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Sustainability Assessment of Combined Cooling, Heating, and Power Systems under Carbon Emission Regulations

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Abstract: The combined cooling, heating, and power (CCHP) system, which is a sustainable distributed energy system, has attracted increasing attention due to the associated economic, environmental, and energy benefits. Currently, the enforcement of carbon emission regulations has become an increasingly concerning issue globally. In this paper, a multi-objective optimization model is established to evaluate the CCHP system under two different carbon emission regulation policies in terms of economic benefit, environmental sustainability, and energy advantage. A nonlinear programming optimization model is formulated and solved by using the particle swarm optimization (PSO) algorithm. The results from the case studies demonstrate that when considering carbon tax regulation, the cost savings of the optimal CCHP system strategy were on average 10.0%, 9.1%, 17.0%, 22.1%, and 20.9% for the office, supermarket, hotel, school, and hospital in China, respectively, compared with the conventional energy supply system. On the other hand, when considering carbon trading regulation, the optimal CCHP system strategy can lead to a 10.0%, 8.9%, 16.8%, 21.6%, and 20.5% cost-saving for the five different building categories, respectively. Furthermore, the optimal CCHP system strategy for the five buildings, i.e., an average of 39.6% carbon dioxide emission (CDE) reduction and 26.5% primary energy consumption (PEC) saving, can be achieved under carbon emission regulations.

Keywords: combined cooling; heating and power system; sustainability; carbon tax regulation; cost-saving ratio; carbon trading regulation; carbon dioxide emission reduction; primary energy saving

1. Introduction

With the rise of industry and population in the world, it is estimated that the global energy demand will increase by 37% from 2013 to 2035 [1]. Statistically, about 70% of the generated electricity was produced by burning fossil fuels from conventional power plants in 2012 [2]. As a result, worldwide greenhouse gas (GHG) emissions have been increasing, and global warming is becoming a serious threat to future generations [3]. In recent years, the combined cooling, heating, and power (CCHP) system as a sustainable distributed energy system has gained considerable popularity compared to conventional power systems for energy supply, due to several advantages, e.g., higher overall energy efficiency, lower pollution emissions, lower cost, resource sustainability, and flexible adaption for the ratio of electricity to heating [4,5].

The single performance (e.g., economic, environmental criteria) of CCHP systems can be improved by optimal configurations and operation strategies [6–9]. For example, Ahn et al. [10] focused on performance analysis for CCHP systems based on different time period operational costs and payback periods by considering various local climates, power generation equipment sizes, and utility tariff structures. Since carbon dioxide emission is related to global warming, He et al. [11] proposed a

low-carbon cost optimization model considering the constraints of electric and natural gas characters to reduce CO₂ emission. Zhang et al. [12] explored the exergetic and exergoeconomic assessment of the CCHP system firing biogas and natural gas coupled with a ground source heat pump (GSHP) under different ratios of gas mass and key parameters (i.e., fuel prices, service life, biomass, and natural gas cost).

Actually, the different performances of CCHP systems are related to each other. To study the tradeoff among various criteria, a comprehensive evaluation of the CCHP system could be established to achieve system energy efficiency [13–15]. Feng et al. [16] compared the two CCHP systems under three operation strategies with the objectives of the energy-saving rate, CO₂ emission reduction, and operation cost reduction. Wang et al. [17] described the 4E (e.g., energy, exergy, exergoeconomic, and environmental) criteria investigating the performance of a CCHP gas turbine system assisted by solar. Wang et al. [18] studied the energy dispatch optimization problem of a solar-driven CCHP system and formulated a multi-objective model with average useful output and total heat transfer area as performance criteria. When uncertainties are considered, He et al. [19] developed a novel interval multi-objective decision-making method based on sustainability performance to rank the alternative CCHP systems. In addition, Hu and Cho [20] presented a stochastic model to optimize the CCHP system to minimize cost, CO₂ emission, and primary energy consumption, and then the CCHP system operation strategy for office buildings in different cities were analyzed in the case study. However, the influences of government policies on the multi-objective assessment of CCHP systems are less characterized and analyzed.

In addition, policy is one of the key aspects impacting the performances of the CCHP system, such as the feed-in tariff policy and carbon emission regulations. In particular, carbon emission regulations (e.g., carbon tax policy, carbon trading mechanism, and carbon offset policy) cannot be neglected because government-related policies have been developing rapidly. For example, a carbon trading market for national electricity sectors was established in China in 2017 [21]. The impacts of different carbon regulatory policies have been studied in various optimization problems, such as the biodiesel supply chains manage problem [22], production configuration problem [23], and green supply chain design problem [24].

Currently, studies regarding the effect of carbon emission regulations on the optimal CCHP system based on economic performance have emerged. In current literature, most studies are carried out to optimize and evaluate CCHP systems considering only one kind of carbon emission policy [25–28]. For instance, considering the carbon tax policy, Zeng et al. [27] proposed a novel off-design optimization model to study CCHP coupled with the GSHP system while annual primary energy saving ratio (PESR), carbon dioxide emission reduction ratio (CDERR), and cost-saving ratio (COSR) were adopted as a comprehensive optimization objective. Li et al. [28] focused on the effects of carbon trading and feed-in electricity tariff policies on the criteria of the CCHP system, based on economic, energy, and environmental aspects. Then, residential buildings were used to illustrate the efficiency of the model under five operation strategies. Therefore, it is of great importance to incorporate both carbon tax and carbon trading mechanisms into the CCHP system optimization problem.

To the best of authors' knowledge, few studies have investigated the impacts of different carbon emission regulations and building categories on the multi-objective assessment of the CCHP system. To fill this gap in the literature, the economic benefit, environmental sustainability, and energy advantage of the CCHP system for different building categories considering different carbon emission regulations are studied. To achieve this goal, a nonlinear programming (NLP) model is established to optimize the CCHP system operating problem. The particle swarm optimization (PSO) algorithm is adopted to solve the NLP model. The potential benefits regarding COSR, CDERR, and PESR for the CCHP system compared to the separate system are tested. In the case studies, the economic, environmental, and energy performances of the optimal CCHP system are evaluated under carbon tax and carbon trading regulations for five different commercial building categories (i.e., office, supermarket, hotel, school, and hospital) in Shanghai, China.

The proposed research has three major contributions, as follows:

- (1). A multi-objective optimization model is presented to evaluate the CCHP system under carbon tax and carbon trading regulations.
- (2). The PSO algorithm is applied to solve the proposed NLP model with the purpose of fast convergence speed and high solving efficiency.
- (3). The economic benefits, environmental sustainability, and energy advantage of the CCHP system based on COSR, CDERR, and PESR are analyzed and compared for the different building categories.

