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Multi-stage planning of integrated electricity-gas-heating system in the context of carbon emission reduction

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ABSTRACT

In order to facilitate the carbon emission reduction to mitigate climate change, this paper proposes a coordinated multi-stage planning strategy for the transmission-level integrated electricity-gas-heating system. The strategy coordinates installations of gas-fired generation plants, renewable energy plants, gas wells, power-to-gas plants, transmission lines and pipelines, considering retirements of coal-fired generation plants. It can help facilitate carbon emission reduction of the electricity system as well as the integrated energy system. The objective is to minimize the total present value of the investment and the operation economic cost, with consideration of constraints from each sub-system and carbon emission restriction. In the case studies, the proposed planning strategy is verified to be able to obtain the installation plan of the related facilities. With which the system can reduce the proportion of fossil fuel energy utilization and increase renewable energy utilization. Hence, carbon emission reduction is achieved. In addition, it has demonstrated that integrating the multi-energy systems can help reduce the economic cost in the planning result.

1. Introduction

In order to mitigate climate change, countries around the world are actively taking measures for carbon emission reduction across various sectors. In 2015, 195 countries signed the Paris Agreement under the United Nations Framework Convention on Climate Change [1], which emphasizes the paramount significance of reducing the emission of greenhouse gas, mainly represented by carbon dioxide. In recent years, more and more countries and organizations have begun to take measures to reduce carbon emission, like China, USA, EU etc. Hence, carbon emission reduction is becoming a consensus in the world.

Due to the presence of large-scale fossil fuel-fired generation plants, the electricity transmission system has been one of the major carbon emission sources, so it takes an important responsibility in this process. Usually, the measures of the electricity system include the retirement of high-emission generation plants and the installation of low-emission generation plants as well as renewable energy plants. However, high penetration of intermittent renewable energy would make it difficult for the electricity system to guarantee the real-time balance between generation and consumption [2].

In recent years, with the continuous development of integration facilities, the connections of electricity system with other energy systems are being strengthened, such as with gas system [3] and district heating system [4]. Then, the concept of the integrated energy system was formed and continuously developed [5,6]. This kind of integration makes the energy network heterogeneous, rather than containing only one kind of energy. Hence, related works are needed to investigate the mechanism of energy conversion and transmission in this kind of energy network.

In this field, the relevant theoretical research and engineering practice are actively conducted. Refs. [7–9] revealed the large-scale new flexibility released by integrating heterogeneous energy networks, and elucidated the mechanism of using such flexibility to increase renewable energy penetration. The work created a new direction of multi-energy flows management. Refs. [8–10] proposed an original energy circuit model, it unified the mathematical models of the heterogeneous energy networks to convert the complex partial differential equations into algebraic equations. The work represents the breakthrough progress in solving the bottleneck problems of efficiency and reliability in computing large-scale integrated energy systems, and lays the foundation for the online analysis and optimization of large-scale integrated energy systems. Furthermore, the research team has firstly developed an Integrated Energy Management System (IEMS) and used it in industrial practices with significant performance improvements in the world [9].

In particular, it has been verified that the flexibility of gas and heating systems can help electricity system guarantee power balance and increase renewable energy utilization [11], and contribute to carbon

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Nomenclature

Indices

S	Set of indices determined by the related superscripts

Constant Parameters

BUD	Budget for investment cost of related sub-system
C	Cost parameter determined by the related superscripts and subscripts
CAP	Cap for CO_2 emission
E	Emission coefficient of CO_2
EF	Energy conversion efficiency of the related facility
ES	Amount of heating energy stored in the district heating system
LP	Linepack amount
N	Constant value to represent the number determined by the related superscripts
NK	Number of extreme points in the feasible operation region of the CHP plant
R	Ratio or rate determined by the related superscripts and subscripts
Z	Binary parameter to represent the state of related coal-fired generation facilities
P, Φ, H	Electricity,gas,heating flow value

Decision Variables

$cost$	Related investment or operation economic cost determined by the superscripts and subscripts
es	Amount of heating energy stored in the district heating system
lp	Linepack amount
z	Binary variable to represent the state of related facilities
α	variable to determine the operation point of the CHP plant
p, ϕ, h	Electricity,gas,heating flow value

Superscripts

B	Bus in the electricity system
CFCHP	Coal-fired combined heat and power plant
CFTU	Coal-fired thermal unit plant
CHP	combined heat and power plant, including the coal-fired and the gas-fired
CO_2	Carbon dioxide
CT	Curtailment
D	Demand
DHS	District heating system
E,C	Existing,candidate facilities
F	Fuel cost
E,G,H	Electricity,gas,heating
GFCHP	Gas-fired combined heat and power plant
GFTU	Gas-fired thermal unit plant
GW	Gas well
I,O	Investment,operation cost
L	Transmission line in the electricity system
N	Node in the gas system
NF,NT	From,to node
NS	non-supplied
P, Φ,H	Electricity,gas,heating flow
PF,PT	From,to pipeline
PV	Photovoltaic power plant
P2G	Power to gas plant
RD,RU	Ramping down,up
RE	Renewable power plant, including the wind power and the photovoltaic power
S	Supply
T	Time period
TU	thermal unit plant, including the coal-fired and the gas-fired
W	Wind power plant

Subscripts

b	Bus in the electricity system
d	Day
g	Generation facility
j	District heating system
k	kth extreme point in the feasible operation region of the related CHP plant
l	Transmission line in the electricity system
n	Node in the gas system
p	Pipeline in the gas system
s	Planning stage
t	Time period

emission reduction. However, the connections among these kinds of energy systems are not strong enough at the current stage. Accordingly, the related planning strategy is needed to facilitate the interconnections among these energy systems and help the transition from a state of relatively high emission to that of low emission. Hence, it is of great meaning to investigate the coordinated planning strategy of the integrated electricity-gas-heating system (IEGHS) in the context of carbon emission reduction.

There have been many investigations focused on the planning of the integrated electricity and gas system, especially at the transmission level. [12] proposes a two-stage stochastic planning method of interdependent gas and electrical power transmission system, and analyzes the balance between building gas-related facilities and power-related facilities. [13] proposes a security-constrained planning strategy for integrated electricity and gas system, the candidate facilities include transmission lines, pipelines and gas compressors. [14] proposes a three-level robust co-planning method for integrated power and gas system with high penetration of renewable energy, in which the three levels are used to minimize the investment cost, determine the worst possible case and minimize the overall operation cost, respectively. However, these works all adopt the single-stage framework for the planning investigation. In this framework, the planning decisions are made for the target time point and then are used during the whole planning horizon [15]. Accordingly, the possibility of further investment decisions is difficult to be considered.

To deal with this problem, the multi-stage framework can be a kind of solution [15]. In this framework, a group of planning decisions are made for different stages during the whole planning horizon. Accordingly, it allows the planner to adapt to afterwards changes in the energy system. There have been some works conducted in this direction. A bi-level planning method is proposed in [16] to coordinate the generation evolution plan of integrated gas and power transmission system, in which the upper-level program optimizes the system expansion plan

Table 1
Comparison among recently proposed planning strategies of integrated energy system.

Reference	System level	Multi-stage	CO_2 considered	Number of sub-systems		
				Electricity	Gas	Heating
[12]	Transmission	No	No	One	One	None
[13]	Transmission	No	No	One	One	None
[14]	Transmission	No	No	One	One	None
[16]	Transmission	Yes	Yes	One	One	None
[17]	Transmission	Yes	Yes	One	One	None
[18]	Transmission	Yes	No	One	One	None
[23]	Distribution	Yes	No	One	One	One
[24]	Distribution	Yes	No	One	One	One
This work	Transmission	Yes	Yes	One	One	Multi

and the lower-level solves the economic dispatch of system. [17] proposed a multi-stage planning strategy for the integrated electricity and gas system to facilitate the low-carbon transition, in which the related uncertainties are considered. A chance constraint programming to coordinate the planning decisions of power generation, gas network and storage in the integrated electrical power and gas transmission system is proposed in [18], and a chance constraint programming solution algorithm is adopted to solve the programming problem. The above investigations all focus on planning of integrated power and gas transmission system, but the participation of heating system is not considered.

In many high-latitude areas, the large-scale central power generation plants are usually responsible for supplying heating energy as well. In the north and northeastern provinces of China, combined heat and power (CHP) plants account for 50%–70% of the electricity supply capacity [19]. In Denmark, CHP plants cover around 85% of the total capacity of centralized power generation plants and are responsible for around 70% of district heating energy supply [20]. Therefore, CHP plants play an important role in the planning investigation in such areas. Besides, it has been certified that the flexibility of district heating system can help ensure secure operation and increase renewable energy utilization in electricity system as well as decrease operation cost [10,21]. Hence, it is necessary to consider the flexibility and operation constraints of district heating systems in the planning investigation in high-latitude areas.

