The Feasibility Assessment of Power System Dispatch with Carbon Tax Considerations

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Date Submitted: 2023-02-21

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Citation (overall record, always the latest version): LAPSE:2023.0849
Citation (this specific file, latest version): LAPSE:2023.0849-1
Citation (this specific file, this version): LAPSE:2023.0849-1v1

DOI of Published Version: https://doi.org/10.3390/pr10112321 processes

MDPI

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Citation: Lin, W.-M.; Tu, C.-S.; Lin, S.-J.; Tsai, M.-T. The Feasibility Assessment of Power System Dispatch with Carbon Tax Considerations. *Processes* **2022**, *10*, 2321. https://doi.org/10.3390/pr10112321

Received: 14 October 2022
Accepted: 3 November 2022
Published: 8 November 2022

1. Introduction

Economic dispatch (ED) is used to manage the generating unit output for the purpose of minimizing the total dispatch cost while satisfying operating constraints. However, as global warming increases, handling greenhouse gases (GHGs) has become an important issue to. The investigation by the Intergovernmental Panel on Climate Change (IPCC) found that the GHGs mainly came from CO_2 gas [1]. Increased environmental awareness and the passing of environmental regulations have had a significant impact on the operation of power systems. Environmental concerns force utilities to revise their operating strategies to reduce pollution from coal-fired power plants. The United Nations Framework Convention on Climate Change (UNFCCC) [2] announced the adoption of the carbon tax concept to enforce carbon emission reduction, which later became an internationally recognized carbon emission reduction plan.

Power companies that use fossil fuel-fired plants need to address the emission problem. For example, CO_2 poses a significant risk to the ozonosphere, causing global warming. Another theory suggests that gases are being trapped in the atmosphere, causing a greenhouse effect. Power companies offer their energy to markets by considering emission taxes. A carbon tax has been widely used in different countries as a policing instrument, and it imposes an extra cost on top of the operating cost of generators. Power companies must pay for the external cost of GHG damage to the environment [3]. Levying a carbon tax forces power companies' dispatchers to consider emissions as a cost, and thus, it forms an important constraint in ED. However, in highly complex problems, the solution spaces involved in these applications are large, and the high number of searches and iterations is easily affected by the relevant control parameters. The efficiency may be downgraded. More efficient tools are therefore needed to obtain a better dispatch.

In general, the impact of the future electricity market on GHGs is becoming an issue for attention [4–7]. Power dispatch is an important inspection item for power companies. These scheduling strategies use mathematical minimization tools to seek objective functions while meeting system operating and emission constraints. Most studies use the concept of "emission as cost", whereby emissions are controlled to obtain the minimal cost. Ref. [8] used a numerical polynomial no-convex continuation to solve the economic emission dispatch problem. Ref. [9] considered the dominant power retailer based on the dichotomous-market model to propose a bi-level economic dispatch algorithm.

Ref. [10] used an ε-defined multi-objective genetic algorithm to solve the system economic dispatching problem. Refs. [11–13] proposed a multi-objective mathematical programming approach to solve the economic and emission dispatch in energy markets. A new method was developed for planning energy and environmental systems under the various uncertainties to find optimal energy resource allocation and ideal policies for greenhouse gas reduction [14,15]. Ref. [16] integrated the charging system to perform the economic dispatch of plants for reducing CO_2 emission. Ref. [17] adopted a multi-objective planning approach to minimize power generation costs and decreased CO_2 emission by reducing the dual goals of building a supply dispatch model and target years. Ref. [18] combines quantum-behaved particle swarm optimization (QPSO) with a selective probability operator to find the optimal economic dispatch with valve-point effects and various fuel options. A weighting update artificial bee colony was deployed to solve the economic emission dispatch and demand response problem [19]. However, in most studies, the external pollution cost is converted to the internal cost, and the pollution amount of an individual unit and the minimal total cost are obtained by optimal economic dispatch. Taiwan is a densely populated island with limited natural resources, importing more than 98.1% of its total energy supply. The CO_2 emission in the power sector accounts for an average of 59% of the total CO_2 emissions. The Taiwan Power Company (TPC) is Taiwan's sole utility company. By the end of 2021, Taiwan's total installed capacity was approximately 5115.4 GW, where 67.7% of electricity was generated from fossil fuel-fired plants [20]. The CO_2 emissions of fossil fuel-fired plants amounted to 84,380,000 tons, which is approximately 48% of Taiwan's total annual CO_2 emissions. Although Taiwan is not yet a signatory to the Kyoto Protocol, it still bears responsibility for reducing CO_2 emissions. Therefore, suitable future strategies for the power sector are a very important factor in reducing CO_2 emissions in Taiwan [21,22]. To analyze the feasibility assessment of power system dispatches, strategies, including the usage of the allocation of fossil fuel-fired plants and the introduction of a carbon tax in the power system dispatch, are considered in this paper.