2. Problem Description

Figure 1 displays a schematic of the typical CCHP system. The PGU (power generation unit) supplies the electricity by firing natural gas to the end-user and generates waste heat energy recovered by the heat recovery system to the heating exchanger and absorption chiller. In addition, the end-user electricity demand also can be satisfied from the power grid. The end-user cooling demand can be provided through the electric chiller and absorption chiller. The end-user heating demand (e.g., space water heating, hot water) can be satisfied by the heating exchanger. The auxiliary boiler is used to offer the remaining heat when the heat recovery system cannot afford end-user thermal load. To investigate the performance advantages of the CCHP system, a separate system is presented and is also shown in Figure 1. In the separate system, the electricity, cooling, and thermal loads are satisfied by the conventional power grid, electric chiller, and boiler, respectively.

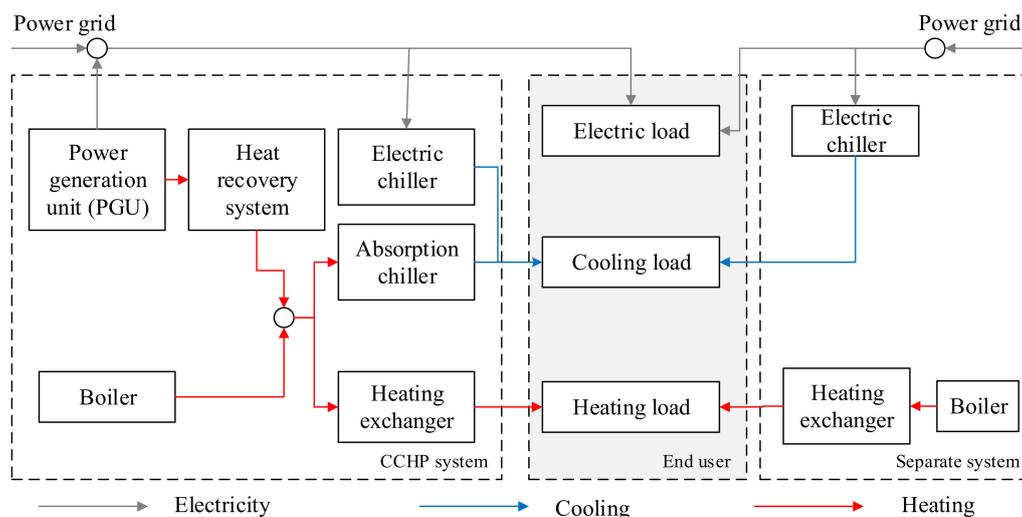


Figure 1. Structure of the combined cooling, heating, and power (CCHP) system and separate system for the end-user.

According to Kang et al. [25] and Li et al. [28], the correlation between the heat and electricity of PGU is assumed to be linear, and the detailed state of the CCHP system is shown in Figure 2. The horizontal coordinate represents the electric energy from PGU firing fuel in the CCHP system, and the vertical coordinate denotes the recovered heating. The solid red line represents the numerical relation between recovered heat and electricity from the PGU. The PGU operates following this red line. The heating and electricity demands of end-users are always changing. Thus, there is a mismatch between energy supply and demand. Therefore, energy dispatch optimization is important, and it is valuable to achieve an optimal operation strategy.

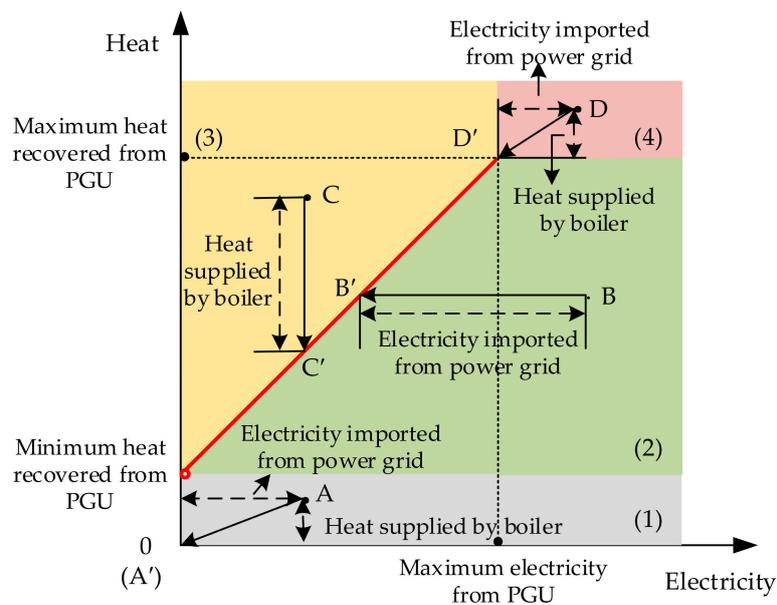


Figure 2. Energy matching map for the CCHP system and the end-user.

In Figure 2, the PGU will not work when the electricity demand of the end-user is zero; otherwise, the heat and electricity are presented in the following ways: Region (1) shows that the electricity demand and heating load of the end-user can be satisfied from the local power grid and boiler, respectively. For example, the PGU will operate at point A' instead of point A. Region (2) signifies the heat from the recovered PGU and electricity from the PGU as well as the power grid, such as the PGU will operate at point B' rather than point B. In Region (3), the electricity is from the PGU, and the heat is from the recover heat and boiler. For example, the CCHP system will operate at point C' instead of point C. Region (4) shows that the PGU works at capacity load. Thus, the rest of the electricity demand can be purchased from the local power grid, and the remaining heating demand can be imported from the boiler. For instance, the PGU operates at a capacity load (point D') instead of point D.

Figures 1 and 2 demonstrate the structure and energy flow between the CCHP system and the power grid. The objective of this research is to identify the optimal strategy for CCHP systems for end-users considering carbon tax and carbon trading policies based on economic, environmental, and energy performances. In the case studies, five different residential buildings in Shanghai were used to investigate whether the CCHP system can achieve COSR, CDERR, and PESR compared with the separate system. It should be pointed out that the effects of carbon tax and carbon trading regulations on the sustainability assessment are analyzed in the case studies.

3. Mathematical Model

An NLP model was developed to study the energy dispatch optimization problem of the CCHP system by considering economic, environmental, and energy aspects under different carbon emission regulations. According to Afzali and Mahalec [29], a mathematical model was formulated to solve the optimal problem of the CCHP system based on the law of energy conservation. The nomenclatures in the mathematical model are shown in Table 1.