There have been works on the planning with consideration of heating system [22]. A coordinated planning strategy for the integrated energy system is proposed in [23], containing a steady-state energy flow model for system analysis and an expansion method to optimize investment plans. [24] proposes a resilient-constrained two-stage expansion planning strategy to optimize the expansion of integrated energy system and improve resilience against hurricanes in the long term. While these works have not emphasized the effect of these strategies on carbon emission reduction. Besides, they are focused on the integrated energy system at the distribution level, which usually contains only one of each kind of sub-system. At the transmission level, there are usually more than one district heating systems contained in the integrated energy system.

Under these circumstances, this paper proposes a multi-stage planning strategy for integrated electricity-gas-heating system at transmission level in the context of carbon emission reduction. In this strategy, the installations of new facilities are coordinated considering the retirements of coal-fired generation plants to smooth the planning process. A comparison between the proposed work and the aforementioned works is shown in Table 1.

From the comparison in the table, it can be observed that the proposed strategy comprehensively considers the heating systems and carbon emission reduction in the integrated energy system at the transmission level, and then its novelty is demonstrated. The main highlights of the paper are as follows: (1) A multi-stage planning strategy of the integrated electricity-gas-heating system at the transmission level in the context of carbon emission reduction is proposed. The planning problem is formulated as mixed-integer linear programming to minimize the total economic cost during the whole planning horizon. (2) To simplify the complexity of the optimization problem, an aggregated model of district heating system is adopted. (3) Contributions from the flexibility of the gas and heating systems are demonstrated by comparison among different cases in the case study.

The remaining part of this paper is organized as follows. Section 2 describes the structure of the investigated integrated electricity-gas-heating system and explains the modeling assumptions. Section 3 formulates the optimization problem of the proposed planning strategy. Section 4 describes and analyzes the case study results. Section 5 gives the conclusion.

2. System structure and assumptions

In this section, the structure of the transmission-level IEGHS is described, and then the related assumptions for the planning investigation are given.

2.1. System structure

The structure of the transmission-level IEGHS considered in this paper is shown in Fig. 1. It consists of one electricity transmission system (ETS), one gas transmission system (GTS) and a number of district heating systems (DHSs).

In the electricity system, the demand is supplied by the coal-fired generation plants, the gas-fired generation plants and the renewable energy plants. In more detail, the coal-fired generation plants include the coal-fired thermal unit (CFTU) plant and the coal-fired CHP (CFCHP) plant, the gas-fired generation plants include the gas-fired thermal unit (GFTU) plant and the gas-fired CHP (GFCHP) plant, and renewable energy plants include the wind (W) power plant and the photovoltaic (PV) power plant. The thermal unit plant is the traditional generation plant, which outputs electricity power into the system, but not the heating energy. In the gas system, the demand is supplied by the gas well (GW) and the power to gas (P2G) plant. In the heating systems, the demand is supplied by the CHP plants, including the CFCHP plant and the GFCHP plant.

The GFTU, P2G, CFCHP and GFCHP plants act as the integration facilities in the integrated energy system. In this work, it is assumed that the GFTU plant is operated by the electricity system, it consumes gas and outputs electricity power. The P2G plant is operated by the gas system, it consumes power and outputs gas. The CFCHP and the GFCHP plant are operated by the heating systems, they output heating and electricity power energies. In addition, the GFCHP plant consumes gas from the gas system. The related energy flows among different sub-systems are illustrated in Fig. 1.

2.2. Assumptions

The proposed planning strategy is based on the following assumptions [17].

(1) The centralized management framework is adopted, and a perfectly competitive market is assumed.

(2) Retirement plans of coal-fired plants (CFTU plant and CFCHP plant) are assumed to be determined before the planning optimization [17].

(3) Each planning stage is represented by a single representative year [15], and each representative year is represented by several representative days [25,26].

(4) The time resolution of the energy flow is set as one hour, and each representative day contains 24 h.

(5) Short-term operation flexibility is mainly supported by the conventional plants and the flexibility from gas and heating systems, demand responses and energy storage facilities are not considered.

(6) The CHP plants are assumed to be operated by the district heating systems, and this assumption is often adopted in other related works [27,28].

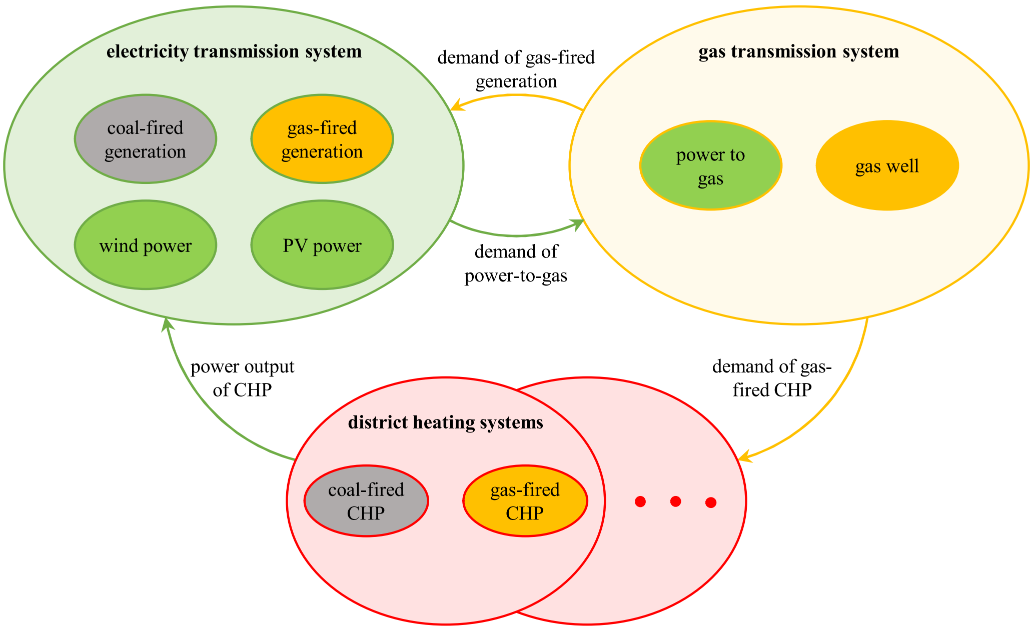


Fig. 1. Structure of the transmission-level integrated electricity-gas-heating system.

3. Formulation of optimization problem

The optimization problem of the proposed planning strategy is formulated in this section. Firstly, the objective function is introduced. Then, the constraints from each sub-system and carbon emission restriction are described. At last, the formulated optimization problem is summarized, and the framework of the proposed planning strategy is illustrated.

3.1. Objective function

The objective function (1) is to minimize the present value [18] of the total economic cost during the whole planning horizon, and the cost is composed of the investment cost and the operation cost of each sub-system. The ratio factor R^{M} is to ensure that the calculated operation cost has the proper order of the magnitude [29].

$$\begin{aligned}\min \quad & \sum_{s\in\mathcal{S}^{\mathrm{S}}} R^{\mathrm{DP}}_{s}\left(cost^{\mathrm{E,I}}_{s}+cost^{\mathrm{G,I}}_{s}+cost^{\mathrm{H,I}}_{s}\right)\\ & + R^{\mathrm{M}}\sum_{s\in\mathcal{S}^{\mathrm{S}}}\sum_{d\in\mathcal{S}^{\mathrm{D}}} R^{\mathrm{DP}}_{s}\left(cost^{\mathrm{E,O}}_{d,s}+cost^{\mathrm{G,O}}_{d,s}+cost^{\mathrm{H,O}}_{d,s}\right) \qquad (1)\end{aligned}$$

3.1.1. Calculation of investment cost

More specifically, the investment cost of the electricity system is calculated in (2). The first to the third terms in it are the investment costs of candidate GFTU plants, renewable energy (including wind power and PV power) plants and electricity transmission lines, respectively.

$$\begin{aligned}cost^{\mathrm{E,I}}_{s} = & \sum_{g\in\mathcal{S}^{\mathrm{GFTU,C}}} C^{\mathrm{I}}_{g,s}\left(z_{g,s}-z_{g,s-1}\right)+\sum_{g\in\mathcal{S}^{\mathrm{RE,C}}} C^{\mathrm{I}}_{g,s}\left(z_{g,s}-z_{g,s-1}\right)\\ & +\sum_{l\in\mathcal{S}^{\mathrm{L,C}}} C^{\mathrm{I}}_{l,s}\left(z_{l,s}-z_{l,s-1}\right) \qquad (2)\end{aligned}$$