This paper sets out to construct a model for the feasibility assessment of a power system dispatch by considering CO_2 emissions. With various carbon taxes and horizon year loads, objectives including minimal total cost and minimal emissions are formulated, subject to operational constraints and emission conditions. A modified particle swarm optimization with time-varying acceleration coefficient (MPSO-TVAC) method is proposed to achieve this objective of optimal operation. The proposed MPSO-TVAC method is developed in such a way that PSO with the time-varying acceleration coefficient (TVAC) algorithm [23,24] is applied as a base-level search. To enhance the performance of the proposed algorithm, a power flow model with equivalent current injection (ECI) [25] was used to solve the power flow of power systems. The various scenarios associated with different levels of carbon taxes and loads are demonstrated by the simplified TPC 345 KV system [26]. Results can help decision-makers to achieve optimal economic dispatch and operation and optimize the tradeoffs between carbon taxes and economic objectives.

2. Problem Formulation

Objective Function and Constraints

The unit's dispatch problem with CO_2 emissions was described as a bi-objective problems.

(1) Minimal total cost

$$Min.\ TC = \sum_{i=1}^{N} [\ F_i(P_i) + E_i(P_i) \times Tax_{price}] \text{NT\$/h} \tag{1}$$

(2) Minimal CO_2 emissions

$$Min.\ Emi\_\mathrm{CO_2} = \sum_{i=1}^{N} E_i(P_i) \text{Ton/h} \tag{2}$$

The CO_2 emission model may be defined as the amount of fuel consumed. For the TPC 345KV system, the model of CO_2 emissions is formulated by the IPCC [1] as:

$$E_i(\ P_i\ ) = H(P_i) \times 4.1868 \times \frac{44}{12} \times CEP_i \times COR_i \tag{3}$$

$H(P_i) = d_i + e_iP_i + f_iP_i{}^2 + g_iP_i^3$ gives the thermal conductivity of each type of unit; d_i, e_i, f_i, g_i are the coefficients of the emission of unit i; CEP_i is the CO_2 emission parameter of unit i (21.1 kgC/GJ for oil, 25.8 kgC/GJ for coal, 15.3 kgC/GJ for natural gas); and COR_i is the CO_2 rate of unit i(0.99 for oil, 0.98 for coal, 0.995 for natural gas).

The constraints are considered as follows.

1. The lower and upper limits of the generating capability.

$$P_{i,\ \min} \le P_i \le P_{i,\ \max} \tag{4}$$

2. The balance of power flow equations.

$$\sum_{i=1}^{N} P_i = \sum_{k=1}^{N} P_{load\_k} + P_{loss} \tag{5}$$

3. The lower and upper limits of the voltage.

$$V_i^{\min}| \ \le \ |\ V_{\ i}\ | \ \le \ |\ V_i^{\max}\ | \tag{6}$$

4. The inequality constraints with the capacity limits of branches:

$$|S_j| \le S_j^{\max} \tag{7}$$

5. The inequality constraints are the total amount of CO_2 emission constraints:

$$0 \le \sum_{i=1}^{N} E_i(P_i) \le \mathrm{CO_2}\_Cap \tag{8}$$

P_{loss} is the transmission line loss (MW). The formulation of P_{loss} is defined as

$$P_{loss} = \frac{1}{2} \sum_{i=1}^{NB} \sum_{j=1}^{NB} \mathrm{Re}\ [\ Y_{ij}]\ \left[|V_i|^2\ +\ |V_j|^2\ -\ 2\,|V_i|\ |V_j| \cos\theta_{ij}\right] \tag{9}$$

3. The Proposed Methodology

3.1. Power Flow Model with ECI

In the Newton–Raphson technique, a Jacobian matrix was usually used to model the power components [27]. For the Newton–Raphson method, the mismatch function can be written in the rectangular form as:

$$\begin{bmatrix} \Delta P_i \\ \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} \frac{\partial P_i}{\partial e_i} & \frac{\partial P_i}{\partial f_i} \\ \frac{\partial Q_i}{\partial e_i} & \frac{\partial Q_i}{\partial f_i} \end{bmatrix} \begin{bmatrix} \Delta e_i \\ \\ \Delta f_i \end{bmatrix} \tag{10}$$

$\Delta\ P_i = P_{i,sch} - P_{i,cal}$ and $\Delta\ Q_i = Q_{i,sch} - Q_{i,cal}$. $P_{i,sch} = -P_{di}$ is the net real power at the i-th bus; $Q_{i,sch} = -Q_{di}$, which is the net reactive power at the i-th bus; $P_{i,cal} / Q_{i,cal}$ is the real/reactive power, which is calculated by power flow analysis.

The Jacobian matrix is shown in Equation (11):

$$J = \begin{bmatrix} \frac{\partial P_i}{\partial e_i} & \frac{\partial P_i}{\partial f_i} \\ \frac{\partial Q_i}{\partial e_i} & \frac{\partial Q_i}{\partial f_i} \end{bmatrix} \tag{11}$$

The mismatch function with the ECI-based power flow is rewritten in Equation (12).

$$\begin{bmatrix} \Delta\ I^r \\ \\ \Delta\ I^i \end{bmatrix} = \begin{bmatrix} \frac{\partial I^r}{\partial e} & \frac{\partial I^r}{\partial f} \\ \frac{\partial I^i}{\partial e} & \frac{\partial I^i}{\partial f} \end{bmatrix} \begin{bmatrix} \Delta e \\ \\ \Delta f \end{bmatrix} \tag{12}$$

$\Delta\ I = I^{eqv} - I^{cal} = \Delta\ I^r + j\Delta\ I^i$ and $\Delta\ V = \Delta\ e + j\Delta\ f$ are the real and imaginary components of the mismatch currents and mismatch voltages, respectively; I^{cal} is obtained from the power flow. I^{eqv} is given by:

$$I^{eqv} = \left(\frac{P + jQ}{V}\right)^* = \mathrm{Re}(I^{eqv}) + j\mathrm{Im}(I^{eqv}) \tag{13}$$

P, Q, and V are the real power, imaginary power, and voltage at a swing bus, respectively; P and Q are also the net power at a swing bus.