Table 1. Nomenclatures in the mathematical model.

Description	
Indices	
t	Index of the slotted interval, $t = 1, 2, \dots, T$
T	Total time period
Parameters	
a	Natural gas to electricity conversion coefficient of the PGU
b	Natural gas to electricity conversion parameter of the PGU
η_{rec}	Natural gas to heating conversion efficiency for the PGU
η_{boiler}	Natural gas to heating conversion efficiency of the auxiliary boiler
η_h	Thermal efficiency of the heating exchanger
COP_{ac}	Heating to cooling energy conversion efficacy of the absorption chiller
COP_{ec}	Electricity to cooling conversion competence of the electric chiller
$E_{load,t}$	Electricity demand of the end-user at time t
$Q_{cloud,t}$	Cooling demand of the end-user at time t
$Q_{hload,t}$	Heating load of the end-user at time t
Decision variables (at time t)	
$F_{pgu,t}$	Natural gas quantity of the PGU (kWh)
$F_{boiler,t}$	Natural gas quantity of the auxiliary boiler (kWh)
$E_{pgu,t}$	Electricity from the PGU firing natural gas (kWh)
$E_{grid,t}$	Electricity procured from the local power grid (kWh)
$E_{b,t}$	Electricity supplied to the end-user (kWh)
$E_{ec,t}$	Electric energy amount by the electric chiller consuming (kWh)
$Q_{pgu,t}$	Heating recovered from the PGU (kWh)
$Q_{boiler,t}$	Heating generated by the boiler (kWh)
$Q_{hac,t}$	Heating energy consumption of the absorption chiller (kWh)
$Q_{lhe,t}$	Heating energy consumption of the heating exchanger (kWh)
$Q_{ac,t}$	Cooling supplied by the absorption chiller (kWh)
$Q_{ec,t}$	Cooling supplied by the electric chiller (kWh)

3.1. Constraints

Using these parameters and variables, the NLP model for the CCHP system operation problem was formulated, and the energy balances, consisting of electricity balance, heating balance, and cooling balance, are expressed as Constraints (1)–(12).

$$F_{pgu,t} = \begin{cases} a \cdot E_{pgu,t} + b & \text{if } E_{pgu,t} > 0 \\ 0 & \text{other} \end{cases} \quad \forall t, \quad (1)$$

$$E_{pgu,t} + E_{grid,t} = E_{b,t} + E_{ec,t} \quad \forall t, \quad (2)$$

$$E_{b,t} \geq E_{load,t} \quad \forall t, \quad (3)$$

$$Q_{pgu,t} + Q_{boiler,t} \geq Q_{hac,t} + Q_{lhe,t} \quad \forall t, \quad (4)$$

$$Q_{pgu,t} = F_{pgu,t} \eta_{rec} \quad \forall t, \quad (5)$$

$$Q_{boiler,t} = F_{boiler,t} \eta_{boiler} \quad \forall t, \quad (6)$$

$$Q_{hac,t} \cdot COP_{ac} = Q_{ac,t} \quad \forall t, \quad (7)$$

$$Q_{ec,t} = E_{ec,t} \cdot COP_{ec} \quad \forall t, \quad (8)$$

$$Q_{ac,t} + Q_{ec,t} \geq Q_{load,t} \quad \forall t, \quad (9)$$

$$Q_{ac,t} = 0.5 \cdot Q_{load,t} \quad \forall t, \quad (10)$$

$$Q_{hhe,t} \cdot \eta_h \geq Q_{load,t} \quad \forall t, \quad (11)$$

$$F_{pgu,t}, F_{boiler,t}, E_{pgu,t}, E_{grid,t}, E_{b,t}, E_{ec,t}, Q_{pgu,t}, Q_{boiler,t}, Q_{hac,t}, Q_{hhe,t}, Q_{ac,t}, Q_{ec,t} \geq 0 \quad \forall t. \quad (12)$$

As for the electricity balance, Constraint (1) shows that the electricity from PGU firing natural gas equals fuel consumption with natural gas to electricity conversion parameters. Constraint (2) ensures that the sum of electricity from PGU and procured from the power grid can be used to satisfy the electricity demand and electric chiller consumption. Constraint (3) represents that the electricity demand of the end-user must be satisfied.

With regard to the heating/cooling balance, Constraint (4) means that the heating energy from the PGU and boiler in the CCHP system can be delivered to the heat exchanger and absorption chiller. The heating energy is generated from the PGU and boiler, as shown in Constraints (5) and (6). Constraints (7) and (8) describe that the cooling energy from electric chiller and absorption chiller equals the electricity and heating consumption multiplied by the conversion parameters, respectively. Constraint (9) indicates that the cooling generated by the hybrid chiller is provided for the cooling demand of end-user. Constraint (10) shows that the cooling generated by the absorption chiller is assumed to account for fifty percent in total cooling energy. Constraint (11) states that the heating energy generated by the heating exchanger should satisfy the heating demand of the end-user. In addition, Constraint (12) defines the decision variables.

3.2. Carbon Emission Regulations

Carbon tax and carbon trading regulations are enforced in most countries. A carbon tax policy is that a tax is imposed on the amount of total emission based on the CO₂ emission tax price. Moreover, according to UN IPCC, the carbon tax price adopted in some developed countries is \$20–\$100/ton. The carbon trading mechanism, where a carbon trading market is developed, is another widely adopted carbon emission regulation. The government gives the user a certain amount of carbon emission allowances, and the user can purchase or sell parts of the allowance to keep its operation. Ideally, the carbon trading price is flexible according to the market supply and demand relation.

