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Influence Evaluation of Integrated Energy System on the Unit Commitment in Power System

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ABSTRACT This article presents a research on unit commitment(UC), which consider the interaction between conventional power system and district-level integrated energy system(IES). The increasing number and scale of IES projects at distribution network bring incremental effect to the whole energy system. Their influence on power system transmission level unit commitment becomes one of the notable topics. Within these IES projects, gas-power and cooling-heating-power are two main types of 'integrated' forms. In this article, a model system is built for UC analysis in which several district-level IESs are connected to a conventional power system. Heating, cooling and electrical forms of energy are integrated in these IESs. The UC problem is modeled and solved by mixed integer linear programming(MILP), the partial load characteristics of these power plants are handled by piecewise linearization. The common piecewise linearization method used in power and gas system is modified to reduce binary variables and constraints. The purpose of this modification is to increase the MILP solving speed. Case studies are carried out to evaluate the influence of IESs on two different time scales. The simulation result shows that the application of IESs can reduce the whole energy system service cost. As the number of applied district-level IESs increases, the cost reduction becomes more significant. The reduction relies on preventing high-cost small capacity plants go into operation, reducing the number of generator startup, and choosing an economical power output level. These benefits are owing to the reinforcement from gas network via CCHPs (Combine cooling, heating and power) and the buffer from multiple forms of energy storage devices (thermal and cooling).

INDEX TERMS Integrated energy system, combined cooling heating and power (CCHP), thermal and cooling storage system, unit commitment, mixed-integer linear programming, piecewise linearization.

NOMENCLATURE

VARIABLES

C^{total}	Total cost of the whole system. ($)
C^{fuel}	Cost of fuel consumption. ($)
$C^{\text{o\&m}}$	Cost of equipment operation and maintenance. ($)
$E_t^{\text{coal}}, E_t^{\text{gas}}$	Coal and gas consumption at t-th hour. (MWh)
$Pin_{d,t}^{\text{cchp}}$	CCHP input power in d-th district at t-th hour. (MW)
$Pout_{d,t}^{\text{cchp\_e}}$	CCHP electric output power in d-th district at t-th hour. (MW)
$Pout_{d,t}^{\text{cchp\_t}}$	CCHP thermal output power in d-th district at t-th hour. (MW)
$Pout_{d,t}^{\text{cchp\_c}}$	CCHP cooling output power in d-th district at t-th hour. (MW)
$Pin_{d,t}^{\text{hpc}}, Pout_{d,t}^{\text{hpc}}$	Cooling heat pump input and output power in d-th district at t-th hour. (MW)
$Pin_{d,t}^{\text{hph}}, Pout_{d,t}^{\text{hph}}$	Heating heat pump input and output power in d-th district at t-th hour. (MW)
$Pin_{d,t}^{\text{cs}}, Pout_{d,t}^{\text{cs}}$	Cooling storage charge and discharge power in d-th district at t-th hour. (MW)
$Pin_{d,t}^{\text{ts}}, Pout_{d,t}^{\text{ts}}$	Thermal storage charge and discharge power in d-th district at t-th hour. (MW)

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$Es^{cs}_{d,t}$	Energy stored in cooling storage device in d-th district at t-th hour. (MWh)
$Es^{ts}_{d,t}$	Energy stored in thermal storage device in d-th district at t-th hour. (MWh)
$P^{cl}_{d,t}$	Cooling load power in d-th district at t-th hour. (MW)
$P^{hl}_{d,t}$	Thermal load power in d-th district at t-th hour. (MW)
$P^{el}_{d,t}$	Electric load power in d-th district at t-th hour. (MW)
$Pin_{g,t}$, $Pout_{g,t}$	Input and output power of g-th generator at t-th hour. (MW)
$cu_{g,t}$	Status of g-th generator at t-th hour (1 for on, 0 for off).
$y_{g,t}$	Binary auxiliary variables for g-th generator start up at t-th (1 for start up, otherwise 0)
$z_{g,t}$	Binary auxiliary variables for g-th generator shut down at t-th (1 for shut down, otherwise 0).
$y^{cold}_{g,t}$	Binary auxiliary variables for g-th generator cold start up at t-th (1 for cold start up, otherwise 0).
x_i	Non-negative continuous auxiliary variables for piecewise linearization.
y_i	Non-negative binary auxiliary variables for piecewise linearization.