The constant Jacobian matrix is written in Equation (14).

$$J = \begin{bmatrix} G & -B \\ B & G \end{bmatrix} \tag{14}$$

G and B are the conductance and the admittance matrices, respectively.

3.2. MPSO-TVAC Method

In the PSO system [28], birds (particle) aggregation optimizes a certain goal function. Each particle knows its current sweet spot (*pbest*), which is analogous to each particle's personal experiences. Each particle also knows the current global optimal position (*gbest*) of all particles in the population. PSO can have multiple solutions at the same time, and there is a cooperative relationship between particles to share messages. Through specific algorithms, each particle can regulate its position to decide the search direction according to its search memory and that of the other particles. It also tries to reach compatibility between the local search and the global search. The search memory of a particle is the goal function and the optimal position found by the particle.

The velocity by using PSO-TVAC is described in Equation (15). A certain velocity is calculated due to the position of individuals gradually closer to *pbest* and *gbest*. The current position is modified in Equation (16).

$$\begin{aligned} v_s^{t+1} &= \left[c_1 = \left(c_{1f} - c_{1i}\right) \cdot \frac{iter}{iter_{\max}} + c_{1i}\right] \cdot rand \cdot \left(pbest_s^t - p_s^t\right) \\ &+ \left[c_2 = \left(c_{2f} - c_{2i}\right) \cdot \frac{iter}{iter_{\max}} + c_{2i}\right] \cdot rand \cdot \left(gbest^t - p_s^t\right) \end{aligned} \tag{15}$$

$$P_s^{t+1} = P_s^t \; + \; V_s^{t+1} \tag{16}$$

MPSO-TVAC introduces an operator, a "random feasible solution", into the PSO-TVAC to increase the search ability. The "random feasible solution" process adds the proper random feasible own best position into the velocity vector when the solution is searched in each generation. MPSO-TVAC can be employed in the algorithm to make the search algorithm more efficient at the end of the search, and the success rate of the search for a global optimum can be increased. The formulation of MPSO-TVAC is expressed as Equation (17).

$$\begin{aligned} v_s^{t+1} &= \left[c_1 = \left(c_{1f} - c_{1i}\right) \cdot \frac{iter}{iter_{\max}} + c_{1i}\right] \cdot rand \cdot \left(pbest_r^t - p_s^t\right) \\ &+ \left[c_2 = \left(c_{2f} - c_{2i}\right) \cdot \frac{iter}{iter_{\max}} + c_{2i}\right] \cdot rand \cdot \left(gbest^t - p_s^t\right) \end{aligned} \tag{17}$$

$pbest_r^t$ is the own best position of the random particle r in all feasible particles at iteration t.

3.3. The Implement of the Proposed Algorithm

The proposed algorithm is described as follows.

(a) Calculate the load data and installed capacity of the TPC system at a horizon year. The load data include the peak load of the year, average load of the year, and off-peak load of the year in different horizon years. The installed capacity of the TPC system includes the capacity of coal generation, the capacity of oil generation, the capacity of gas generation and the capacity of nuclear generation in different horizon years.

(b) Input the line data and bus data of the TPC system. The bus data include the types of generators and the load in the horizon year.

(c) Randomly initialize 30 particles with a generator-viable output in the PV buses.

$$P_i^k = {P^k}_{i\,,\,\min} \; + \; N(0,1)^k * \left(P_{i,\max} - P_{i,\min}\right)\,,\; k = 30 \tag{18}$$

$N(0,1)$ is the normal distribution with mean 0 and standard deviation 1.

(d) Use ECI to perform the power flow procedure and calculate the fitness values of each particle. The fitness function is defined in Equation (19).

$$Fitness_i = Obj(\Re_\mathrm{i}) + \sum_{\mathrm{m}=1}^{\mathrm{ne}} \lambda_{\mathrm{eq,\,m}} |\mathrm{h}(\Re_\mathrm{i})|^2 + \sum_{\mathrm{n}=1}^{\mathrm{nm}} \lambda_{\mathrm{ineq},\,n} |\mathrm{g}(\Re_\mathrm{i}) - \mathrm{g}_{\mathrm{lim}}|^2 \tag{19}$$

where *Obj* is the objective function; $\mathrm{h}(\Re_\mathrm{i})$ and $\mathrm{g}(\Re_\mathrm{i})$ are the equality and inequality constraints, such as Equations (4)~(8); ne and nm are the numbers of the equality and inequality constraints; and $\lambda_{\mathrm{eq,\,m}}$ and $\lambda_{\mathrm{ineq,\,n}}$ are the penalty factors that can be adjusted in the optimization procedure. $\mathrm{g}_{\mathrm{lim}}$ is defined by

$$\mathrm{g}_{\mathrm{lim}} = \begin{cases} \Re_i & if \quad \Re_{i,\,\min} \le \Re_i \le \Re_{i,\,\max} \\ \Re_{\min} & if \quad \Re_i < \Re_{i,\,\min} \\ \Re_{\max} & if \quad \Re_i > \Re_{i,\,\max} \end{cases} \tag{20}$$