3.3. Objective Functions

3.3.1. Economic Assessment

To measure the economic benefit of the CCHP system over the separate system, COSR, namely the percentage of the reducing *COST* (cost) of the CCHP system, in contrast to the separate system, is selected to evaluate the economic performance. As the optimization objective of the CCHP system, maximal COSR is expressed by Formula (13). $COST_{separate}$ represents the minimal cost of boiler consumed fuel and power grid purchased electricity in the separate system, which is expressed as Equation (14). In addition, $COST_{cchp}$ equals to $COST_{basic}$, $COST_{tax}$, $COST_{trading}$ representing the cost of the CCHP system operation under no carbon emission regulations, under carbon tax regulation, and under carbon trading regulation, respectively. c_f represents the natural gas price and c_e denotes the electricity price.

$$\text{MaxCOSR} = \frac{\text{COST}_{\text{separate}} - \text{COST}_{\text{cchp}}}{\text{COST}_{\text{separate}}} \cdot 100\%, \quad (13)$$

$$\text{COST}_{\text{separate}} = \min \sum_t \{c_f \cdot F_{\text{boiler},t} + c_e \cdot E_{\text{grid},t}\}. \quad (14)$$

In the CCHP system, the cost contains the natural gas cost from PGU and boiler consumption and electricity cost from the power grid. $\text{COST}_{\text{basic}}$ denotes the basic cost of the CCHP system without carbon emission regulations, which can be calculated from Equation (15).

$$\text{COST}_{\text{basic}} = \sum_t \{c_f \cdot (F_{\text{pgu},t} + F_{\text{boiler},t}) + c_e \cdot E_{\text{grid},t}\}. \quad (15)$$

With the carbon tax regulation, in addition to the cost, a carbon tax cost depending on CDE (carbon dioxide emission) and c_{tax} (carbon tax price) is also added to the cost. Hence, COST_{tax} can be calculated from Equation (16) and CDE can be obtained from Equation (17). μ_f and μ_e are the carbon emission conversion factors of natural gas and electricity, respectively.

$$\text{COST}_{\text{tax}} = \text{COST}_{\text{basic}} + c_{\text{tax}} \cdot \text{CDE}, \quad (16)$$

$$\text{CDE} = \sum_t \{\mu_f \cdot (F_{\text{pgu},t} + F_{\text{boiler},t}) + \mu_e \cdot E_{\text{grid},t}\}. \quad (17)$$

Considering the carbon trading policy, a carbon trading cost is added to the cost. $\text{CDE}_{\text{right}}$ indicates the government allocating carbon emission allowances for users, and c_{trading} is the trading price. The carbon emission allowances are assigned by the government and different values of CDE are permitted. It signifies that the end-user can sell or purchase carbon allowances to maintain its operation. $\text{COST}_{\text{trading}}$ represents the cost of the CCHP system under carbon trading policy, which can be described as Equation (18).

$$\text{COST}_{\text{trading}} = \text{COST}_{\text{basic}} - c_{\text{trading}} \cdot (\text{CDE}_{\text{right}} - \text{CDE}). \quad (18)$$

3.3.2. Environmental Assessment

It is of great importance that fuel is used more efficiently to reduce environmental damage and improve environmental sustainability. Generally, global warming is regarded as an important and key environmental issue which is closely related to CO₂. Therefore, in this research, the CDERR is adopted to denote the environmental sustainability index. Referring to the definition of COSR, the amount of CDERR means the environmental benefits accomplished by using the CCHP system over the separate system. Maximal CDERR is regarded as the objective and can be obtained from objective Function (19), to ensure the best environmental sustainability of the CCHP system.

$$\text{MaxCDERR} = \frac{\text{CDE}_{\text{separate}} - \text{CDE}_{\text{cchp}}}{\text{CDE}_{\text{separate}}} \cdot 100\%. \quad (19)$$

The carbon dioxide emission (CDE) of the CCHP system contains the carbon dioxide from the PGU and boiler firing natural gas, and public power grid burning fossil fuel. CDE_{cchp} denotes the carbon dioxide emission from the power grid, PGU, and boiler fuel consumption in the CCHP system. $\text{CDE}_{\text{separate}}$ represents the minimal carbon dioxide emission for burning fuel from the power grid and boiler in the separate system. Hence, CDE_{cchp} and $\text{CDE}_{\text{separate}}$ can be calculated via Equations (20) and (21), respectively.

$$\text{CDE}_{\text{cchp}} = \sum_t \{\mu_f \cdot (F_{\text{pgu},t} + F_{\text{boiler},t}) + \mu_e \cdot E_{\text{grid},t}\}, \quad (20)$$

$$CDE_{separate} = \min \sum_t \{ \mu_f \cdot F_{boiler,t} + \mu_e \cdot E_{grid,t} \}. \quad (21)$$

3.3.3. Energy Assessment

To evaluate the energy benefits of the CCHP system, the PESR is chosen as the energy index. Similarly, PESR is introduced as the proportion of the PEC (primary energy consumption) saved in the CCHP system, compared with the separate system. Function (22) is used to calculate the maximal PESR, which is selected as one of the optimization objectives.

$$\text{MaxPESR} = \frac{PEC_{separate} - PEC_{cchp}}{PEC_{separate}} \cdot 100\%. \quad (22)$$

PEC_{cchp} is the primary energy consumption from the PGU and boiler firing natural gas, and power grid burning fossil fuel in the CCHP system. $PEC_{separate}$ represents the lowest primary energy consumption (PEC) from the boiler and power grid burning fuel in the separate system. Furthermore, PEC_{cchp} can be calculated from Equation (23) and $PEC_{separate}$ can be obtained from Equation (24). k_f and k_e represent the site-to-primary energy conversion factors of fuel and electricity, respectively.

$$PEC_{cchp} = \sum_t \{ k_f \cdot (F_{pgu,t} + F_{boiler,t}) + k_e \cdot E_{grid,t} \}, \quad (23)$$

$$PEC_{separate} = \min \sum_t \{ k_f \cdot F_{boiler,t} + k_e \cdot E_{grid,t} \}. \quad (24)$$

4. Solution Approach

The NLP model is formulated for the multi-objective CCHP optimization problem under different carbon emission regulations. The NLP program is an NP-hard problem and needs heavy computational time. Therefore, the heuristic algorithm can be used to solve the NLP program with higher computational efficiency. As one of the popular heuristic algorithms, the PSO algorithm has obtained much attention. The PSO algorithm proposed by Kennedy and Eberhart can address the limitations of nonlinear and discrete decision variables [30,31]. Furthermore, the PSO algorithm has been broadly applied to solve a large variety of optimization problems owing to its good performance within a reasonable time and fast convergence rate, e.g., green lock scheduling problem [32], irrigation and power production management [33], and transportation network problem [34].

Therefore, the PSO algorithm is applied in this work to search for the near-optimal dispatch strategy for the CCHP system. In the PSO algorithm, each candidate solution of the CCHP operational strategy is considered as a particle in the swarm. The population size is denoted by N_p . Each particle is characterized by a location vector $L_p (p = 1, 2, \dots, N_p)$ and a velocity vector $v_p (p = 1, 2, \dots, N_p)$, and it can move around the searching space over iterations.