PARAMETERS

c^{coal}_t, c^{gas}_t	Coal and gas price at t-th hour. (\$/MWh)
c^{start}_g, $c^{cold\_start}_g$	Start cost and cold start cost of g-th generator. (\$)
$Cap_{g,min}$, $Cap_{g,max}$	Minimum and maximum output power of g-th generator. (MW)
a_g	Parameters in quadratic form g-th generator fuel cost function. (1/MW)
b_g	Parameters in quadratic form g-th generator fuel cost function.
c_g	Parameters in quadratic form g-th generator fuel cost function. (MW)
$n_{interval}$	Number of intervals which the non-linear generator fuel cost function is divided into during linearization.
$l_{interval}$	Length of each intervals which are divided on the non-linear cost function curve. (MW)
$n_1, n_2, n_3, n_4, n_5, n_6$	Points on cost function curve which are the boundary of each intervals. (MW)
T^{off}_g	Minimum outage time for g-th generator. (h)
T^{cold}_g	Cold start up time for g-th generator. (h)
$Cap^{cchp\_e}_{d,min}$, $Cap^{cchp\_e}_{d,max}$	Minimum and maximum output electric power of CCHP in d-th district. (MW)
$\eta^{cchp\_e}_d$	Electric efficiency of CCHP in d-th district.
$Cap^{cchp\_c}_{d,min}$, $Cap^{cchp\_c}_{d,max}$	Minimum and maximum output cooling power of CCHP in d-th district. (MW)
$\eta^{cchp\_c}_d$	Cooling efficiency of CCHP in d-th district.
$Cap^{cchp\_t}_{d,min}$, $Cap^{cchp\_t}_{d,max}$	Minimum and maximum output thermal power of CCHP in d-th district. (MW)
$\eta^{cchp\_t}_d$	Thermal efficiency of CCHP in d-th district.
$Cap^{hpc}_{d,min}$, $Cap^{hpc}_{d,max}$	Minimum and maximum output power of cooling heat pump in d-th district. (MW)
COP^{hpc}_d	Efficiency of cooling heat pump in d-th district.
$Cap^{hph}_{d,min}$, $Cap^{hph}_{d,max}$	Minimum and maximum output power of heating heat pump in d-th district. (MW)
COP^{hph}_d	Efficiency of heating heat pump in d-th district.
$Pin^{cs}_{d,min}$, $Pin^{cs}_{d,max}$	Minimum and maximum charge power of cooling storage in d-th district. (MW)
$Pout^{cs}_{d,min}$, $Pout^{cs}_{d,max}$	Minimum and maximum discharge power of cooling storage in d-th district. (MW)
$Cap^{cs}_{d,min}$, $Cap^{cs}_{d,max}$	Minimum and maximum storage energy of cooling storage in d-th district. (MWh)
ηin^{cs}_d, ηout^{cs}_d	Charge and discharge efficiency of cooling storage in d-th district.
$Pin^{ts}_{d,min}$, $Pin^{ts}_{d,max}$	Minimum and maximum charge power of thermal storage in d-th district. (MW)
$Pout^{ts}_{d,min}$, $Pout^{ts}_{d,max}$	Minimum and maximum discharge power of thermal storage in d-th district. (MW)
$Cap^{ts}_{d,min}$, $Cap^{ts}_{d,max}$	Minimum and maximum storage energy of thermal storage in d-th district. (MWh)
ηin^{ts}_d, ηout^{ts}_d	Charge and discharge efficiency of thermal storage in d-th district.

SETS

T	Set of simulated hours.

D Set of load districts.
G Set of power generators.

