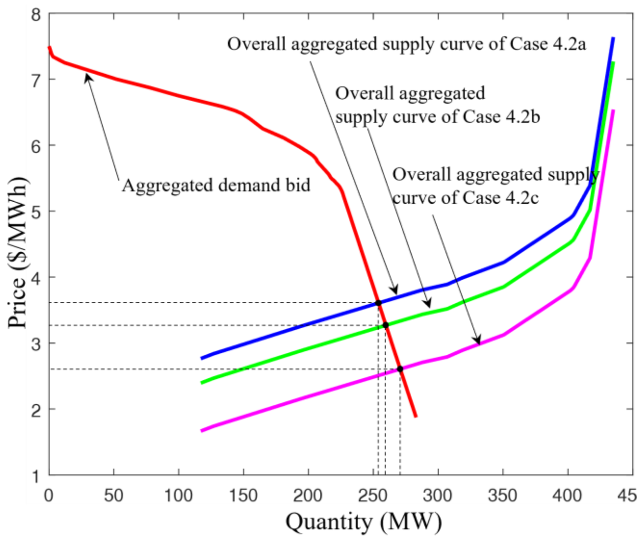

Figure 4.4 The concept of aggregated demand and supply curve

Figure 4.4 illustrates the procurement procedures employed across three distinct scenarios. The analysis begins with Case 4.2a, which serves as the reference scenario. The model considers only the essential costs associated with energy generation, as specified by Equation (4.9). In this scenario, the supply curve mirrors that of a conventional electricity market, where CCE, CRE, and RECR are treated as independent entities. The primary supply offer comprises several components that function independently of the objective function described in Equation (4.13). In Case 2b, the procurement framework integrates the CCE associated with energy generation into the objective function, as described in Equation (4.11). While the CRE and RECR components remain unchanged in the primary supply offer, the inclusion of the CCE leads to a downward shift in the supply curve compared to Case 4.2a. Finally, Case 4.2c adopts a more comprehensive approach by incorporating all cost factors related to carbon emissions, renewable energy generation, and the price of RECs into a unified supply curve, as outlined in Equation (4.12). This comprehensive integration results in a further downward shift in the curve of supply compared to both Cases 4.2a and 4.2b. Tables 4.1 and 4.3 provide a thorough examination of the simulation outcomes for each case study belonging to the SSA and DSA schemes, respectively. These tables provide a comprehensive summary of the main discoveries and practical observations obtained from the simulations. In Table 4.1, Case 4.1a, the GENCOs aim to minimise the CG while ensuring that the total electricity demand of 283.4 MW is met (excluding DSB). The costs of RE and RECR are disregarded. As a result, the CG is \$560.4716/h, corresponding to 0.2815 ton/h of carbon emissions, resulting in a CCE of \$8.7259/h. The combined cost of CG and CCE amounts to \$569.1959/h. When including the CRE and RECR of \$226.25/h and \$119/h, respectively, the TC reaches \$676.4459/h. Although this case minimises CG, leading to lower initial costs, the overall costs are higher due to the exclusion of CCE, CRE, and RECR.