Different from single-stage planning, decisions in multi-stage planning are not made for a single time period, but for a group of planning stages. Hence, the candidate facilities can be installed in different stages within the horizon, which adds further burden for calculating the costs in different stages. In order to solve this, a binary variable is assigned to each candidate facility and is used to indicate its installation state. Take $z_{g,s}$ as an example, $z_{g,s}=0$ means that the candidate facility g has not been installed by the end of the planning stage s, and $z_{g,s}=1$ means that it is installed in the stage s. If a facility G is installed in a specific stage S, it has $z_{G,s}=0$ for $s\leq S-1$ and $z_{G,s}=1$ for $s\geq S$. Then, it can have $z_{G,s}-z_{G,s-1}=0$ for $s\leq S-1$ as well as $s\geq S+1$, and $z_{G,s}-z_{G,s-1}=1$ only when $s=S$. With this scheme, the cost of the related facility can be considered in the correct stage in the investment cost calculation. More examples of the adopted scheme can be found in other related works, such as [17,30,31].

The investment cost of the gas system is calculated in (3). The first to the third terms in it are the investment costs of the candidate gas wells, P2G plants and gas transmission pipelines, respectively.

$$\begin{aligned}cost^{\mathrm{G,I}}_{s} = & \sum_{g\in\mathcal{S}^{\mathrm{GW,C}}} C^{\mathrm{I}}_{g,s}\left(z_{g,s}-z_{g,s-1}\right)+\sum_{g\in\mathcal{S}^{\mathrm{P2G,C}}} C^{\mathrm{I}}_{g,s}\left(z_{g,s}-z_{g,s-1}\right)\\ & +\sum_{p\in\mathcal{S}^{\mathrm{P,C}}} C^{\mathrm{I}}_{p,s}\left(z_{p,s}-z_{p,s-1}\right) \qquad (3)\end{aligned}$$

The investment cost of district heating systems is calculated in (4), and it is the cost of the candidate GFCHP plants.

$$cost^{\mathrm{H,I}}_{s} = \sum_{g\in\mathcal{S}^{\mathrm{GFCHP,C}}} C^{\mathrm{I}}_{g,s}\left(z_{g,s}-z_{g,s-1}\right) \qquad (4)$$

3.1.2. Calculation of operation cost

The operation cost of the electricity system is calculated in (5), the first to the fourth terms in it are the fuel cost of CFTU plants, the carbon emission penalty cost of all TU (including CFTU and GFTU) plants, the curtailment penalty cost of renewable energy plants and the penalty cost of non-supplied electricity demand.

$$\begin{aligned}cost^{\mathrm{E,O}}_{d,s} = & \sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{g\in\mathcal{S}^{\mathrm{CFTU}}} C^{\mathrm{F}}_{g,s}p_{g,t,d,s}+\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{g\in\mathcal{S}^{\mathrm{TU}}} C^{\mathrm{CO_2}}_{s}E^{\mathrm{CO_2}}_{g}p_{g,t,d,s}\\ & +\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{g\in\mathcal{S}^{\mathrm{RE}}} C^{\mathrm{CT}}_{g,s}\left(\overline{P}_{g,t,d,s}-p_{g,t,d,s}\right)\\ & +\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{b\in\mathcal{S}^{\mathrm{B}}} C^{\mathrm{NS,P}}_{s}\left(P^{\mathrm{D}}_{b,t,d,s}-p^{\mathrm{S}}_{b,t,d,s}\right) \qquad (5)\end{aligned}$$

The operation cost of the gas system is calculated in (6), the first to the third terms in it are the generation cost of gas wells, the incentivization of carbon absorption of the P2G plant and the penalty cost of non-supplied gas demand. Since the production process of power to gas should consume carbon dioxide [32], the emission rate of the P2G plant has a negative value.

$$cost^{\mathrm{G,O}}_{d,s} = \sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{g\in\mathcal{S}^{\mathrm{GW}}} C^{\mathrm{G}}_{g,s}\phi_{g,t,d,s}+\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{g\in\mathcal{S}^{\mathrm{P2G}}} C^{\mathrm{CO_2}}_{s}E^{\mathrm{CO_2}}_{g}\phi_{g,t,d,s}$$

$$+\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{n\in\mathcal{S}^{\mathrm{N}}} C_s^{\mathrm{NS},\Phi}\left(\Phi^{\mathrm{D}}_{n,t,d,s}-\phi^{\mathrm{S}}_{n,t,d,s}\right) \tag{6}$$

The operation cost of the heating systems is calculated in (7), the first to the third terms in it are the fuel cost of the CFCHP plant, the carbon emission penalty cost of all CHP (including CFCHP and GFCHP) plants, and the penalty cost of non-supplied heating demand.

$$\begin{aligned} cost^{\mathrm{H,O}}_{d,s} = &\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{g\in\mathcal{S}^{\mathrm{CFCHP}}}\left(C^{\mathrm{F,H}}_{g,s}h_{g,t,d,s}+C^{\mathrm{F,P}}_{g,s}p_{g,t,d,s}\right)\\ &+\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{g\in\mathcal{S}^{\mathrm{CHP}}} C^{\mathrm{CO_2}}_s\left(E^{\mathrm{CO_2,H}}_g h_{g,t,d,s}+E^{\mathrm{CO_2,P}}_g p_{g,t,d,s}\right)\\ &+\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{j\in\mathcal{S}^{\mathrm{DHS}}} C^{\mathrm{NS,H}}_s\left(H^{\mathrm{D}}_{j,t,d,s}-h^{\mathrm{S}}_{j,t,d,s}\right) \end{aligned} \tag{7}$$

3.2. Constraints from electricity system

The constraints from the electricity system include those of binary variable, generation plant, power flow, and etc. They are described in detail in this section.

3.2.1. Constraints of binary variable

In order to correctly characterize the facility installation in the multi-stage planning, the constraints of binary variable in (8)–(9) need to be considered. These constraints enforce that once the candidate facility is built in a specific planning stage, the value of its binary indicating variable is changed to one and is kept at this value in all the remaining stages [33,34]. More examples of this scheme can be found in the related works, such as [30,31].

$$z_{g,s}\ge z_{g,s-1},\quad \forall g\in\mathcal{S}^{\mathrm{GFTU,C}}\cup\mathcal{S}^{\mathrm{RE,C}},\ \forall s\in\mathcal{S}^{\mathrm{S}} \tag{8}$$

$$z_{l,s}\ge z_{l,s-1},\quad \forall l\in\mathcal{S}^{\mathrm{L,C}},\ \forall s\in\mathcal{S}^{\mathrm{S}} \tag{9}$$

3.2.2. Constraints of TU plant

For the TU plants, (10)–(12) are the constraints for their outputs. In more detail, (10) means that the output of the CFTU plant should be within the output capacity before retirement and be equal to zero after retirement. (11) means that the output of the existing GFTU plant should be within the output capacity during the whole planning horizon. (12) means that the output of the candidate GFTU should be equal to zero before installation and be within the output capacity after installation.

$$0\le p_{g,t,d,s}\le Z_{g,s}\overline{P}_g,\quad \forall g\in\mathcal{S}^{\mathrm{CFTU}},\ \forall t\in\mathcal{S}^{\mathrm{T}},\ \forall d\in\mathcal{S}^{\mathrm{D}},\ \forall s\in\mathcal{S}^{\mathrm{S}} \tag{10}$$

$$0\le p_{g,t,d,s}\le \overline{P}_g,\quad \forall g\in\mathcal{S}^{\mathrm{GFTU,E}},\ \forall t,\ \forall d,\ \forall s \tag{11}$$

$$0\le p_{g,t,d,s}\le z_{g,s}\overline{P}_g,\quad \forall g\in\mathcal{S}^{\mathrm{GFTU,C}},\ \forall t,\ \forall d,\ \forall s \tag{12}$$

For the simplicity of description, $\forall t\in\mathcal{S}^{\mathrm{T}}$, $\forall d\in\mathcal{S}^{\mathrm{D}}$ and $\forall s\in\mathcal{S}^{\mathrm{S}}$ in the formulas are abbreviated as $\forall t$, $\forall d$ and $\forall s$, respectively.