I. INTRODUCTION

Due to the negative effect of global warming, the reduction of greenhouse gas emission is catching more and more attention. Integrated energy system provides a smart solution to reduce CO_2 emission, improve energy consumption efficiency and reduce the energy supply cost [1]. Located close to energy customers, district-level IESs are widely analyzed, whose interaction between microgrid are mentioned in previous research [2]. References [3]–[5] provide district-level IES examples which contain basic elements such as distribute heat and power generators, renewable energy convertors as well as multiple forms of energy storage devices. It is worth mentioning that several IESs are modeled by a very popular method named energy hub which is firstly mentioned in [6], and the advantages of this method are listed in [2]. Mathematically, the analysis of IES is an optimization problem, and plenty of previous works have the objective function of minimizing the energy consumption for a certain area during a certain period. For example, [7] models a combination of power and heat system, which increase the economic efficiency of the integrated energy system compared with separate power and heat systems. On the other hand, CO_2 emission reduction is another common objective function used in previous research, [3] presents an integration of decentralized energy systems including heat, power and distributed renewable energy.

Compared with district-level IES, regional IES enlarges the geographical perspective and the energy carriers are also different. Reference [8] builds an expansion planning model for the power and gas combination network based on the widely analyzed power and gas integration system operated by National Grid in UK. The integration element of these two networks is gas turbine. The object is to reduce the network expansion cost and fulfill the energy consumption in the future. The scenario of UK power and gas network in 2030 is analyzed and the planning suggestions are provided. Reference [9] presents a hydro-thermal unit commitment problem in which the mixed integer nonlinear programming (MINLP) is solved by Benders decomposition(BD). Reference [10] proposes a combination of intermittent renewable power generation and hydrogen production, the advantage of this system is smoothing the power injection and releasing the burden of power network. As mentioned above, electric power is an irreplaceable part of regional integrated energy system due to its fast, flexible and high-capacity transmission characteristic.

In the power system of most developing countries, thermal power accounts for a large proportion of electric power generation due to the economic advantage of fossil fuel, for example coal. This situation could exist for a long time, although it has significant negative effect to the environment. The research of thermal power is always a hot topic during decades, [11] solves an optimization problem in which thermal power plant has an interaction with pumped-storage units. Reference [12] provides a solution for thermal plant peak shaving by applying battery energy storage system, and the cooperation between these two elements is analyzed. As for the research focuses on the thermal power plant, UC is an important part which catches a lot of attention. Reference [13] summarizes the basic concepts of the UC problem including general background, mathematical problems and solving methods, while [14] gives an overview of UC as an optimization problem. To increase the calculation efficiency, [15] develops a tight and compact UC model which take ramp rate into consideration. The UC thermal plant model in [16] takes spin reserve and ramp rate into account and the nonlinear issue is solved by piecewise linearization method. It is worth to mention that, this linearization method involves additional binary auxiliary variables and increases the solving time. So, a method is applied to reduce the number of binary auxiliary variables in this article. Above the previous works, the interaction between conventional power plant and district-level IES is lack of research, although the importance of this work keeps increasing as more and more district-level ISEs is coming into operation. In this article, a model is built in which IESs interact with thermal power plants. The influence on UC results in power system transmission level is evaluated.

The research on the interaction between conventional power system and IESs is an optimization problem in mathematics, so a proper optimization method is needed. Reference [17] applies MILP to solve an IES model based on CCHP, the model is developed in MATLAB environment. Besides traditional optimization methods, metaheuristic algorithms are also widely used in IES research due to their strong ability of solving nonlinear problem. Reference [18] optimizes a combined gas and power network expansion plan using NSGA-II method which belongs to genetic algorithms. Particle based optimization method is also widely used, [19], [20] apply GSO (group search optimizer) and PSO (particle swarm optimization) to the optimize the operation of IES respectively.

In this article, MILP is chosen for optimizing the combination system model because of the fast calculation speed of commercial MILP solver, for example GUROBI and CPLEX. The nonlinear issue which describes the power plant partial load effect in this project is linearized by piecewise linearization method according to [21]–[23]. The linearization method proposed in [21]–[23] is modified in this article to reduce number of additional binary auxiliary variables and improve MILP solving efficiency.

This article has a background that traditional power system who contains large amount of coal-fired thermal power plant is gradually integrated with other types of energies due to the increasing number of district-level IESs. To increase the energy supply efficiency, district-level IESs are built to replace the traditional energy supply mode in big cities which consumes electricity to serve electrical, heating and cooling loads. Energy distributers also wish to reduce their supply cost by applying IES in their districts to make more profits.