If one or more variables violate their constraints, the penalty factors will be increased, and the corresponding individuals will be rejected to avoid an unfeasible solution. The fitness values are sorted in descending order from the maximum value ($Fitness_{i,\ \max}$) to minimum value ($Fitness_{i,\ \min}$).

(e) The fitness value of each particle with the *pbest* is compared. If the fitness value is smaller than *pbest*. The value set as the current *pbest*.

(f) Find the best particle associated with the minimal *pbest* of all particles, and the value of this is set as the *gbest*.

(g) Update the vectors of velocity and position of each particle by using Equations (16) and (17).

(h) The stopping condition is the maximal number of iterations. If the target has not yet been reached, then return to Step (c) and repeat the operation. A total of 500 generations are set out in this paper.

(i) Calculate the total cost, the generation of the plants, and the CO_2 emissions.

Figure 1 shows the flowchart of the proposed methodology.

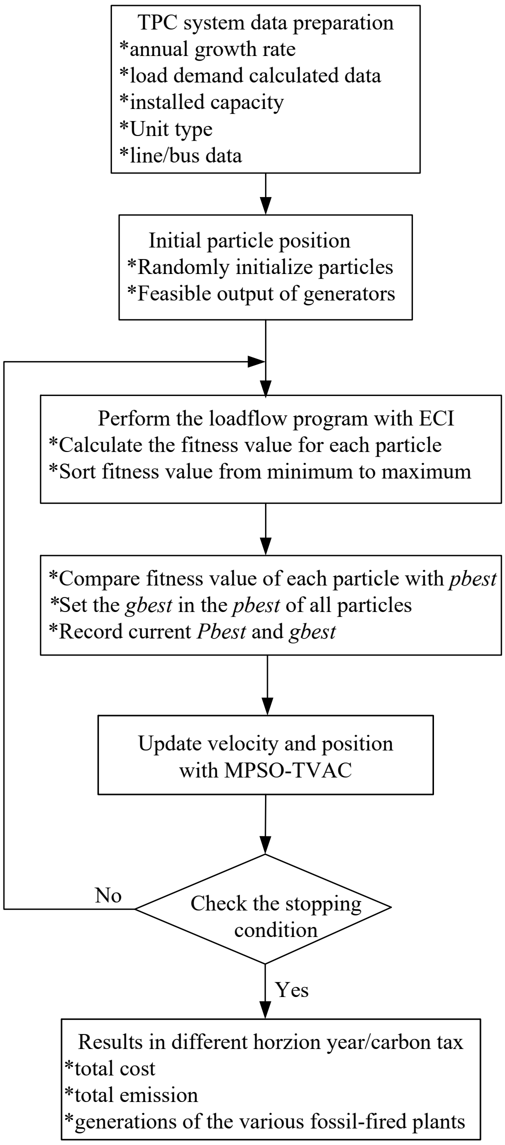

Figure 1. Flowchart of the proposed methodology.

4. Case Study

The proposed approach was tested on a simplified TPC 345 KV system. The generating technologies consist of nuclear-, coal-, gas-, and oil-fired plants. The installed capacity of different generating technologies in the committed schedule planning is shown in Table 1. The coal-fired plants, gas-fired plants, renewable power plants, and total capacity of the TPC system will increase in the future. As some nuclear plants are scheduled to be decommissioned in 2022, the capacity of nuclear power generation will decrease in the same year. The load of the TPC system in the different horizon years is shown in Table 2. All data were obtained from the TPC Power Development Planning [29]. Three cases with three different carbon taxes were analyzed to assess the feasibility of the proposed algorithm. The three cases are expressed as

Table 1. The capacity of different generation types in the TPC system.

	Type Year	Coal	Oil	Gas	Nuclear	Renewable Power	Total (MVA)
Capacity (MVA)	2012	12,637.2	2750	15,203	5144	2712	38,446.2
	2017	14,237.2	2750	16,133	5144	2824	41,088.2
	2022	20,837.2	2750	24,634.5	4602	4264	57,087.7

Table 2. The load of the TPC system in different horizon years.

	Load Status Year	Peak Load of Year	Average Load of Year	Off-Peak Load of Year
Load (MW)	2012	33,927	24,816	15,706
	2017	40,263	29,451	18,337
	2022	47,033	34,403	20,465

1. Case 1: Minimal total cost without the total amount of CO_2 emission constraints
2. Case 2: Minimal CO_2 emissions
3. Case 3: Minimal total cost with the total amount of CO_2 emission constraints

All case studies were analyzed with Matlab 7.3 on a 3.2 GHz Core2 computer with 4G MB RAM. The three horizon years 2012, 2017, and 2022 were used to estimate the economic dispatch of the TPC system. The carbon tax of NT$500/ton, NT$1500/ton, and NT$2500/ton were used in our study.