The constraint of the ramping limitation for these plants [35] is (13). It means that the output difference between any two consecutive operation time periods should be kept within the ramping capability limitation. More specifically, the time scale is one hour in this work.

$$-\overline{P}^{\mathrm{RD}}_g\le p_{g,t,d,s}-p_{g,t-1,d,s}\le \overline{P}^{\mathrm{RU}}_g,\quad \forall g\in\mathcal{S}^{\mathrm{TU}},\ \forall t,\ \forall d,\ \forall s \tag{13}$$

3.2.3. Constraints of renewable energy plant

The renewable energy plant in this work includes the wind power plant and the PV power plant. (14) ensures that the output of the existing renewable energy plant cannot exceed the maximum value in the corresponding time period. (15) ensures that the output of the candidate renewable energy plant should be equal to zero before installation and be within the maximum value after installation.

$$0\le p_{g,t,d,s}\le \overline{P}_{g,t,d,s},\quad \forall g\in\mathcal{S}^{\mathrm{RE,E}},\ \forall t,\ \forall d,\ \forall s \tag{14}$$

$$0\le p_{g,t,d,s}\le z_{g,s}\overline{P}_{g,t,d,s},\quad \forall g\in\mathcal{S}^{\mathrm{RE,C}},\ \forall t,\ \forall d,\ \forall s \tag{15}$$

3.2.4. Constraints of electricity power flow

Since the planning investigation usually involves a time horizon spanning a number of years, the detailed power flow model would make the optimization problem too complex. Similar to those adopted in the gas system [36–38], a brief power flow model is adopted here, and the related constraints are as follows. The constraint of power balance is (16), which enforces that the electricity power flowing into the bus should be equal to that flowing out.

$$\begin{aligned} &\sum_{l\in\mathcal{S}^{\mathrm{LT}}_b} p_{l,t,d,s}+\sum_{g\in\mathcal{S}^{\mathrm{TU}}_b} p_{g,t,d,s}+\sum_{g\in\mathcal{S}^{\mathrm{RE}}_b} p_{g,t,d,s}+\sum_{g\in\mathcal{S}^{\mathrm{CHP}}_b} p_{g,t,d,s}\\ &=\sum_{l\in\mathcal{S}^{\mathrm{LF}}_b} p_{l,t,d,s}+p^{\mathrm{S}}_{b,t,d,s}+\sum_{g\in\mathcal{S}^{\mathrm{P2G}}_b} p^{\mathrm{D}}_{g,t,d,s},\quad \forall b\in\mathcal{S}^{\mathrm{B}},\ \forall t,\ \forall d,\ \forall s \end{aligned} \tag{16}$$

The limitations of power flow through electricity transmission lines are as follows, including the existing and the candidate ones. In more detail, (17) means that the power flow through the existing transmission line should be kept within its transmission capacity. (18) means that the power flow through the candidate line should be equal to zero before installation and be kept within the capacity after installation.

$$-\overline{P}_l\le p_{l,t,d,s}\le \overline{P}_l,\quad \forall l\in\mathcal{S}^{\mathrm{L,E}},\ \forall t,\ \forall d,\ \forall s \tag{17}$$

$$-z_{l,s}\overline{P}_l\le p_{l,t,d,s}\le z_{l,s}\overline{P}_l,\quad \forall l\in\mathcal{S}^{\mathrm{L,C}},\ \forall t,\ \forall d,\ \forall s \tag{18}$$

3.2.5. Constraints of non-supplied rate

In the planning investigation, the energy demand is not necessarily to be fully supplied. It means that the actual supplied power on the electricity bus may not always be equal to the demand value. However, to restrict the non-supplied rate, the related constraints should be added to the optimization.

The constraints are as follows. (19) means that the actual supplied power should be no larger than the demand value. (20) means that the average value of the non-supplied rate during each planning stage should be kept within the maximum limitation.

$$0\le p^{\mathrm{S}}_{b,t,d,s}\le P^{\mathrm{D}}_{b,t,d,s},\quad \forall b\in\mathcal{S}^{\mathrm{B}},\ \forall t,\ \forall d,\ \forall s \tag{19}$$

$$\frac{\sum_{d\in\mathcal{S}^{\mathrm{D}}}\sum_{t\in\mathcal{S}^{\mathrm{T}}}\sum_{b\in\mathcal{S}^{\mathrm{B}}}\left[\left(P^{\mathrm{D}}_{b,t,d,s}-p^{\mathrm{S}}_{b,t,d,s}\right)\Big/P^{\mathrm{D}}_{b,t,d,s}\right]}{N^{\mathrm{D}}N^{\mathrm{T}}N^{\mathrm{B}}}\le R^{\mathrm{NS,P}}_s,\quad \forall s \tag{20}$$

3.2.6. Constraint of integration facility

The GFTU plant is an integration facility between the electricity and the gas systems. It is taken as a consumption facility in the gas system and as a generation facility in the electricity system [39]. The relationship between its gas consumption and power generation is calculated as follows.

$$\phi^{\mathrm{D}}_{g,t,d,s}=\frac{p_{g,t,d,s}}{EF_g},\quad \forall g\in\mathcal{S}^{\mathrm{GFTU}},\ \forall t,\ \forall d,\ \forall s \tag{21}$$

3.2.7. Constraint of investment budget

During the whole planning horizon, an investment budget is assumed for each kind of sub-system in each planning stage. Accordingly, the investment cost should be restricted within the related budget amount [17]. For the electricity system, the constraint of investment cost is (22).

$$cost^{\mathrm{E,I}}_s\le BUD^{\mathrm{E}}_s,\quad \forall s \tag{22}$$

3.3. Constraints from gas system

Constraints from the gas system include those of binary variable, generation facility, gas flow, and etc. They are described in detail in this section.

3.3.1. Constraints of binary variable

The constraints of the binary variables of candidate gas well, P2G plant and gas transmission pipeline are described in (23)–(24), which enforce the value of the indicating variable be equal to zero before installation and be equal to one after installation [33,34].

$$z_{g,s} \geq z_{g,s-1}, \quad \forall g \in \mathcal{S}^{\mathrm{GW,C}} \cup \mathcal{S}^{\mathrm{P2G,C}}, \ \forall s \tag{23}$$

$$z_{p,s} \geq z_{p,s-1}, \quad \forall p \in \mathcal{S}^{\mathrm{P,C}}, \ \forall s \tag{24}$$

3.3.2. Constraints of generation facility

The gas generation sources considered in this work include the gas well and the P2G plant, and the output constraints are as follows. (25) means that the output of the existing facility should be kept within the capacity limitation. (26) means that the output of the candidate facility should be equal to zero before installation and be kept within the capacity limitation after installation.

$$0 \leq \phi_{g,t,d,s} \leq \overline{\Phi}_g, \quad \forall g \in \mathcal{S}^{\mathrm{GW,E}} \cup \mathcal{S}^{\mathrm{P2G,E}}, \ \forall t, \ \forall d, \ \forall s \tag{25}$$

$$0 \leq \phi_{g,t,d,s} \leq z_{g,s}\overline{\Phi}_g, \quad \forall g \in \mathcal{S}^{\mathrm{GW,C}} \cup \mathcal{S}^{\mathrm{P2G,C}}, \ \forall t, \ \forall d, \ \forall s \tag{26}$$

3.3.3. Constraints of gas flow

The linearized gas flow model is employed in this work, since it is believed to be sufficient for the planning investigation and is often used in other related works [31,40,41]. The following constraint means that the total gas inflow and outflow on each node should be balanced.

$$\begin{aligned} &\sum_{p \in \mathcal{S}_n^{\mathrm{PT}}} \phi^{\mathrm{T}}_{p,t,d,s} + \sum_{g \in \mathcal{S}_n^{\mathrm{GW}}} \phi_{g,t,d,s} + \sum_{g \in \mathcal{S}_n^{\mathrm{P2G}}} \phi_{g,t,d,s} = \sum_{p \in \mathcal{S}_n^{\mathrm{PF}}} \phi^{\mathrm{F}}_{p,t,d,s} + \phi^{\mathrm{S}}_{n,t,d,s} \\ &\quad + \sum_{g \in \mathcal{S}_n^{\mathrm{GFTU}}} \phi^{\mathrm{D}}_{g,t,d,s} + \sum_{g \in \mathcal{S}_n^{\mathrm{GFCHP}}} \phi^{\mathrm{D}}_{g,t,d,s}, \quad \forall n \in \mathcal{S}^{\mathrm{N}}, \ \forall t, \ \forall d, \ \forall s \end{aligned} \tag{27}$$