The main propose of applying CCHP is to reduce the consumption of electricity which generated from coal in order to reduce air pollution. And the proposes of applying thermal and cooling storage devices are to achieve the function of peak-load shifting and to reduce the energy supply cost.

A plenty of research focus on the interaction between electric power system and other types of systems including natural gas system and heating system. Within these works, many researchers treat the power system as an infinite bus. Reference [29] develops an optimal planning model of a power and heat integrated system with detailed thermal storage, network and load models and specifies the influence of applying these models. Reference [30] analyzes the demand respond based on the heat and electricity system, the aim for this work is to improve the consumption of renewable energy. In the combined heat and power system, thermal energy storage can improve the behavior of the whole system, for example [31] mentions the benefit of thermal storage which is the improvement of CHP flexibility. The key component of heat and power system is CHP which connects gas system to integrated energy system, [32] proposes a novel decomposing strategy to solve the energy flow in integrated gas-power-heat system. Within [32], the power, gas and thermal energy flows are considered. Besides CHP, power-to-gas (P2G) technology provides another integration way between these two systems. However, the application of this technology highly depends on the efficiency of equipment and the price of electric power and natural gas [33].

Some researchers started to move their concern to the unit commitment problem in power and heat integrated system, and power system is not treated as infinite bus. Reference [34] proposes a method for solving decentralized unit commitment problem with large number of CHPs and power generators. Reference [35] develops a combined power and heating system in which the unit commitment in power system is considered. The proposed integrated model shows the benefit on wind energy consumption, which is achieved by thermal storage in heating system. The above research projects mainly concentrate on the solving methods of UC in a system with multiple forms of energy and the 'unit' contains thermal power plant and CHP.

In this article, research focuses on the changes of power system transmission level UC, these changes are related to the application of IES which contains CCHP and energy storage devices. In the beginning, one single district-level IES has little influence on the operation of transmission level power system. However, as more and more IESs in distribution level energy system are applied, the total capacity of IESs increases to a level that can influence the result of UC in transmission level power system. The idea is expressed in Fig.1 below.

This article mainly contributes on evaluating the incremental effect of IESs to UC in power system. Secondly, energy storage device and CCHP in IES are the key components who effect the UC results, their function and behavior are analyzed. Finally, the widely used piecewise linearization method in the previous UC research works is modified, the new method has fewer binary variables and constraints which leads to the improvement of MILP solving speed.

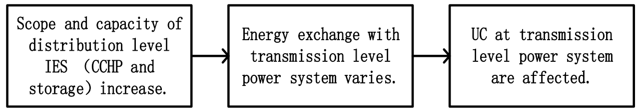

FIGURE 1. Relationship between distribution level IES application and transmission level power system UC.

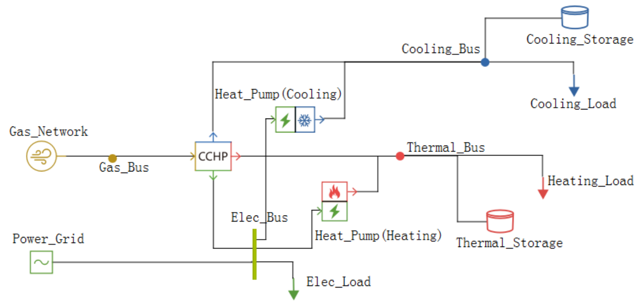

FIGURE 2. Structure of a district-level IES interconnected with conventional power system and natural gas system.

II. MODEL FORMULATION

A. COMBINED MODEL OF THERMAL POWER PLANT AND IES

In this article, a combination of power plant and IES is modelled based on a central area of a typical Chinese city in summer when cooling load is a significant part among the whole electricity consumption.

1) DETAIL STRUCTURE OF A DISTRICT-LEVEL IES

The equipment detail in a single district-level IES is shown in Fig.2 below.

A gas fired CCHP is the core equipment which satisfies the electrical, heating and cooling loads. The detail structure within CCHP is presented in Fig.3, a natural gas turbine generates electricity and uses the exhaust gas to produce hot and cold fluid. CCHP can improve the efficiency by recycling wasted heat to provide heating and cooling energy. Based on previous research, natural gas network has a much stronger ability to handle the peak load compared with electrical power network, the gas transmission pipe can even act as a role of storage named linepack, which is quite different from electric power line. It is obvious that, releasing the burden of power system during peak time is another reason of choosing gas fired CCHP for the IES.