Table 4.1 The simulation results of the single-side auction scheme

Single-Side Auction Scheme					
Variable	**Case 4.1a**	**Variable**	**Case 4.1b**	**Variable**	**Case 4.1c**
$P_{G,1}$ (MW)	131.1915	$P_{G,1}$ (MW)	129.7861	$P_{G,1}$ (MW)	136.3033
$P_{G,2}$ (MW)	37.66	$P_{G,2}$ (MW)	38.6909	$P_{G,2}$ (MW)	40.3185
$P_{G,5}$ (MW)	17.7328	$P_{G,5}$ (MW)	18.0543	$P_{G,5}$ (MW)	18.6249
$P_{G,8}$ (MW)	10	$P_{G,8}$ (MW)	10	$P_{G,8}$ (MW)	10
$P_{G,11}$ (MW)	10	$P_{G,11}$ (MW)	10	$P_{G,11}$ (MW)	10
$P_{G,13}$ (MW)	12	$P_{G,13}$ (MW)	12.0001	$P_{G,13}$ (MW)	12
$V_{G,1}$ (p.u.)	1.1	$V_{G,1}$ (p.u.)	1.1	$V_{G,1}$ (p.u.)	1.1
$V_{G,2}$ (p.u.)	1.0894	$V_{G,2}$ (p.u.)	1.0894	$V_{G,2}$ (p.u.)	1.0892
$V_{G,5}$ (p.u.)	1.0675	$V_{G,5}$ (p.u.)	1.0677	$V_{G,5}$ (p.u.)	1.0667
$V_{G,8}$ (p.u.)	1.0756	$V_{G,8}$ (p.u.)	1.0755	$V_{G,8}$ (p.u.)	1.0747
$V_{G,11}$ (p.u.)	1.0406	$V_{G,11}$ (p.u.)	1.0995	$V_{G,11}$ (p.u.)	1.0532
$V_{G,13}$ (p.u.)	1.1	$V_{G,13}$ (p.u.)	1.1	$V_{G,13}$ (p.u.)	1.1
T_1 (p.u.)	1.0057	T_1 (p.u.)	0.9691	T_1 (p.u.)	0.9836
T_2 (p.u.)	1.048	T_2 (p.u.)	1.0997	T_2 (p.u.)	1.0993
T_3 (p.u.)	0.9577	T_3 (p.u.)	0.9576	T_3 (p.u.)	0.9586
T_4 (p.u.)	0.9569	T_4 (p.u.)	0.9563	T_4 (p.u.)	0.9562
$X_{C,1}$ (p.u.)	-2	$X_{C,1}$ (p.u.)	-2.7089	$X_{C,1}$ (p.u.)	-2.0003
$X_{C,2}$ (p.u.)	-10.1685	$X_{C,2}$ (p.u.)	-10.1703	$X_{C,2}$ (p.u.)	-10.1672
$f_{4.1a}$ ($/h)	**560.4716**	CG($/h)	560.5064	CG ($/h)	587.0209
CE (t/h)	0.2815	CE (t/h)	0.2793	CE (t/h)	0.2883
CCE ($/h)	8.7259	CCE ($/h)	8.6589	CCE ($/h)	8.9364
$CG+CCE$ ($/h)	569.1959	**$f_{4.1b}$ ($/h)**	**569.1649**	$CG+CCE$ ($/h)	595.9573
CRE ($/h)	226.25	CRE ($/h)	226.2499	CRE ($/h)	180.7007
$RECR$ ($/h)	119	$RECR$ ($/h)	119	$RECR$ ($/h)	104.8712
TC ($/h)	**676.4459**	**TC ($/h)**	**676.4149**	**$f_{4.1c}$ ($/h)**	**671.7868**

Table 4.2 The best, worst, average, median and standard deviation of TC from 30 trial solutions of Case 4.1c

The proposed single-side auction scheme in Case 4.1c					
	Best	*Worst*	*Average*	*Median*	*S.D.*
TC ($/h)	671.78682	671.79634	671.79233	671.79433	0.00388