A series of numbers is randomly generated for all decision variables from their ranges as the initial solution. The position and velocity can be updated according to the Equations (25)–(27).

$$v_p(n+1) = w \cdot v_p(n) + c_1 \cdot r_1 \cdot (L_{PB,p}(n) - L_p(n)) + c_2 \cdot r_2 \cdot (L_{GB}(n) - L_p(n)), \quad \forall p, n, \quad (25)$$

$$L_p(n+1) = L_p(n) + v_p(n+1) \quad \forall p, n, \quad (26)$$

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter_{max}} \cdot n \quad \forall n, \quad (27)$$

Here, n and $n+1$ represent n^{st} and $(n+1)^{st}$ iteration, respectively. c_1 , c_2 are positive learning factors and r_1 , r_2 are randomly generated from 0 to 1. w is the inertia weight and is used to control

the convergence behavior of the PSO. w_{max} and w_{min} signify the maximal and minimal inertia weight, respectively. $iter_{max}$ is the maximal number of iterations. $L_{PB,p}(n)$ is the p particle's best solution depending on its experience in the n iteration. $L_{GB}(n)$ represents the global best position of the entire swarm according to total swarm's historical experience in the n iteration.

By using the PSO algorithm, the near-optimal strategy for the CCHP system can be obtained. The implementation of the PSO algorithm can be depicted briefly as follows:

Step 1: Input the parameters of the PSO algorithm, including $c_1, c_2, r_1, r_2, w_{max}, w_{min}, iter_{max}$.

Step 2: Generate initial position L_p and velocity v_p of each particle randomly.

Step 3: Update the position $L_p(n)$ and velocity $v_p(n)$.

Step 4: Calculate the fitness of each particle according to the objective function.

Step 5: Update iteration number $n = n + 1$.

Step 6: Update pbest $L_{PB,p}$ and gbest L_{GB} .

Step 7: If $n < iter_{max}$, return Step 5; otherwise, proceed with Step 8.

Step 8: Output the optimal solution.

5. Case Studies

To investigate the sustainability assessment of the CCHP system with economic, environmental, and energy aspects using the formulated NLP model, the five different commercial building categories (i.e., office, supermarket, hotel, school, and hospital) were selected for analysis, which are all located in Shanghai, China. According to Jing et al. [35], the electrical loads during different seasons are similar, while the heating and cooling loads vary dramatically according to building categories. In addition, buildings almost have lower heating demands in the summer season and lower cooling demands in the winter season. Therefore, in the transition seasons, one-day energy demand profiles of the buildings are complex. Owing to space limitation, the economic benefit, environmental sustainability, and energy advantage of adopting CCHP systems for the office, supermarket, hotel, school, and hospital in transition seasons were investigated.

5.1. Pre-Set Parameters

In the CCHP system, input technical parameters have been summarized in Table 2 [36,37]. The commercial electric price and natural gas price of Shanghai are shown in Table 3 [38]. Carbon emission conversion parameters of electricity and fuel in Shanghai and primary energy consumption parameters [39] are also set in Table 3. The system configuration and parameters were considered to be the same for the five commercial buildings. The 24 h electricity, cooling, and heating loads of the office, supermarket, hotel, school, and hospital of Shanghai in a typical transition season are shown in Figure 3 [35]. In addition, the value of parameters in the separate system was the same as the values in the CCHP system.

Table 2. Value of the combined cooling, heating, and power (CCHP) equipment parameter settings.

Notation	Description	Value
COP_{ec}	Electricity to cooling conversion competence of the electric chiller	3.5
COP_{ac}	Heating to cooling energy conversion efficacy of the absorption chiller	0.7
a	Natural gas to electricity conversion coefficient of the PGU	2.7
b	Natural gas to electricity conversion parameter of the PGU	11.66
η_{rec}	Natural gas to heating conversion efficiency for the PGU	0.8
η_{boiler}	Natural gas to heating conversion efficiency of the auxiliary boiler	0.85
η_h	Thermal efficiency of the heating exchanger	0.8