4.1. The Analysis of Case 1

The analysis of case 1 has three scenarios, which vary with the different carbon tax levels. The minimal total cost is an objective function, which sets the carbon taxes at 500 NT$/ton, 1500 NT$/ton, and 2500 NT$/ton without considering CO_2 emission constraints. Table 3 shows the summary of the simulation results of Case 1. In 2012, when the carbon tax was set at 500 NT$/ton, the carbon emission was higher than when the carbon tax was set at 1500 NT$/ton and 2500 NT$/ton. As the capacity of coal-fired plants is expected to increase in 2022, the CO_2 emissions produced will be nearly twice the emission output in 2012. The average costs are 3142.95 NT$/MW, 3665.53 NT$/MW, and 4251.42 NT$/MW if the carbon taxes are 500 NT$/ton, 1500 NT$/ton, and 2500 NT$/ton in 2012, respectively. Due to the increased cost of fuels, the average costs in 2017 and 2022 will double and triple, respectively, compared to the average cost in 2012. According to the data of the TPC [20], the average annual carbon emission in 2012 was 0.536 kg/kwh. As shown in Table 3, the results for 2012 and 2017 are close to the data of the TPC. As more coal-fired plants will commit in 2022, the average annual carbon emission will approach to 0.65 kg/kwh. The executed time of Case-1 is about 53.2 s.

Table 3. The summary of the simulation results of Case 1.

Horizon Year 2012						
Carbon Tax		Peak Load of Year	Average Load of Year	Off-Peak Load of Year	Total of One Year	Average
500 NT$/ton	Cost(NT$)	136,452,446	73,822,304	41,327,484	713,713,197,945	3142.95 NT$/MW
	Emission	18,997 ton	14,349 ton	4714 ton	121,181,245 ton	0.53 kg/kwh
1500 NT$/ton	Cost(NT$)	150,614,562	89,076,059	46,494,151	832,169,107,728	3665.53 NT$/MW
	Emission	18,643 ton	14,030 ton	4714 ton	118,744,464 ton	0.52 kg/kwh
2500 NT$/ton	Cost(NT$)	172,235,055	104,020,822	51,236,443	961,375,061,557	4251.42 NT$/MW
	Emission	18,831 ton	13,500 ton	4634 ton	115,948,849 ton	0.51 kg/kwh
Horizon year 2017						
Carbon tax		Peak load of year	Average load of year	Off-peak load of year	Total of one year	Average
500 NT$/ton	Cost(NT$)	291,992,877	166,171,774	82,239,628	1,565,816,472,262	5839.18 NT$/MW
	Emission	22,795 ton	17,349	7060 ton	147,997,680 ton	0.55 kg/kwh
1500 NT$/ton	Cost(NT$)	315,083,938	183,244,938	91,535,179	1,715,700,961,250	6395.39 NT$/MW
	Emission	22,755 ton	16,895 ton	7249 ton	145,591,889 ton	0.54 kg/kwh
2500 NT$/ton	Cost(NT$)	344,727,851	210,355,403	103,532,154	1,868,646,826,363	6954.14 NT$/MW
	Emission	22,899 ton	15,805 ton	6802 ton	143,753,562 ton	0.53 kg/kwh
Horizon year 2022						
Carbon tax		Peak load of year	Average load of year	Off-peak load of year	Total of one year	Average
500 NT$/ton	Cost(NT$)	559,436,600	332,369,666	158,359,723	3,080,730,478,567	9798.19 NT$/MW
	Emission	29,718 ton	24,620 ton	9929 ton	205,297,648 ton	0.65 kg/kwh
1500 NT$/ton	Cost(NT$)	583,498,540	358,510,171	145,496,362	3,254,828,575,287	10,436.28 NT$/MW
	Emission	29,606 ton	24,449 ton	8496 ton	202,243,434 ton	0.65 kg/kwh
2500 NT$/ton	Cost(NT$)	607,219,762	406,551,480	159,594,639	3,588,460,506,084	11,514.25 NT$/MW
	Emission	29,469 ton	23,010 ton	8785 ton	194,192,570 ton	0.62 kg/kwh

Figure 2 shows the relationship between emission and time. Because nuclear plants are scheduled to be decommissioned, while coal-fired plants are added into the TPC system, the incremental emissions from 2017 to 2022 are greater than those from 2012 to 2017. Table 4 shows the generation of the various fossil fuel-fired plants. The generation of coal-fired plants decreases with a higher carbon tax, and vice versa. Table 4 shows that minimal operational costs in the different horizon years lead to the commission of more coal-fired units than gas-fired plants at a NT$500/ton carbon tax, and conversely, more gas-fired units will be committed at a NT$2500/ton carbon tax.