The gas flow limitations at the two terminal nodes of each pipeline are given as follows. (28) means that the gas flows in the existing pipeline should be kept within the capability limitation. (29) means that the gas flows in the candidate pipeline should be equal to zero before installation and be kept within the capability limitation after installation.

$$\underline{\Phi}_p \leq \phi^{\mathrm{F}}_{p,t,d,s} \leq \overline{\Phi}_p, \quad \underline{\Phi}_p \leq \phi^{\mathrm{T}}_{p,t,d,s} \leq \overline{\Phi}_p, \quad \forall p \in \mathcal{S}^{\mathrm{P,E}}, \ \forall t, \ \forall d, \ \forall s \tag{28}$$

$$\begin{aligned} &z_{p,s}\underline{\Phi}_p \leq \phi^{\mathrm{F}}_{p,t,d,s} \leq z_{p,s}\overline{\Phi}_p, \quad z_{p,s}\underline{\Phi}_p \leq \phi^{\mathrm{T}}_{p,t,d,s} \leq z_{p,s}\overline{\Phi}_p, \\ &\quad \forall p \in \mathcal{S}^{\mathrm{P,C}}, \ \forall t, \ \forall d, \ \forall s \end{aligned} \tag{29}$$

3.3.4. Constraints of linepack

The linepack of the pipeline is constrained as follows, (30) means that the variation of linepack is determined by the value in the last time period and the gas flows at the two terminal nodes [42]. (31) means that the value of linepack of the existing pipeline should be kept within the limitation, (32) means that the value of linepack of the candidate pipeline should be equal to zero before installation and be kept within the limitation after installation.

$$lp_{p,t,d,s} = lp_{p,t-1,d,s} + \phi^{\mathrm{F}}_{p,t,d,s} - \phi^{\mathrm{T}}_{p,t,d,s}, \quad \forall p \in \mathcal{S}^{\mathrm{P}}, \ \forall t, \ \forall d, \ \forall s \tag{30}$$

$$\underline{LP}_p \leq lp_{p,t,d,s} \leq \overline{LP}_p, \quad \forall p \in \mathcal{S}^{\mathrm{P,E}}, \ \forall t, \ \forall d, \ \forall s \tag{31}$$

$$z_{p,s}\underline{LP}_p \leq lp_{p,t,d,s} \leq z_{p,s}\overline{LP}_p, \quad \forall p \in \mathcal{S}^{\mathrm{P,C}}, \ \forall t, \ \forall d, \ \forall s \tag{32}$$

In order to ensure the flexibility capability of linepack, the following constraint should be added to the optimization. It means that the linepack value at the end of each day should be equal to that at the beginning.

$$lp_{p,N^{\mathrm{T}},d,s} = LP_{p,0,d,s}, \quad \forall p \in \mathcal{S}^{\mathrm{P}}, \ \forall t, \ \forall d, \ \forall s \tag{33}$$

3.3.5. Constraints of non-supplied rate

Similar to those in the electricity system, the constraints of non-supplied rate in the gas system are as follows. The value of actual supplied gas flow is limited in (34), and the average value of the non-supplied rate is limited in (35).

$$0 \leq \phi^{\mathrm{S}}_{n,t,d,s} \leq \Phi^{\mathrm{D}}_{n,t,d,s}, \quad \forall n \in \mathcal{S}^{\mathrm{N}}, \ \forall t, \ \forall d, \ \forall s \tag{34}$$

$$\frac{\sum_{d \in \mathcal{S}^{\mathrm{D}}} \sum_{t \in \mathcal{S}^{\mathrm{T}}} \sum_{n \in \mathcal{S}^{\mathrm{N}}} \left[\left(\Phi^{\mathrm{D}}_{n,t,d,s} - \phi^{\mathrm{S}}_{n,t,d,s} \right) \Big/ \Phi^{\mathrm{D}}_{n,t,d,s} \right]}{N^{\mathrm{D}} N^{\mathrm{T}} N^{\mathrm{N}}} \leq R^{\mathrm{NS},\Phi}_s, \quad \forall s \tag{35}$$

3.3.6. Constraint of integration facility

For the P2G plant, it is taken as the consumption facility in the electricity system and as the generation facility in the gas system. The relationship between the power demand and the gas flow output is as follows [43].

$$p^{\mathrm{D}}_{g,t,d,s} = \frac{\phi_{g,t,d,s}}{EF_g}, \quad \forall g \in \mathcal{S}^{\mathrm{P2G}}, \ \forall t, \ \forall d, \ \forall s \tag{36}$$

3.3.7. Constraint of investment budget

The constraint of investment cost in the gas system is (37), which means that the total investment cost should be kept within the investment budget in each planning stage.

$$cost^{\mathrm{G,I}}_s \leq BUD^{\mathrm{G}}_s, \quad \forall s \tag{37}$$

3.4. Constraints from heating systems

The constraints from the heating systems include those of binary variable, CHP plant, heating supply balance, and etc. They are described in detail in this section.

3.4.1. Constraint of binary variable

The constraint of the binary variable limitation of the candidate GFCHP plant is as follows. It means that the binary variable value of the related plant should be equal to zero before installation and be equal to one after installation.

$$z_{g,s} \geq z_{g,s-1}, \quad \forall g \in \mathcal{S}^{\mathrm{GFCHP,C}}, \ \forall s \tag{38}$$

3.4.2. Constraints of CHP plant

The relationships between the heating and electricity power outputs of the CHP plants are as follows. The constraints of the CFCHP plant are (39)–(41), they ensure the output be within the operation region before retirement and be equal to zero after retirement.

$$\begin{aligned} &h_{g,t,d,s} = \sum_{k=1}^{NK_g} \alpha_{k,g,t,d,s} H_{k,g}, \quad p_{g,t,d,s} = \sum_{k=1}^{NK_g} \alpha_{k,g,t,d,s} P_{k,g}, \\ &\quad \forall g \in \mathcal{S}^{\mathrm{CHP}}, \ \forall t, \ \forall d, \ \forall s \end{aligned} \tag{39}$$

$$0 \leq \alpha_{k,g,t,d,s} \leq 1, \quad \forall g \in \mathcal{S}^{\mathrm{CHP}}, \ \forall t, \ \forall d, \ \forall s \tag{40}$$

$$\sum_{k=1}^{NK_g} \alpha_{k,g,t,d,s} = Z_{g,s}, \quad \forall g \in \mathcal{S}^{\mathrm{CFCHP}}, \ \forall t, \ \forall d, \ \forall s \tag{41}$$

The constraints of the existing GFCHP plant are (39)–(40) and (42), they ensure the output be within the operation region during the whole planning horizon.

$$\sum_{k=1}^{NK_g} \alpha_{k,g,t,d,s} = 1, \quad \forall g \in \mathcal{S}^{\mathrm{GFCHP,E}}, \ \forall t, \ \forall d, \ \forall s \tag{42}$$

The constraints of the candidate GFCHP plant are (39)–(40) and (43), they ensure the output be equal to zero before installation and be within the operation region after installation.

$$\sum_{k=1}^{NK_g} \alpha_{k,g,t,d,s} = z_{g,s}, \quad \forall g \in \mathcal{S}^{\mathrm{GFCHP,C}}, \ \forall t, \ \forall d, \ \forall s \tag{43}$$

The ramping constraint of the CHP plant power output is as follows. It means that the electricity power output difference between any two consecutive operation time periods should be kept within the ramping capability limitation. The time scale is one hour in this work.

$$-\overline{P}_g^{\mathrm{RD}} \le p_{g,t,d,s} - p_{g,t-1,d,s} \le \overline{P}_g^{\mathrm{RU}}, \quad \forall g \in S^{\mathrm{CHP}},\ \forall t,\ \forall d,\ \forall s \tag{44}$$

3.4.3. Constraints of heating supply balance

Typically, the coverage area of a district heating system is much smaller than that of an electricity or a gas transmission system, but its complexity is not significantly inferior to theirs. Besides, there are usually a number of heating systems contained in the transmission-level integrated electricity-gas-heating system. Hence, the adoption of detailed heating system model would significantly increase the complexity of the optimization problem. Due to this reason, an aggregated representation model is adopted here. The constraints are formulated as follows, and the detailed descriptions of the model can be found in [7].

$$es_{j,t,d,s} = es_{j,t-1,d,s} + \sum_{g\in S_j^{\mathrm{CHP}}} h_{g,t,d,s} - h_{j,t,d,s}^{\mathrm{S}}, \quad \forall j \in S^{\mathrm{DHS}},\ \forall t,\ \forall d,\ \forall s \tag{45}$$

$$\underline{ES}_{j,t,d,s} \le es_{j,t,d,s} \le \overline{ES}_{j,t,d,s}, \quad \forall j \in S^{\mathrm{DHS}},\ \forall t,\ \forall d,\ \forall s \tag{46}$$