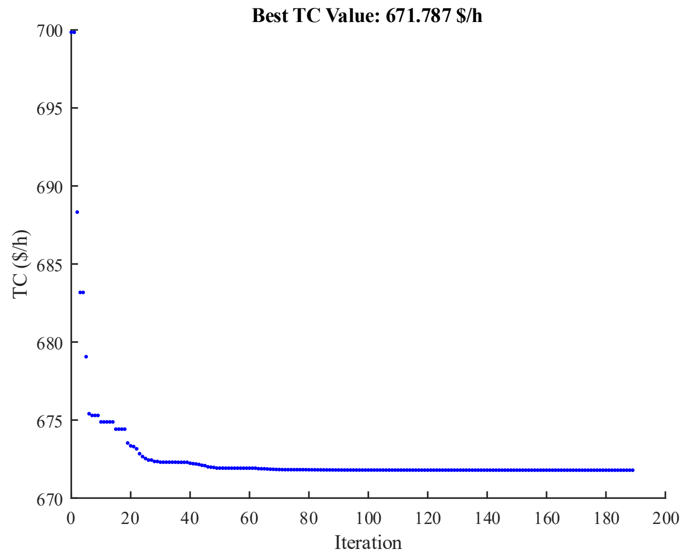

Figure 4.5 The convergence plot of the proposed method for Case 4.1c

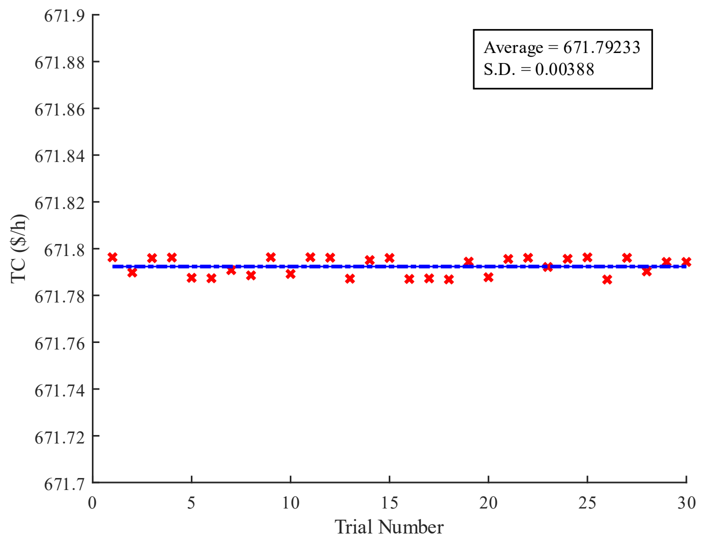

Figure 4.6 The solution with 30 trials of the proposed method run for Case 4.1c

Table 4.3 The simulation results of the double-side auction scheme

Double-Side Auction Scheme					
Variable	Case 4.2a	Variable	Case 4.2b	Variable	Case 4.2c
$P_{G,1}$ (MW)	160.7767	$P_{G,1}$ (MW)	157.0837	$P_{G,1}$ (MW)	157.0787
$P_{G,2}$ (MW)	44.7773	$P_{G,2}$ (MW)	45.6763	$P_{G,2}$ (MW)	45.6665
$P_{G,5}$ (MW)	20.0314	$P_{G,5}$ (MW)	20.3626	$P_{G,5}$ (MW)	20.3569
$P_{G,8}$ (MW)	11.7235	$P_{G,8}$ (MW)	13.9315	$P_{G,8}$ (MW)	13.9504
$P_{G,11}$ (MW)	10.0000	$P_{G,11}$ (MW)	10.0004	$P_{G,11}$ (MW)	10.0001
$P_{G,13}$ (MW)	12.0000	$P_{G,13}$ (MW)	12.0001	$P_{G,13}$ (MW)	12.0000
$V_{G,1}$ (p.u.)	1.1000	$V_{G,1}$ (p.u.)	1.1000	$V_{G,1}$ (p.u.)	1.1000
$V_{G,2}$ (p.u.)	1.0882	$V_{G,2}$ (p.u.)	1.0884	$V_{G,2}$ (p.u.)	1.0884
$V_{G,5}$ (p.u.)	1.0631	$V_{G,5}$ (p.u.)	1.0637	$V_{G,5}$ (p.u.)	1.0638
$V_{G,8}$ (p.u.)	1.0711	$V_{G,8}$ (p.u.)	1.0715	$V_{G,8}$ (p.u.)	1.0716
$V_{G,11}$ (p.u.)	1.1000	$V_{G,11}$ (p.u.)	1.0992	$V_{G,11}$ (p.u.)	1.0434
$V_{G,13}$ (p.u.)	1.1000	$V_{G,13}$ (p.u.)	1.1000	$V_{G,13}$ (p.u.)	1.1000
T_1 (p.u.)	1.0478	T_1 (p.u.)	1.0886	T_1 (p.u.)	0.9955
T_2 (p.u.)	0.9000	T_2 (p.u.)	0.9017	T_2 (p.u.)	1.0810
T_3 (p.u.)	1.0089	T_3 (p.u.)	0.9646	T_3 (p.u.)	0.9670
T_4 (p.u.)	0.9769	T_4 (p.u.)	0.9595	T_4 (p.u.)	0.9606
$X_{C,1}$ (p.u.)	-44.9998	$X_{C,1}$ (p.u.)	-3.8756	$X_{C,1}$ (p.u.)	-2.0011
$X_{C,2}$ (p.u.)	-8.9948	$X_{C,2}$ (p.u.)	-10.1110	$X_{C,2}$ (p.u.)	-10.0668
$P_{RE,7}$ (MW)	12.0000	$P_{RE,7}$ (MW)	12.0000	$P_{RE,7}$ (MW)	12.0000
$P_{RE,21}$ (MW)	10.0000	$P_{RE,21}$ (MW)	10.0000	$P_{RE,21}$ (MW)	10.0000
$P_{D,2}$ (MW)	21.7000	$P_{D,2}$ (MW)	21.7000	$P_{D,2}$ (MW)	21.7000
$P_{D,3}$ (MW)	2.4000	$P_{D,3}$ (MW)	2.4000	$P_{D,3}$ (MW)	2.4000
$P_{D,4}$ (MW)	7.6000	$P_{D,4}$ (MW)	7.6000	$P_{D,4}$ (MW)	7.6000
$P_{D,5}$ (MW)	94.2000	$P_{D,5}$ (MW)	94.2000	$P_{D,5}$ (MW)	94.2000
$P_{D,7}$ (MW)	22.8000	$P_{D,7}$ (MW)	22.8000	$P_{D,7}$ (MW)	22.8000
$P_{D,8}$ (MW)	30.0000	$P_{D,8}$ (MW)	30.0000	$P_{D,8}$ (MW)	30.0000
$P_{D,10}$ (MW)	0.0000	$P_{D,10}$ (MW)	0.0000	$P_{D,10}$ (MW)	0.0000
$P_{D,12}$ (MW)	11.2000	$P_{D,12}$ (MW)	11.2000	$P_{D,12}$ (MW)	11.2000
$P_{D,14}$ (MW)	6.2000	$P_{D,14}$ (MW)	6.2000	$P_{D,14}$ (MW)	6.2000
$P_{D,15}$ (MW)	8.2000	$P_{D,15}$ (MW)	8.2000	$P_{D,15}$ (MW)	8.2000