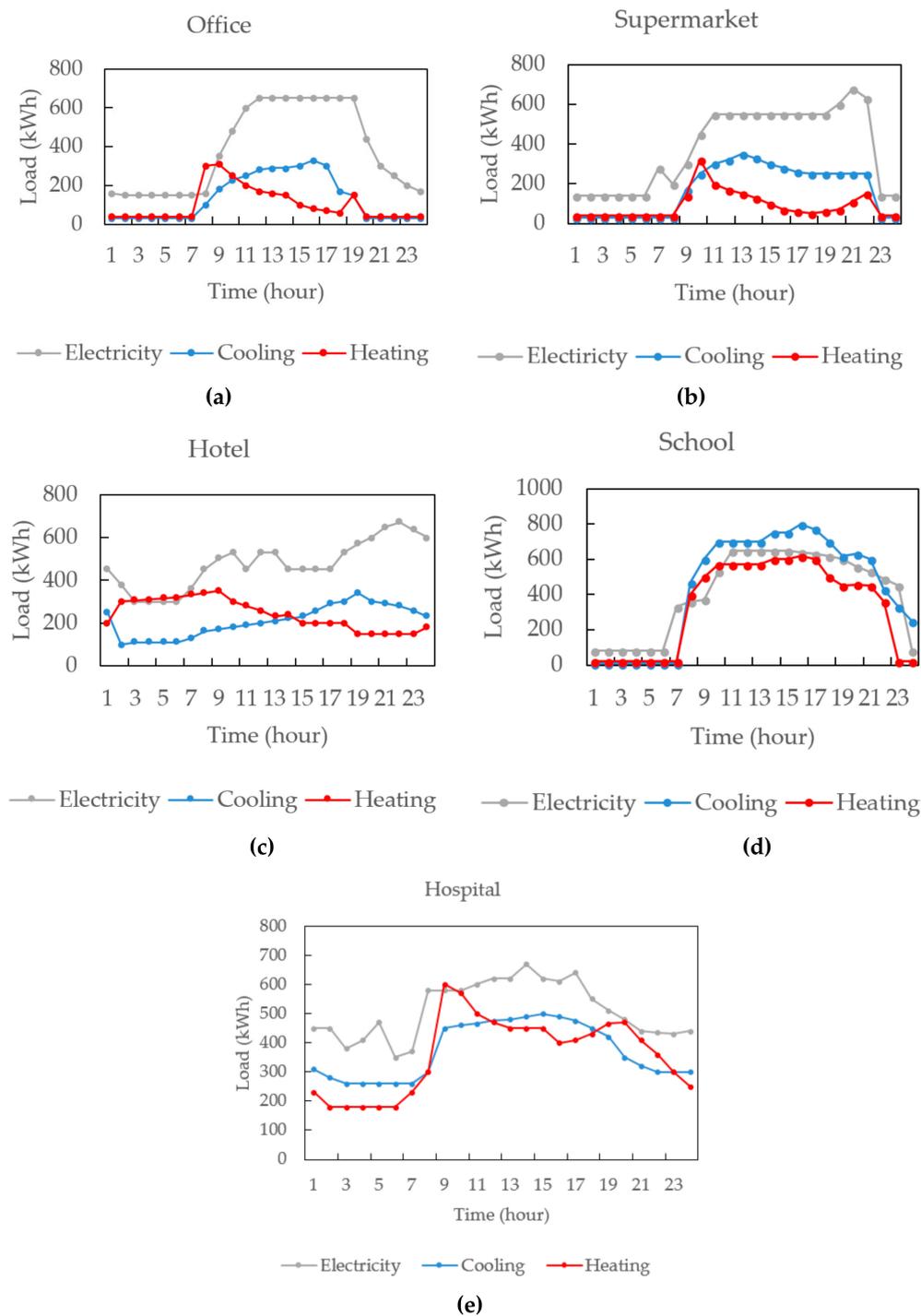


Figure 3. One-day energy demand profiles for five different building categories of Shanghai in the transition season. (a) Office; (b) supermarket; (c) hotel; (d) school; (e) hospital.

For the carbon emission regulations, the carbon tax price is comparatively lower in developing countries, such as China [40]. In the case studies, a carbon tax fee varying from \$1/ton to \$30/ton was adopted in subsequent performance analysis. The carbon trading price was assumed to be constant in a stable trading market [28]. A trading price variation range of \$1/ton to \$10/ton and carbon emission allowances from the set [0.6, 0.7, 0.8, 0.9, 1.0] were chosen in the subsequent performance analysis.

The optimization problems are solved in MATLAB by using the PSO algorithm, and the optimal schedule for the CCHP system can be obtained. By trying different parameter combinations, 2000 and

200 were selected as a reasonable population size and a maximal number of iterations to balance the optimal strategy and computational cost. The c_1 and c_2 were assumed as 2; the w_{max} and w_{min} were adopted to be 0.9 and 0.4, respectively. The computer used was a laptop with an Intel(R) Core(TM) i5–5200U CPU @ 2.20GHz processor, and a 4GB memory.

Table 3. The data of the CCHP system for sustainability assessment in Shanghai, China.

Notation	Description	Value
c_e	Electricity price (\$/kWh)	0.11
c_f	Natural gas price (\$/m ³)	0.54
μ_e	CO ₂ conversion factor of electricity (kg/kWh)	0.22
μ_f	CO ₂ conversion factor of natural gas (kg/kWh)	0.88
k_e	Site-to-primary energy conversion factor of electricity	3.336
k_f	Site-to-primary energy conversion factor of natural gas	1.047

Note: $0.54\$/m^3 = 0.054\$/kWh$, $1kg = 10^{-3}ton$.

5.2. Economic Performance Analysis

5.2.1. No Carbon Emission Regulations

When the carbon emission regulations are not taken into consideration, COSR of the optimal CCHP system over the separate system is shown in Figure 4. The cost savings of the office, supermarket, hotel, school, and hospital were 9.3%, 8.2%, 16.0%, 20.3%, and 19.5% by using the CCHP system, respectively. It is observed that the cost-saving ratio for the school using the CCHP system was higher than other buildings. The reason is that the energy loads of the school are usually larger than other buildings and then can be supplied more by the CCHP system, which leads to further cost-savings obtained.

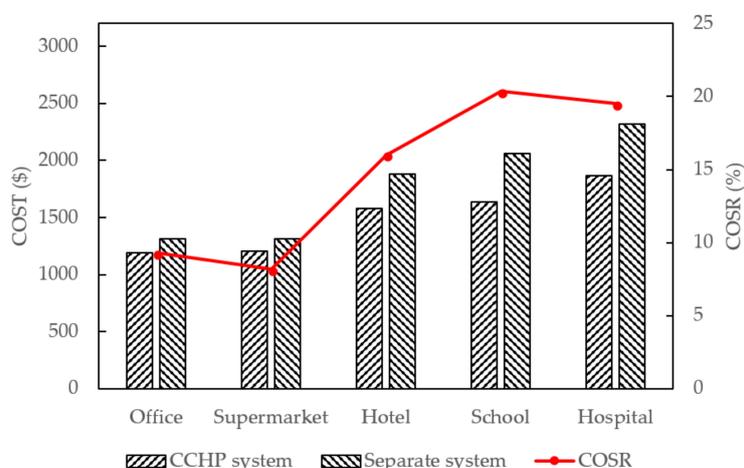


Figure 4. Cost (COST) and cost-saving ratio (COSR) of the CCHP system for five different building categories without carbon emission regulations in the transition season.

5.2.2. Analysis of Carbon Tax Regulation

Considering carbon tax regulation, Figure 5 illustrates the influence of different carbon taxes on carbon tax cost and COSR of the CCHP system for the five different commercial buildings in Shanghai when the objective is to maximize COSR. Figure 5a reveals that the carbon tax cost increased linearly with carbon tax per unit changing, and it can be observed that the amount of carbon emission for the optimal decision variables was not impacted by carbon tax ranging from \$1/ton to \$30/ton. Figure 5b indicates that the COSR of the office, supermarket, hotel, school, and hospital increased when the carbon tax was from \$1/ton to \$30/ton. Figure 5a,b also show that carbon tax policy had less influence on the office and supermarket because the carbon emissions of the two building categories was less than other buildings.