In order to ensure flexibility from the district heating systems, the following constraint should be added to the optimization problem. It means that the heating energy stored in the heating system at the end of each day should be equal to that at the beginning.

$$es_{j,N^{\mathrm{T}},d,s} = ES_{j,0,d,s}, \quad \forall j \in S^{\mathrm{DHS}},\ \forall t,\ \forall d,\ \forall s \tag{47}$$

3.4.4. Constraints of non-supplied rate

In each heating system, (48) is the limitation of the supplied heating energy, which means that the supplied heating energy should be no more than the demand value. (49) is the limitation of the non-supplied heating energy, it means that the average non-supplied rate in each planning stage should be restricted within the related value.

$$0 \le h_{j,t,d,s}^{\mathrm{S}} \le H_{j,t,d,s}^{\mathrm{D}}, \quad \forall j \in S^{\mathrm{DHS}},\ \forall t,\ \forall d,\ \forall s \tag{48}$$

$$\frac{\sum_{d\in S^{\mathrm{D}}} \sum_{t\in S^{\mathrm{T}}} \sum_{j\in S^{\mathrm{DHS}}} \left[\left(H_{j,t,d,s}^{\mathrm{D}} - h_{j,t,d,s}^{\mathrm{S}} \right) \big/ H_{j,t,d,s}^{\mathrm{D}} \right]}{N^{\mathrm{D}} N^{\mathrm{T}} N^{\mathrm{DHS}}} \le R_s^{\mathrm{NS,H}}, \quad \forall s \tag{49}$$

3.4.5. Constraint of integration facility

The GFCHP is considered as the consumption facility in the gas system, and as the generation facility in the electricity and heating systems. Its gas flow demand is calculated as follows [24].

$$\phi_{g,t,d,s}^{\mathrm{D}} = \frac{h_{g,t,d,s}}{EF_g^{\mathrm{H}}} + \frac{p_{g,t,d,s}}{EF_g^{\mathrm{P}}}, \quad \forall g \in S^{\mathrm{GFCHP}},\ \forall t,\ \forall d,\ \forall s \tag{50}$$

3.4.6. Constraint of investment budget

The constraint of investment cost in the heating systems is (37), which means that the total investment cost should be kept within the investment budget in each planning stage.

$$cost_s^{\mathrm{H,I}} \le BUD_s^{\mathrm{H}}, \quad \forall s \tag{51}$$

3.5. Constraint of carbon emission restriction

The CO_2 is mainly emitted from the TU plant in the electricity system and the CHP plant in the heating systems. Besides, the P2G plant in the gas system can absorb part of it when producing gas, which means that it has a negative value of the emission rate. Hence, the constraint of the carbon emission restriction of the whole IEGHS in each planning stage can be written as follows [17].

$$\begin{aligned} R^{\mathrm{M}} \sum_{d\in S^{\mathrm{D}}} \sum_{t\in S^{\mathrm{T}}} \Bigg[& \sum_{g\in S^{\mathrm{TU}}} E_g^{\mathrm{CO_2}} p_{g,t,d,s} + \sum_{g\in S^{\mathrm{P2G}}} E_g^{\mathrm{CO_2}} \phi_{g,t,d,s} \\ & + \sum_{g\in S^{\mathrm{CHP}}} \left(E_g^{\mathrm{CO_2,H}} h_{g,t,d,s} + E_g^{\mathrm{CO_2,P}} p_{g,t,d,s} \right) \Bigg] \le CAP_s^{\mathrm{CO_2}}, \quad \forall s \end{aligned} \tag{52}$$

3.6. Summary of optimization problem

After the descriptions in the above text, the optimization problem for the multi-stage planning has been formulated. It is summarized as follows.

Objective function: (1), based on (2)–(7)
Constraints from electricity system: (8)–(22)
Constraints from gas system: (23)–(37)
Constraints from heating systems: (38)–(51)
Constraint of carbon emission restriction: (52)

This optimization problem is a mixed-integer linear programming optimization, and it can be solved with the guarantee of global optimum by the related off-the-shelf solvers, such as the Gurobi solver [44].

The framework of the proposed planning strategy is illustrated in Fig. 2, the three main parts in it are the inputs, the optimization and the outputs. In the inputs part, the system structure and the related parameters are obtained and input into the model. Then, the optimization problem as summarized above is formulated. After solving the optimization, the outputs are obtained, including the minimum economic costs, the installation plan of related candidate facilities, the carbon emission reduction plan, etc. In this framework, the multi-stage planning of the integrated electricity-gas-heating system can be conducted.

4. Case study

In order to verify the effectiveness of the proposed planning strategy, the case studies are conducted in this section. The programming is conducted on Matlab R2022b [45] with Yalmip toolbox [46,47], and the optimizations are solved with the Gurobi Solver [44].

4.1. System description

The structure of the case system is illustrated in Fig. 3 with indicating numbers of related facilities. The integrated electricity-gas-heating system consists of one IEEE 39-bus electricity transmission system [48], one 20-node gas transmission system [49], and three 12-node district heating systems. The parameters of the case system can be obtained from [50].

4.2. Input parameters

The whole planning horizon is set as 15 years and is divided into 3 stages, with 5 years for each stage. Each stage is represented by one year [15], and each year is represented by four days, characterizing Spring, Summer, Autumn and Winter. The energy demands of the four days in each sub-system [51,52] in the first stage are illustrated in Fig. 4, and a 3% of yearly load increasing rate is assumed for each sub-system.

The curves of the maximum values of the available renewable energy outputs [53] are illustrated in Fig. 5. They are values of the percentages of the installation capacities.

Regarding the carbon emission caps in (52) for the planning stages, they can be determined by the planner based on factors like the current status of energy system, the economic development plan, the environment protection requirement, etc. In this case, the caps are set as 2.0×10^8 Ton for the first stage, 1.5×10^8 Ton for the second stage and 0.5×10^8 Ton for the third stage.

4.3. Planning result

In this section, the results of the planning strategy are described and analyzed.

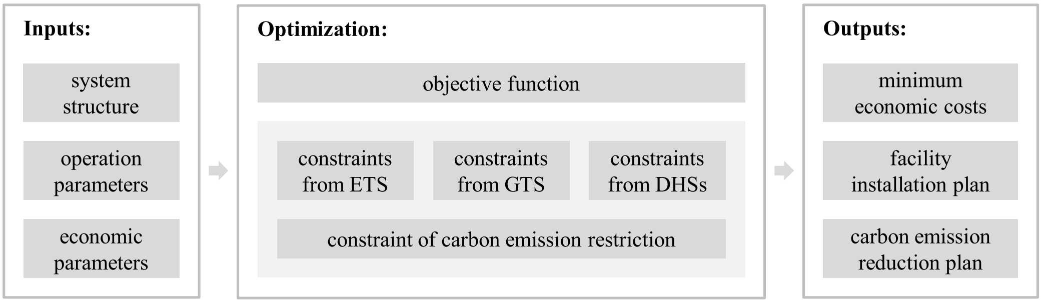


Fig. 2. Framework of the proposed planning strategy of the integrated electricity-gas-heating system.