Table 4.3 The simulation results of the double-side auction scheme (Continued)

Double-Side Auction Scheme					
Variable	Case 4.2a	Variable	Case 4.2b	Variable	Case 4.2c
$P_{D,16}$(MW)	3.5000	$P_{D,16}$(MW)	3.5000	$P_{D,16}$(MW)	3.5000
$P_{D,17}$ (MW)	9.0000	$P_{D,17}$ (MW)	9.0000	$P_{D,17}$ (MW)	9.0000
$P_{D,18}$ (MW)	3.2000	$P_{D,18}$ (MW)	3.2000	$P_{D,18}$ (MW)	3.2000
$P_{D,19}$ (MW)	9.5000	$P_{D,19}$ (MW)	9.5000	$P_{D,19}$ (MW)	9.5000
$P_{D,20}$ (MW)	2.2000	$P_{D,20}$ (MW)	2.2000	$P_{D,20}$ (MW)	2.2000
$P_{D,21}$ (MW)	17.5000	$P_{D,21}$ (MW)	17.5000	$P_{D,21}$ (MW)	17.5000
$P_{D,23}$ (MW)	3.2000	$P_{D,23}$ (MW)	3.2000	$P_{D,23}$ (MW)	3.2000
$P_{D,24}$ (MW)	8.7000	$P_{D,24}$ (MW)	8.7000	$P_{D,24}$ (MW)	8.7000
$P_{D,26}$ (MW)	0.0000	$P_{D,26}$ (MW)	0.0000	$P_{D,26}$ (MW)	0.0000
$P_{D,29}$ (MW)	2.4000	$P_{D,29}$ (MW)	2.4000	$P_{D,29}$ (MW)	2.4000
$P_{D,30}$ (MW)	10.6000	$P_{D,30}$ (MW)	10.6000	$P_{D,30}$ (MW)	10.6000
CG ($/h)	688.3934	CG ($/h)	688.4189	CG ($/h)	698.4132
CE (t/h)	0.3307	CE (t/h)	0.3225	CE (t/h)	0.3225
TC ($/h)	698.4948	TC ($/h)	698.2676	TC ($/h)	698.2632
$f_{4.2a}$	**565.7062**	$f_{4.2b}$	**555.6818**	$f_{4.2c}$	**555.8363**
SW	**555.6048**	SW	**555.8318**	SW	**555.8363**