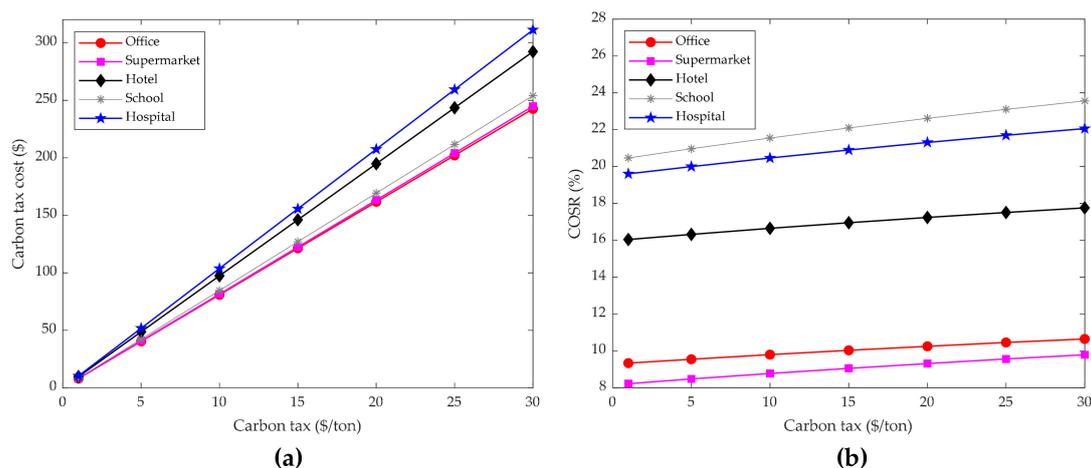


Figure 5. Impacts of various carbon taxes on (a) carbon tax cost; (b) COSR of the CCHP system for five different building categories in the transition season.

Furthermore, it can be observed from Figure 5 that the office, supermarket, hotel, school, and hospital could achieve averagely cost savings of 10.0%, 9.1%, 17.0%, 22.1%, and 20.9% by adopting the CCHP system considering carbon tax policy, respectively. Comparing the results in Figure 4 to the ones in Figure 5, it can be observed that the five different building categories using the CCHP system had a higher cost-saving ratio which increased by 0.7%, 0.9%, 1.0%, 1.8%, and 1.4% under the carbon tax policy than the situation without carbon emission regulations, respectively.

5.2.3. Analysis of Carbon Trading Regulation

With the guidance of the carbon trading mechanism, the relationships between the COSR of adopting the optimal CCHP system strategy and carbon trading price, as well as carbon emission allowances, are shown in Figure 6. It indicates that the COSR of the five commercial buildings increased with the carbon trading price varying from \$2/ton to 10/ton under certain carbon emission allowances. For example, the COSR of CCHP systems for the office increased from 9.5% to 10.2%, with carbon trading price varying from \$2/ton to \$10/ton with a 0.6-ton carbon emission allowance. In addition, Figure 6 also shows that the COSR of CCHP systems for the five commercial buildings increased by raising the carbon emission allowances from the set [0.6, 0.7, 0.8, 0.9, 1.0] under some carbon trading price. For instance, the COSR of the office increased from 10.2% to 10.6%, with carbon emission allowances varying from 0.6 ton to 1.0 ton with \$10/ton carbon trading.

Compared with the separate system, the optimal CCHP system strategy can lead to 10.0%, 8.9%, 16.8%, 21.6%, and 20.5% in cost savings for the office, supermarket, hotel, school, and hospital in Shanghai, respectively, considering carbon trading policy. As shown in Figures 4 and 6, using the CCHP system for the five different buildings appears to be more economically viable considering carbon trading policy than that without carbon emission regulations. Moreover, the cost-saving ratio of the school adopting the optimal CCHP system has increased the largest by 1.3%, considering the carbon trading policy compared to that without carbon emission regulations.

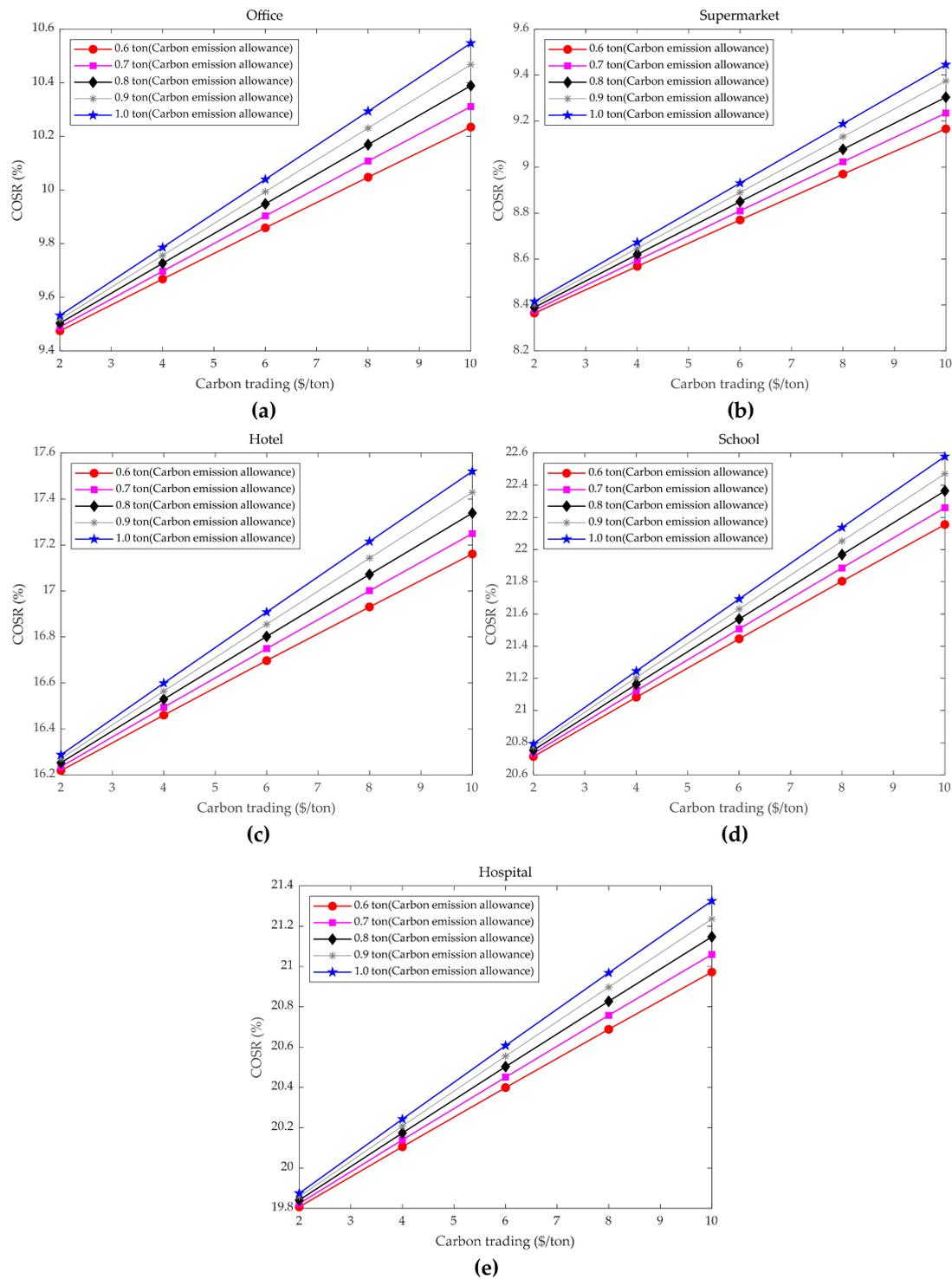


Figure 6. The effect of carbon trading policy on COSR of the CCHP system for five different building categories in the transition season. (a) Office; (b) supermarket; (c) hotel; (d) school; (e) hospital.