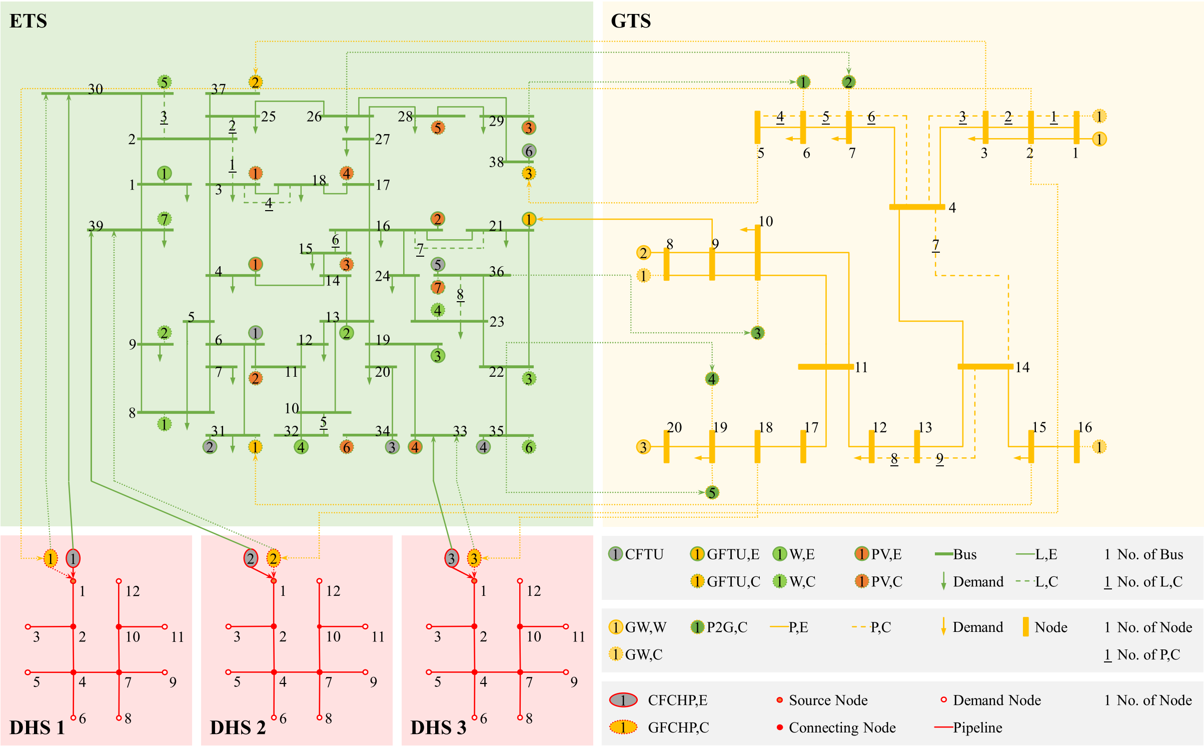


Fig. 3. Structure of the case system.

Table 2
Installation plan of the candidate facilities.

Sub-System	Facility	Stage 1	Stage 2	Stage 3
Electricity	PV	1,5	3,4	2,7
	W	6	3,4,7	1,2,5
	GFTU	2	1	
	L	2	7	3
Gas	GW		1	3
	P2G	2	5	3
	P	1,8,9	6	2
Heating	GFCHP	1	2	3

4.3.1. *Installation plan of candidate facilities*

After simulation, the installation plan of the candidate facilities is listed in Table 2, the number in it represents the corresponding candidate facilities as illustrated in Fig. 3.

As can be observed from the table, in the electricity system, the candidate wind and PV power plants will be installed successively during the planning stages, the GFTU plants are installed in the first and the second stages to help ensure the power supply in case of insufficient renewable energy output. In the gas system, two candidate gas wells are built in the second and third stages due to the increasing gas demand and the installation of gas-fired generations. In the heating systems, three candidate GFCHP plants are installed successively to take the heating supply role after the retirements of related CFCHP plants. Besides, the candidate transmission lines in the electricity system and pipelines in the gas system are installed during the related stages to increase the transmission capabilities.

4.3.2. *Results of electricity system*

The results of the electricity system are described and analyzed in this section. The evolution of installation capacities of different kinds of energy supply is shown in Fig. 6. The generation facilities included are the CFTU plant (represented as Coal in the figures), the GFTU plant (as Gas), the wind power plant (as W) and the PV power plant (as PV).

From Fig. 6, it can be seen that the total installation capacity keeps increasing during the three planning stages, due to the increase of the electricity demand. Besides, the proportion of fossil fuel based generation capacity keeps decreasing and that of renewable energy capacity keeps increasing. The proportion of renewable energy plant capacity accounts for 54.08% in the first planning stage, 64.75% in the second stage and 75.52% in the third stage. It means that the energy

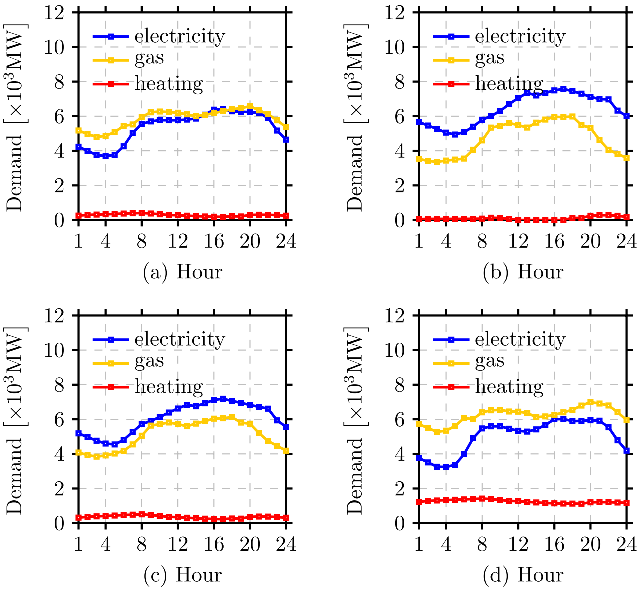


Fig. 4. Curves of the energy demands in the first stage. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

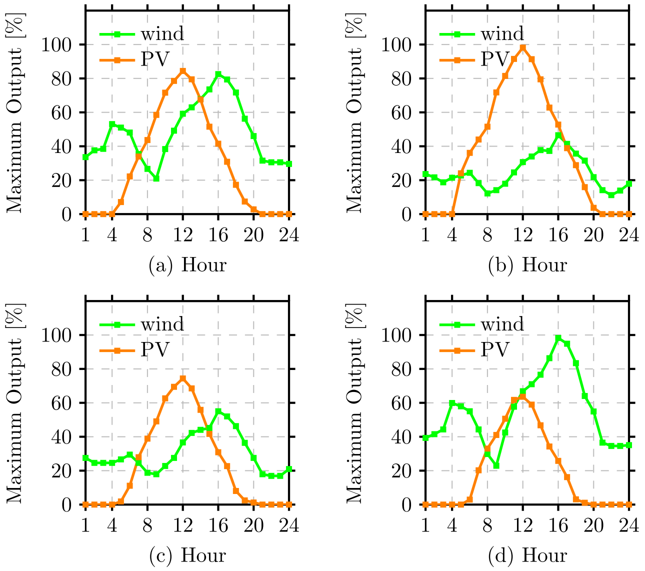


Fig. 5. Curves of the maximum available output percentages of renewable energy. (a) Spring. (b) Summer. (c) Autumn. (d) Winter.

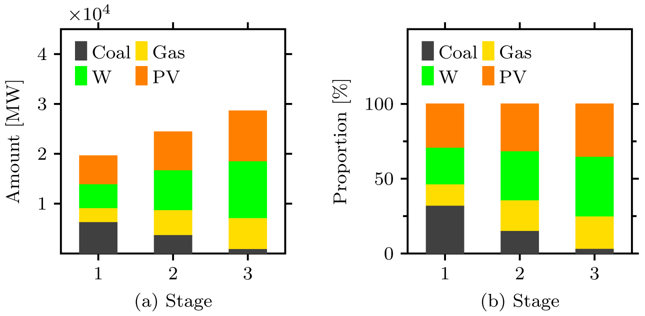


Fig. 6. Installation capacities in the electricity system. (a) Amounts. (b) Proportions.

supply structure in the electricity system transits from the capability with a relatively high carbon emission to that with a low carbon emission.

The evolution of the actual outputs of different kinds of energy supply and the CO_2 emissions during the planning horizon are shown in Fig. 7. From which, it can be seen that the total amount of electricity output keeps increasing due to the demand increase. The proportion of the fossil fuel based outputs keeps decreasing and of the renewable energy outputs keeps increasing, and the CO_2 emission has a significant reduction during the planning horizon. The proportion of renewable energy utilization accounts for 56.73% in the first planning stage, 70.39% in the second stage and 78.86% in the third stage.

In more detail, the total CO_2 emission amount of the electricity transmission system is 88.34 million tons in the first stage, 59.32 million tons in the second stage and 36.17 million tons in the third stage. It means that the proposed planning strategy can help the electricity system achieve carbon emission reduction significantly.

4.3.3. *Results of integrated energy system*

The results of the integrated electricity-gas-heating system are described and analyzed in this section. The evolution of installation capacities of different kinds of energy supply is shown in Fig. 8. In the figures, the legend Coal means the CFTU plant and the CFCHP plant, Gas means the gas well, W means the wind power plant and PV means the PV power plant. Other plants, including the GFTU plant, the P2G plant and the GFCHP plant, are not accounted here, since they are taken as kinds of internal energy conversion plants inside the integrated energy system.