In Case 4.1b, GENCOs are allocated to minimise the aggregated supply curve, which includes CG and CCE generated by power generation. In this scenario, the total electricity demand is 283.4 MW (excluding DSB). CRE and RECR are disregarded. The calculated CG is $560.5045/h, with a CE of 0.2793 ton/h and a CCE of $8.6595/h. The per-hour cost of CG and CCE is $569.1649 when combined. Considering that the CRE and RECR are $226.2499/h and $119/h, respectively, the TC is $676.4149/h. Incorporating CCE results in a slight reduction in total costs relative to Case 4.1a, underscoring the importance of accounting for carbon emissions in the cost structure. In Case 4.1c, the GENCOs are dispatched to minimise the TC by considering an aggregated supply curve for a total electricity demand of 283.4 MW (excluding DSB). The CG is $587.0209/h, with emissions of 0.2883 ton/h and a CCE of $8.93564/h. The combined hourly cost of CG and CCE amounts to \$595.9573. The CRE and RECR are \$180.7007/h and \$104.8712/h, respectively, leading to a TC of \$671.7868/h.

A comparison of price-competition markets across the three case studies, excluding DSB, reveals that Case 4.1b achieves a marginally lower combined CG and CCE of 0.006% than Case 4.1a. Additionally, Case 4.1c demonstrates a significant reduction in TC of 0.6886% compared to both Cases 4.1a and 4.1b. The incorporation of CRE and RECR, along with CCE, presents a more holistic approach that encourages the use of renewable energy and provides a more accurate representation of societal costs, thereby enhancing long-term sustainability and economic efficiency.

Table 4.2 presents the results from 30 trials of the proposed method. In the single-sided auction in Case 4.1c, the best and worst TC values obtained by the PSO algorithm are \$671.7868/h and \$671.7963/h, respectively. The average and median of TC across 30 trials are \$671.7923/h and \$671.7943/h, respectively, with a standard deviation of 0.00388. The convergence diagram in Figure 4.5 demonstrates that the PSO algorithm consistently identifies the optimal solution within a reasonable number of iterations. Figure 4.6 shows the distribution of TC values across the 30 trial solutions for Case 4.1c.

For the DSA scheme shown in Table 4.3, in Case 4.2a, the SW value obtained is 555.6048, focusing solely on CG and DSB. This case optimises SW based on CG and DSB but excludes CCE, CRE, and RECR. Consequently, the initial SW values are lower. In Case 4.2b, the objective is to enhance supply-side performance by incorporating CCE into the aggregated supply curve alongside DSB, while omitting CRE and RECR. The resulting SW value is 555.8318. The inclusion of CCE results in a marginal SW increase of 0.04085% relative to Case 4.2a, highlighting the advantage of accounting for carbon costs. Case 4.2c aims to maximise supply-side profits by integrating CCE, CRE, RECR, and DSB into electricity offer prices. The SW value achieved in this case is 555.8346. Among the cases that consider DSB, Case 4.2c yields the highest SW, underscoring the benefits of a holistic approach that includes economic and environmental factors. Compared to Case 4.2a, the SW in Case 4.2c is 0.04135% higher.