There are two types of storage devices in the IES model, which are thermal and cooling storage. Compared with the expensive battery storage, these two storage forms can improve the finical efficiency of the IES.

In the IES model, two types of heat pump are used to fulfill the cooling and heating load, which act as a backup of CCHP. Instead of generating heating or cooling energy itself, heat pump consumes electricity to transfer energy from low-temperature side to high-temperature side, which usually has a high coefficient of performance (COP).

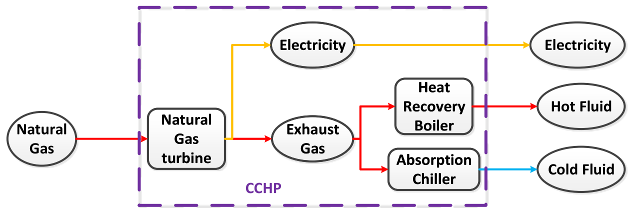

FIGURE 3. Structure of CCHP, in which natural gas is consumed to generate electrical, heating and cooling energy.

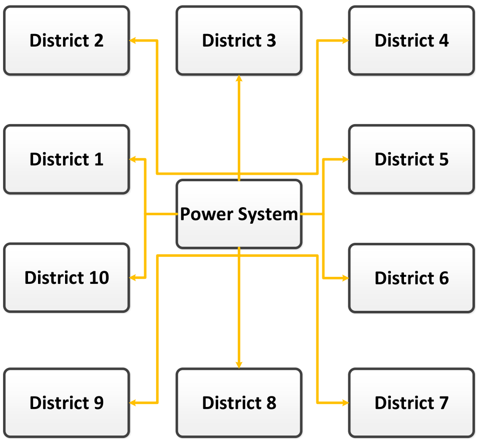

FIGURE 4. Structure of the model used in this article, power system is connected to ten load districts. There are electrical, heating and cooling loads in each district.

2) STRUCTURE OF THE WHOLE ENERGY SYSTEM

As mentioned above, most previous IES research works treat power grid as an infinite bus which is not affected by district-level IES. However, as the number and scale of IES increase, the behavior of IES will significantly affect the power system operation. For this situation, the power system cannot be treated as an infinite bus. To observe this change, a model is built which contains several load districts as well as transmission level power system as seen from Fig.4 below.

Each district has cooling, heating and electric loads, and corresponding to one district-level IES mentioned above. Initially, the energy to serve these loads are all come from power system. In this article, these load districts are equipped with integrated energy components and become IESs one by one.

3) DETAIL STRUCTURE OF POWER SYSTEM

The power system section is modelled to be a unit commitment problem, in which ten thermal power plants are concerned as shown in Fig.5. The generated power serves these ten individual load districts through transmission network.

In this article, several assumptions are made to simply the model and simulation. First, transmission lines in power system are treated as ideal and power losses are neglected because this article mainly focuses on the interaction between power system and IESs. Second, all load centers are set to

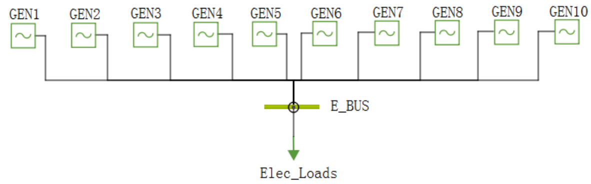

FIGURE 5. Structure of power system, which contains ten thermal generators. This model composes a unit commitment problem.