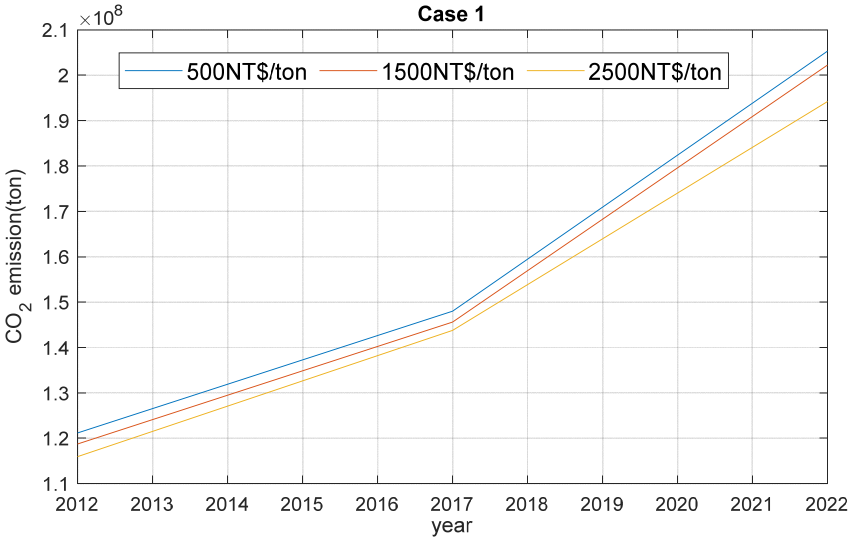

Figure 2. The relationship between emissions and time in the analysis of Case 1.

Table 4. The generation of plants among the various fossil-fired plants in case 1.

The Generation of Plants in 2012			
Carbon Tax (NT$/ton)	Coal-Fired (MW)	Oil-Fired (MW)	Gas-Fired (MW)
500	11,064.74	449.35	6474.18
1500	10,757.12	246.74	6903.38
2500	10,226.81	377.49	7178.99
The generation of plants in 2017			
Carbon tax (NT$/ton)	Coal-fired (MW)	Oil-fired (MW)	Gas-fired (MW)
500	12,944.13	710.25	8730.28
1500	12,532.66	732.07	9020.22
2500	10,945.83	1158.54	10,268.35
The generation of plants in 2022			
Carbon tax (NT$/ton)	Coal-fired (MW)	Oil-fired (MW)	Gas-fired (MW)
500	19,420.63	512.06	7888.85
1500	18,936.22	377.36	8168.05
2500	17,129.18	759.80	9612.13

4.2. The Analysis of Case 2

The analysis of case 2 also has three scenarios that vary with the carbon tax. Table 5 shows the summary of the simulation results. Regardless of the amount of carbon tax, the lowest emission values are close to the same. After the new load growth and the coal-fired plants are added, the annual CO_2 emissions will be approximately 82 million tons, 110 million tons, and 140 million tons in 2012, 2017, and 2022, respectively. In Taiwan, the policy target of CO_2 emissions is to reduce to the power energy emission level in 2000, which was 139.1 million tons. Hence, in the next 10 years, low carbon power needs to be increased. In 2012, 2017, and 2022, the average annual CO_2 emissions were 0.36 kg/kwh, 0.41 kg/kwh, and 0.44 kg/kwh, respectively. As the capacity of gas-fired plants was increased in 2017 and 2022, the average cost in 2017 and 2022 doubled or tripled compared to the average cost in 2012. The value of the average annual CO_2 emissions is smaller than the data of the TPC (0.536 kg/kwh). The executed time of Case 2 is about 54.7 s.

Table 5. The summary of the simulation results of Case 2.

Horizon Year 2012						
Carbon Tax		Peak Load of Year	Average Load of Year	Off-Peak Load of Year	Total of One Year	Average
500 NT$/ton	Cost (NT$)	153,874,048	102,692,259	43,334,881	911,259,092,251	3987.67 NT$/MW
	Emission	16,860 ton	8314 ton	4183 ton	82,376,890 ton	0.36 kg/kwh
1500 NT$/ton	Cost (NT$)	171,617,829	111,440,761	48,116,210	998,442,831,767	4369.32 NT$/MW
	Emission	16,775 ton	8313 ton	4186 ton	82,226,839 ton	0.36 kg/kwh
2500 NT$/ton	Cost (NT$)	188,582,058	119,134,790	52,952,088	1,078,328,301,312	4722.17 NT$/MW
	Emission	16,879 ton	8251 ton	4230 ton	82,111,087 ton	0.36 kg/kwh
Horizon year 2017						
Carbon tax		Peak load of year	Average load of year	Off-peak load of year	Total of one year	Average
500 NT$/ton	Cost (NT$)	295,808,850	225,227,222	93,564,913	1,923,645,203,211	7149.72 NT$/MW
	Emission	22,513 ton	11,454 ton	5263 ton	111,575,762 ton	0.41 kg/kwh
1500 NT$/ton	Cost (NT$)	318,221,540	236,888,584	101,241,288	2,039,398,788,402	7605.25 NT$/MW
	Emission	22,464 ton	11,312 ton	5333 ton	110,774,201 ton	0.41 kg/kwh
2500 NT$/ton	Cost (NT$)	342,560,588	247,064,302	108,146,865	2,149,055,264,813	7980.42 NT$/MW
	Emission	22,581 ton	11,135 ton	5411 ton	110,073,596 ton	0.41
Horizon year 2022						
Carbon tax		Peak load of year	Average load of year	Off-peak load of year	The total of one year	Average
500 NT$/ton	Cost (NT$)	632,318,823	514,811,623	205,315,041	4,308,943,921,217	13,534.66 NT$/MW
	Emission	26,439 ton	14,951 ton	6993 ton	140,638,787 ton	0.44 kg/kwh
1500 NT$/ton	Cost (NT$)	658,896,295	537,733,865	209,411,615	4,491,409,799,498	14,142.42 NT$/MW
	Emission	26,421 ton	14,995 ton	7034 ton	140,915,036 ton	0.44 kg/kwh
2500 NT$/ton	Cost (NT$)	685,741,249	528,474,256	218,453,593	4,497,599,103,860	14,115.03 NT$/MW
	Emission	26,380 ton	14,919 ton	7030 ton	140,400,596 ton	0.446 kg/kwh