5.3. Environmental Performance Analysis

The carbon emission regulations made no difference to the optimal carbon dioxide emission of the CCHP system for the five different buildings when the objective was to maximize CDERR. The CDE and CDERR of the CCHP system over the separate system are shown in Figure 7. It can be observed that using the CCHP system can achieve 34.4%, 34.3%, 39.4%, 46.1%, and 43.7% carbon dioxide emission reduction for the office, supermarket, hotel, school, and hospital compared to the

separate system, respectively. In addition, it demonstrates that school and hospital have more CDERR. To analyze the differences in buildings, it is observed that the energy demands of the school and hospital were higher than in other buildings. As shown in Figures 4–7, an average of 15.3% in cost savings and 39.6% carbon dioxide emission reduction can be achieved for the five buildings by using the CCHP system, compared to the separate system. Moreover, the school adopting the optimal CCHP system can obtain more economic and environmental benefits than other buildings.

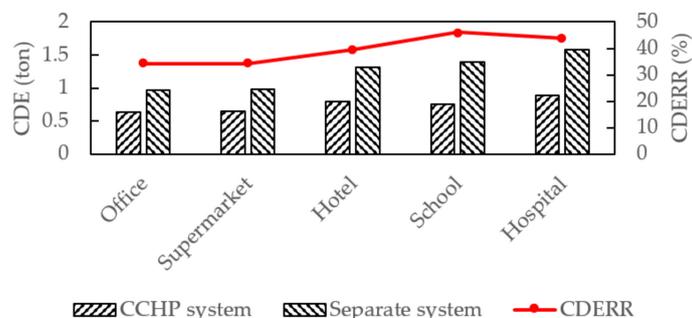


Figure 7. The carbon dioxide emission (CDE) and carbon dioxide emission reduction ratio (CDERR) of the CCHP system for five different building categories compared to the separate system in the transition season.

5.4. Energy Performance Analysis

The optimal primary energy consumption of the CCHP system was not affected by the different carbon emission regulations when the goal was to maximize PESR. Figure 8 presents the PEC and PESR of the optimal CCHP system over the separate system, which shows that using the CCHP system can obtain more energy advantage for all five different buildings. The PESR of the office, supermarket, hotel, school, and hospital were 19.2%, 19.1%, 26.6%, 35.4%, and 32.4%, respectively. In addition, the results from Figure 8 show that school and hospital adopting the CCHP system have a higher primary energy saving ratio. Moreover, as shown in Figures 4–8, the average for the COSR, CDERR, and PESR for the five building categories was 15.3%, 39.6%, and 26.5% by using optimal CCHP system strategy, respectively, compared to the separate system. Furthermore, compared to other buildings, more economic, environmental, and energy advantages were achieved in the school by adopting the CCHP system due to its high energy loads.

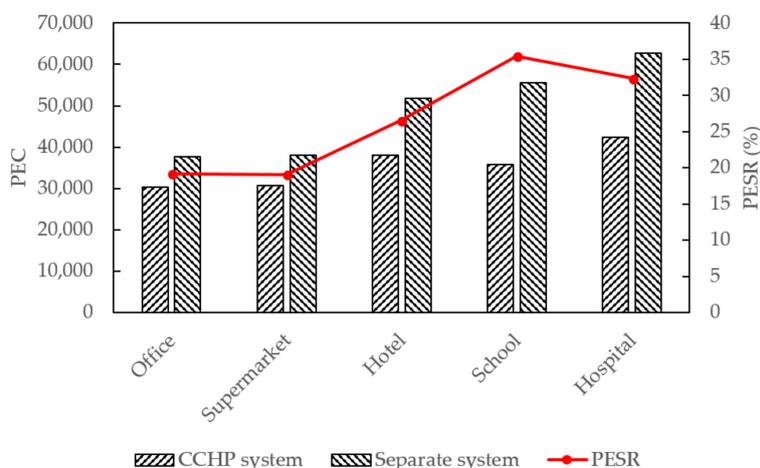


Figure 8. The primary energy consumption (PEC) and primary energy saving ratio (PESR) of the CCHP system for five different building categories compared to the separate system in the transition season.

6. Conclusions

In this research, the economic benefit, environmental sustainability, and energy advantage of CCHP systems compared to the conventional energy supply system under different carbon emission regulations were analyzed. Multi-Objective optimization was proposed based on the measures of COSR, CDERR, and PESR. Moreover, the model was solved using the PSO algorithm. The case results showed that the optimal CCHP system strategy can achieve 9.3%, 8.2%, 16.0%, 20.3%, and 19.5% in cost-saving compared to the separate system for the office, supermarket, hotel, school, and hospital without carbon emission regulations, respectively. Considering carbon tax regulation, the COSR is on average 10.0%, 9.1%, 17.0%, 22.1%, and 20.9% for the office, supermarket, hotel, school, and hospital adopting CCHP systems, respectively, compared to the separate system. Furthermore, the optimal CCHP system strategy compared to the separate system can lead to 10.0%, 8.9%, 16.8%, 21.6%, and 20.5% in cost savings for the office, supermarket, hotel, school, and hospital, respectively, considering carbon trading regulation. In addition, the CDERR and PESR of the CCHP system also can be achieved over the separate system and not affected by the carbon tax and carbon trading regulations when the maximal CDERR and maximal PESR are chosen as optimal objectives, respectively. Moreover, the best economic benefit, environmental sustainability, energy advantage of the CCHP system was achieved for the school than other buildings.

In brief, the CCHP system can achieve an economic benefit, environmental sustainability, and energy advantage under carbon tax and carbon trading regulations compared to the conventional energy supply system. In addition, the government could enforce the carbon emission regulations accordingly to improve the cost-saving of CCHP systems compared to the conventional energy supply system.

In the future, this research can be extended to apply a stochastic programming model to assess the sustainability performance (e.g., environmental aspect) of the CCHP system for different building categories under uncertainties when other carbon emission regulations are taken into consideration.

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