Table 4.4 The best, worst, average, median and standard deviation of TC from 30 trial solutions of Case 4.2c

The proposed double-side auction scheme in Case 4.2c					
	Best	*Worst*	*Average*	*Median*	*S.D.*
SW ($/h)	555.8363	553.9136	555.7468	555.8343	0.3549

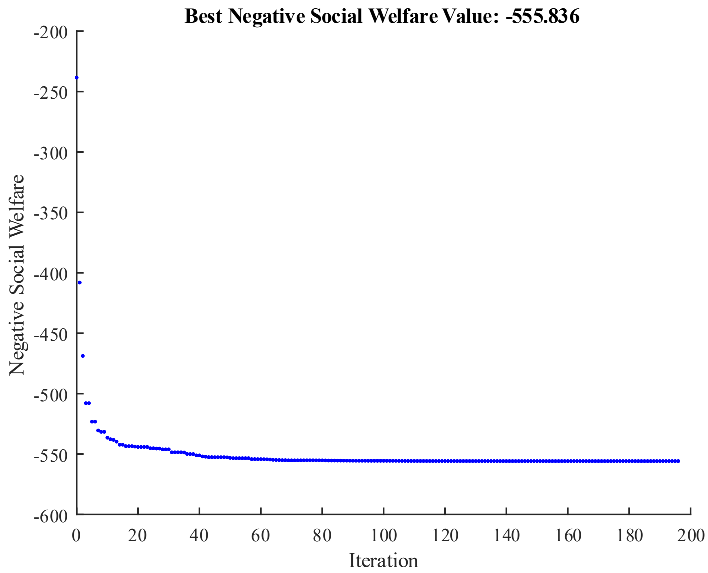

Figure 4.7 The convergence plot of the proposed method for Case 4.2c

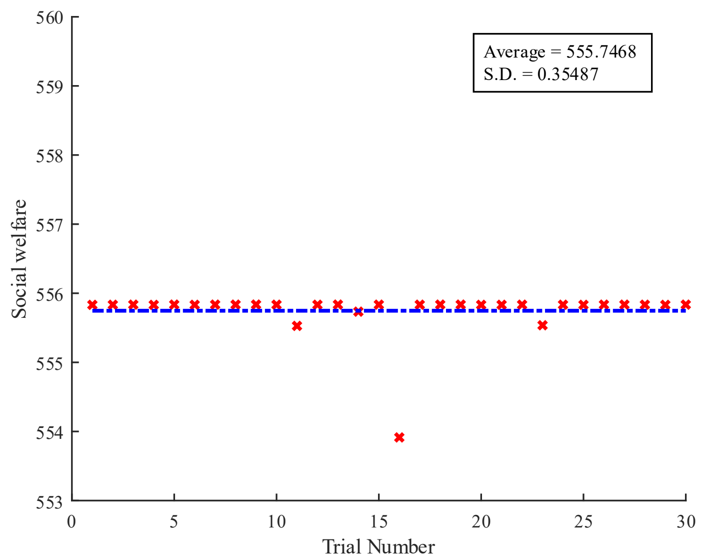

Figure 4.8 The solution with 30 trials of the proposed method run for Case 4.2c

Table 4.4 presents the results from 30 trials of the proposed method. For the double-sided auction in Case 4.2c, the best and worst SW values obtained using the PSO method are 555.8363 and 553.9136, respectively. The average and median of SW values across 30 trials are 555.7468 and 555.8343, with a standard deviation of 0.35487. Additionally, Figure 4.7 illustrates the convergence plot for Case 4.2c, while Figure 4.8 displays the distribution of SW values across the 30 trials.

4.6 Conclusion

This chapter examines the effect of several competitive pricing schemes on the economy and environment of low-carbonising strategies in power systems. The investigation focused on incorporating RECs and DSB using a PSO algorithm. The proposed approach has been applied to the modified IEEE 30-bus system. The occurrences under observation are:

(1) The combined supply offer, including CG, CCE, CRE, and RECR, without DSB, resulted in the most significant decrease in the overall total cost of electricity production, demonstrating the effectiveness of comprehensive optimisation methods.

(2) The DSB and competitive pricing schemes, including the CCE, CRE, and RECR, were considered the most advantageous models. The proposed model illustrates the significance of comprehensive optimisation methodologies for achieving maximum SW and promoting sustainable energy utilisation.

These results highlight the importance of integrating various economic and environmental variables into the optimisation frameworks of low-carbon power systems.