Figure 3 shows the relationship between minimal emission and time. Because the target is to minimize emissions, the carbon emissions are very similar regardless of carbon taxes. Table 6 shows the generation of the various fossil fuel-fired plants. To reach the minimal emissions target, the system will require more gas-fired units than coal-fired plants. There is a clear relationship between carbon taxes and the generation of coal-fired plants.

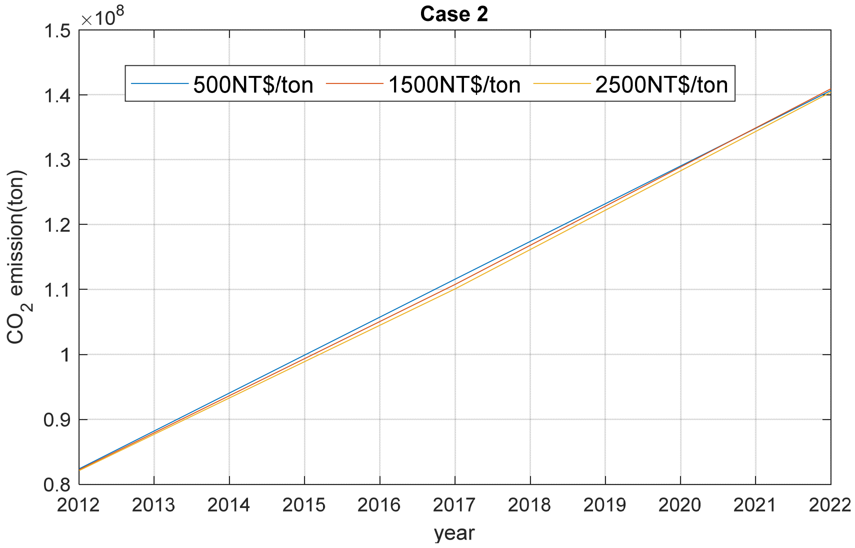

Figure 3. The relationship between emissions and time in the analysis of Case 2.

Table 6. The generation of plants among the various fossil-fired plants in case 2.

The Generation of Plants in 2012			
Carbon Tax (NT$/ton)	Coal-Fired (MW)	Oil-Fired (MW)	Gas-Fired (MW)
500	3312.48	767.04	13,834.22
1500	3280.56	773.11	13,858.82
2500	3315.39	768.89	13,753.46
The generation of plants in 2017			
Carbon tax (NT$/ton)	Coal-fired (MW)	Oil-fired (MW)	Gas-fired (MW)
500	4854.26	2434.09	15,063.41
1500	4730.20	2421.78	15,163.53
2500	4619.85	2248.08	15,539.96
The generation of plants in 2022			
Carbon tax (NT$/ton)	Coal-fired (MW)	Oil-fired (MW)	Gas-fired (MW)
500	5454.50	2161.88	20,633.52
1500	6249.02	1304.11	21,649.37
2500	5739.40	1461.27	21,093.25

4.3. The Analysis of Case 3

Table 7 shows the summary of the simulation results of case 3. As the total amount of CO_2 emissions exhausted in 2022 violates the total amount of CO_2 emission constraints, there are no feasible solutions in this study. After the capacity of gas-fired plants is increased to satisfy the emission constraints, the average costs are higher than the average costs in case 1. As shown in Table 7, due to the consideration of the total amount of CO_2 emission constraints in case 3, the total yearly costs in the different horizon year are nearly the same for the various carbon taxes. In 2012 and 2017, the average annual CO_2 emissions at the various carbon taxes, which range from 0.51 kg/kwh to 0.53 kg/kwh, are smaller than the data of the TPC (0.536 kg/kwh). The executed time of Case 3 is about 56.3 s.

Table 7. The summary of the simulation results of Case 3.