From Fig. 8, it can be seen that the total installation capacity keeps increasing during the three planning stages, because of the increasing energy demand. Besides, the proportion of the fossil fuel based generation capacity keeps decreasing and the renewable energy generation capacity keeps increasing. It means that the energy supply structure of the integrated energy system transits from a capability of relatively high carbon emission to that of low carbon emission.

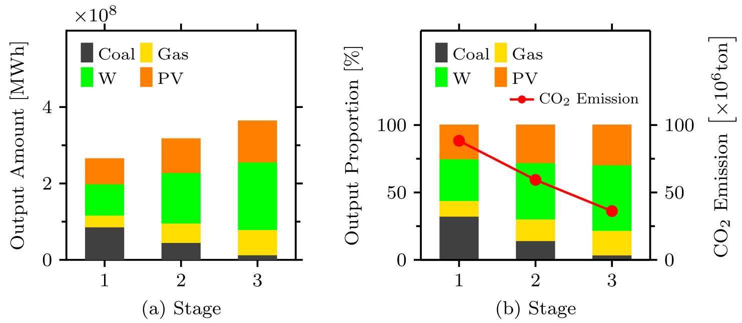
In addition, the evolution of the actual outputs of different kinds of energy supply and the CO_2 emissions in the integrated energy system are shown in Fig. 9. From which, it can be seen that the total amount of energy output keeps increasing due to the increase of the demand. The gas supply accounts for a relatively large proportion, the reason is that the gas energy needs to support not only the demand in the gas system but also the demands of the GFTU plants in the electricity system and the GFCHP plants in the heating systems. The proportion of renewable energy outputs increases during the three stages, and the CO_2 emission has a significant reduction during the planning horizon.

In more detail, the total CO_2 emission amount of the integrated energy system is 106.60 million tons in the first stage, 74.95 million tons in the second stage and 50.00 million tons in the third stage. It demonstrates the performance of the carbon emission reduction of the proposed planning strategy.

4.4. *Impacts of flexibility from integration*

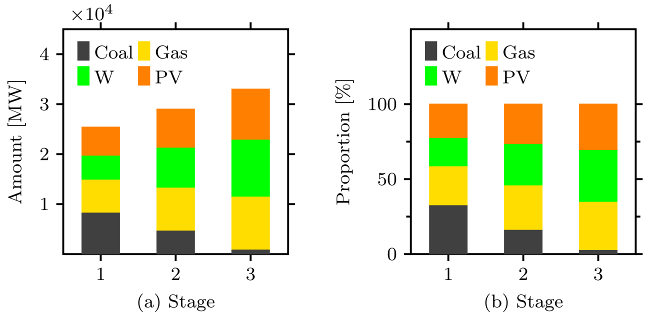
In the proposed planning strategy, the flexibility of the gas system and the heating systems is explored to help improve the performance. In order to verify its effects, four different cases are conducted and compared in this section, and they are described as follows.

Case 1, in which neither the flexibility of the gas system nor of the heating systems is considered. Hence, the constraint $\phi^{\mathrm{F}}_{p,t,d,s} = \phi^{\mathrm{T}}_{p,t,d,s}, \quad \forall p \in \mathcal{S}^{\mathrm{P}},\ \forall t,\ \forall d,\ \forall s$ is added into the optimization. It means that the gas flows at the two terminals of each transmission pipeline have the same value, and then the flexibility of the linepack is omitted. Besides, the constraint $\sum_{g \in \mathcal{S}^{\mathrm{CHP}}_j} h_{g,t,d,s} = h^{\mathrm{S}}_{j,t,d,s}, \quad \forall j \in \mathcal{S}^{\mathrm{DHS}},\ \forall t,\ \forall d,\ \forall s$ is added into the optimization. It means that the total heating output of all CHP plants is equal to the total actual heating supply in each



(a) Stage (b) Stage

Fig. 7. Energy outputs and CO_2 emissions in the electricity system. (a) Amounts of energy outputs. (b) Proportions of energy outputs and emissions of CO_2.



(a) Stage (b) Stage

Fig. 8. Installation capacities in the integrated energy system. (a) Amounts. (b) Proportions.

Table 3
Main results of the economic costs of the four cases.

Case	Flexibility	Cost (×$10^{10}$$)		
		Total	Investment	Operation
1	Neither	5.42	3.86	1.56
2	Only gas	5.05	3.57	1.48
3	Only heating	5.20	3.71	1.49
4	Both	4.82	3.40	1.42

heating system, and then the flexibility of the pipeline storage in the heating systems is omitted.

Case 2, in which only the flexibility from the gas system is considered, and that of the heating systems is not considered. Hence, the constraint $\sum_{g\in\mathcal{S}_j^{\mathrm{CHP}}} h_{g,t,d,s} = h^{\mathrm{S}}_{j,t,d,s}, \quad \forall j \in \mathcal{S}^{\mathrm{DHS}}, \forall t, \forall d, \forall s$ is added into the optimization. Its effect has been described in Case 1 above.

Case 3, in which only the flexibility of the heating systems is considered, and that of the gas system is not considered. Hence, the constraint $\phi^{\mathrm{F}}_{p,t,d,s} = \phi^{\mathrm{T}}_{p,t,d,s}, \quad \forall p \in \mathcal{S}^{\mathrm{P}}, \forall t, \forall d, \forall s$ is added into the optimization. Its effect has been described in Case 1 above.

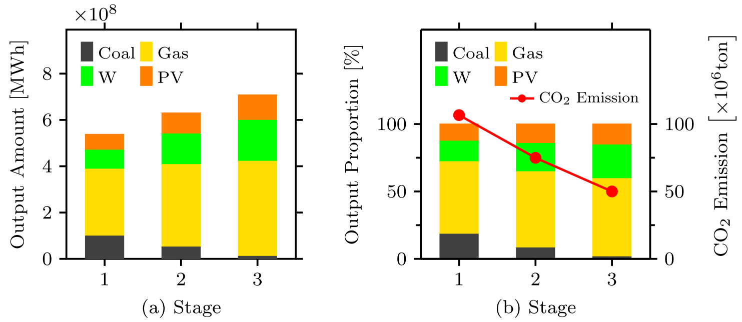
Case 4, which is the proposed strategy. In this case, the flexibility of the gas system and the heating systems are both considered.

After simulation, the main results of the four cases are illustrated in Table 3. It can be seen that the economic costs of Case 1 have the highest values in the four cases, since neither flexibility from the gas system nor the heating systems is considered. Accordingly, the costs of Case 4 have the lowest values, due to the contributions of the flexibility. Besides, the costs of Case 3 are higher than that of Case 2. The reasons mainly come from two sides, the first is that the heating demands are relatively low in the summer season, and the second is that there are only three heating systems considered in the integrated energy system in this case study, which may limit the contribution capability of the heating systems. Compared with Case 1, the total economic cost in Case 4 achieves a decrease of 11.07%, with a decrease of 11.92% in the investment cost and 8.97% in the operation cost. It demonstrates that the flexibility of gas and heating systems adopted in the proposed planning strategy can help decrease the economic cost significantly.

5. Conclusion

A multi-stage planning strategy for the transmission-level integrated electricity-gas-heating system in the context of carbon emission reduction is proposed in this paper. It can coordinate the installations of new facilities considering the retirement of the coal-fired generation plants to help facilitate the carbon emission reduction of the system. The optimization problem is formulated as mixed-integer linear programming to minimize the total economic cost as well as the constraints from each sub-system and carbon emission restriction.

The case study has shown that the proposed planning strategy can help decrease the proportion of high carbon emission generations and increase the proportion of low carbon emission generation and renewable energy. It can also increase the installation of electricity transmission lines and gas transmission pipelines to enhance the transmission capability. It is verified that the proposed planning strategy can help increase renewable energy utilization from the perspective of both the electricity system and the integrated energy system, and facilitate carbon emission reduction. In addition, the comparisons among different cases verify that the consideration of the flexibility from gas and



(a) Stage (b) Stage

Fig. 9. Energy outputs and CO_2 emissions in the integrated energy system. (a) Amounts of energy outputs. (b) Proportions of energy outputs and emissions of CO_2.

heating systems can help decrease the economic cost of the investment and operation in the system planning.

There are some limitations of the proposed work. The sensitivity analyses under various parameter conditions are worth to be conducted. The uncertainty of renewable energy output or energy demand is not considered. These could be the directions of future work.

CRediT authorship contribution statement

Xuewei Wu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Bin Zhang:** Writing – review & editing, Validation, Software. **Mads Pagh Nielsen:** Writing – review & editing, Supervision. **Zhe Chen:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data has been made available online, the link has been provided in the reference.

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