Horizon Year 2012						
CARBON TAX		Peak Load of Year	Average Load of Year	Off-Peak Load of Year	Total of One Year	Average
500 NT$/ton	Cost (NT$)	142,554,095	74,897,394	41,898,689	731,275,414,533	3201.41 NT$/MW
	Emission	19,529 ton	14,291 ton	4886 ton	122,008,876 ton	0.53 kg/kwh
1500 NT$/ton	Cost (NT$)	158,309,491	89,743,767	47,834,002	851,213,119,090	3734.95 NT$/MW
	Emission	18,573 ton	14,159 ton	4852 ton	119,537,619 ton	0.52 kg/kwh
2500 NT$/ton	Cos t(NT$)	177,904,341	105,406,052	52,559,934	980,934,218,911	4313.99 NT$/MW
	Emission	19,012 ton	13,505 ton	4872 ton	116,607,114 ton	0.51 kg/kwh
Horizon year 2017						
Carbon tax		Peak load of year	Average load of year	Off-peak load of year	Total of one year	Average
500 NT$/ton	Cost (NT$)	298,218,408	175,992,025	93,730,596	1,647,739,242,351	6122.63 NT$/MW
	Emission	22,930 ton	15,805 ton	6314 ton	138,463,166 ton	0.51 kg/kwh
1500 NT$/ton	Cost (NT$)	316,656,495	189,385,406	95,349,380	1,758,431,764,881	6543.57 NT$/MW
	Emission	22,707 ton	15,836 ton	6843 ton	138,942,356 ton	0.52 kg/kwh
2500 NT$/ton	Cost (NT$)	343,532,347	205,252,405	104,528,420	1,907,926,211,985	7088.90 NT$/MW
	Emission	22,940 ton	15,767 ton	6731 ton	138,815,337 ton	0.52 kg/kwh

5. Conclusions

Taiwan is committed to build a "nuclear-free homeland" by 2025 as a result of the Basic Environment Law. The Bureau of Energy will draft new regulations to facilitate the phasing out of Taiwan's three existing nuclear power plants. Over the past 5 years, the average annual growth of installed power capacity was 3.1% and the average load growth was about 1.0%. Results will show that the generation deficit created by decommissioning nuclear plants can be filled by fired plants, thereby increasing both the costs and the CO_2 emissions of power generation. Some government strategies for CO_2 emission reduction include increases in the use of natural gas, the development of renewable energy, capacity allocation of fired plants, and the introduction of a carbon tax. Renewable power generators and their production are still in their growth and development stages in Taiwan. Furthermore, there are some unprecedented volatilities and risks involved in renewable energy development.

Because the TPC system is an isolated system unable to connect to other utilities, advancing planning and scheduling of power dispatch is an important issue. This study used an MPSO-TVAC method to analyze the feasibility assessment of the TPC system dispatch by considering CO_2 emissions. To enhance the performance of the proposed algorithm, a power flow model with ECI was used to analyze the power flow of the power systems. Based on the various carbon taxes and the loads in the horizon years, a series of cost and feasibility analyses of the TPC plants were carried out. The relationship between cost and CO_2 emissions was demonstrated by the simplified TPC 345 KV system. The scenarios presented in this study can assist decision-makers to achieve optimal economic dispatch and operation, and also provide an efficient power plan to meet the TPC's CO_2 emission target.

Author Contributions: W.-M.L. is the first author. He provided the project idea, related experiences, system model and revised English. C.-S.T. performed the experiments and conducted the simulations. M.-T.T. assisted the project and prepared the manuscript as the corresponding author. S.-J.L. performed the data collection and computer simulation. All authors discussed the simulation results and approved the publication. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the Scholar Research Funds of Xiamen University Tan Kah Kee College (JG2022SRF03 and JG2021SRF01).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

TC	the total production cost (NT$/h)
N	the total number of generation units
$F_i(P_i)$	the generation cost of power for the *i-th* unit (NT$/h)
P_i	the power output of a committed unit *i*
$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i$	the production cost of unit *i*
a_i, b_i, c_i	the coefficients of the production cost of unit *i*
$E_i(P_i)$	the total amount of CO_2 for the *i-th* unit (ton/h)
Tax_{price}	the carbon tax of CO_2 emission (NT$/Ton)
P_{load_k}	the total load (MW) at *k-th* load bus
$P_{i,\min}/P_{i,\max}$	the lower/upper limits of the real power of the *i-th* unit (MW)
$V_{\min}/V_{\max}$	the lower/upper limits of the voltage of the *i-th* unit (0.97/1.03pu)
CO_2_Cap	the total upper limit of CO_2 emission
V_i	the voltage at bus *i* after load flow analysis
S_j	the line flow of *j-th* branch
$S_j^{\max}$	the maximal flow of *j-th* branch (1000 MW)
NB	the total number of branches in the system
V_i	the voltage of *i-th* bus
Y_{ij}	the admittance of branch $i - j$
$\theta_{ij} = \theta_i - \theta_j$	the voltage phase angle difference between bus-*i* and bus-*j*.
c_{1f},c_{2f}	the initial acceleration constant; in this paper, $c_{1f} = 0.8$, $c_{2f} = 1.9$
c_{1i}, c_{2i}	the final acceleration constant, $c_{1i} = 1.88$, $c_{2i} = 0.7$
$iter_{\max}$	the maximal iteration
$iter$	the current iteration
$rand$	the uniform random value with a range of [0, 1]
P_s^t	the position of particle *s* at iteration *t*
V_s^t	the velocity of particle *s* at iteration *t*
$pbest_s^t$	the own best position of particle *s* at iteration *t*
$gbest^t$	the best particle in the swarm at iteration *t*

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