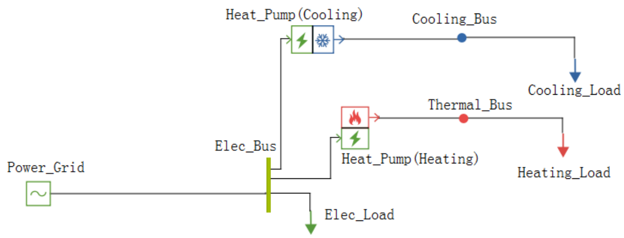

FIGURE 6. Structure of a load district which apply electric only service style and used to compare with IES style.

have the same load curve, due to the reason that the observation of incremental effect of IESs does not require the difference among each load centers. Third, the construction cost of IESs are not considered, since the IESs for each load center are constructed and operated by different energy distributer for their own optimization purpose, which is the passively accepted antecedent condition and will not affect the optimization function of this article. The difference of optimization objective functions between single IES and the whole system can be eliminated by setting a reasonable price mechanism, which is briefly discussed in the "DISCUSSION" part below.

4) MODELLING PROGRESS

Initially, without the application of IES technology, all loads within these ten districts in Fig.4 are served by electricity from power system only, which is the normal case in the urban area in developing countries [28]. In this initial model, heat pumps are applied to fulfill the heating and cooling loads as expressed in Fig.6, and electrical load is served by power system. This is the common design for a South China city that electricity is the only major energy source. The natural gas network is only expected to supply cooking and some hot water load in these area and gas turbine is rarely applied for heating, due to high price of NG. However, the development of CCHP and other integrated energy technology makes the widely application of gas turbine become possible.

As the IES becomes more and more popular, the energy supply mode of these load districts is converted from the electrical supply mode (Fig.6) to integrated energy supply mode (Fig.2) one by one, and finally all these districts become district-level IESs. The impact caused by the above changes on power system unit commitment is analyzed in this article.

B. MATHEMATICAL MODEL DESCRIPTION

The MILP model of the simulated system will be described in the following order: First, several constant sets are specified before describing the model. Then, the objective function and constraints are presented and described.

Set T represents the simulated hours during a day ($T = \{1, 2, 3, \ldots, 24\}$) or a week ($T = \{1, 2, 3, \ldots, 168\}$), and the subscript t means the relevant parameters or variables corresponding to the t-th period of the simulated time. Set D represents the load district number ($D = \{1, 2, 3, \ldots, 10\}$), and the subscript d means the relevant parameters or variables corresponding to the d-th load district. Set G represents the generator number modelled in power system section ($G = \{1, 2, 3, \ldots, 10\}$), and the subscript g means the relevant parameters or variables corresponding to the g-th generator.

1) OBJECTIVE FUNCTION

The objective of this model is to minimize the energy supply cost during a certain period. The total cost is divided into two parts, which are fuel cost and equipment operation and maintenance (O&M) cost as seen in (1) below. Fuel cost is the total fossil fuel consumption for the entire simulation time, as expressed in (2). The O&M cost is determined by the operation condition of energy convertors, including CCHP, heat pumps and storage devices as seen in (3) below, the startup cost of power generators are also taken into consideration in this part.

$$C^{\text{total}} = C^{\text{fuel}} + C^{\text{o\&m}} \tag{1}$$

$$C^{\text{fuel}} = \sum_{t\in T} (\text{c}_t^{\text{coal}} E_t^{\text{coal}} + \text{c}_t^{\text{gas}} E_t^{\text{gas}}) \tag{2}$$

$$\begin{aligned} C^{\text{o\&m}} = &\sum_{t\in T}\sum_{d\in D} (c^{\text{cchp\_e}} Pout_{d,t}^{\text{cchp\_e}} + c^{\text{cchp\_c}} Pout_{d,t}^{\text{cchp\_c}} \\ &+ c^{\text{cchp\_t}} Pout_{d,t}^{\text{cchp\_t}} + c^{\text{hpc}} Pout_{d,t}^{\text{hpc}} + c^{\text{hph}} Pout_{d,t}^{\text{hph}} \\ &+ c^{\text{cs}} Pout_{d,t}^{\text{cs}} + c^{\text{ts}} Pout_{d,t}^{\text{ts}} + c_g^{\text{start}} y_{g,t} \\ &+ (c_g^{\text{cold\_start}} - c_g^{\text{start}}) y_{g,t}^{\text{cold}}) \end{aligned} \tag{3}$$

2) CONSTRAINTS

The consumed coal equals to the sum of generators' input and the consumed gas equals to the sum of CCHPs' input, which are expressed in (4).

$$E_t^{\text{coal}} = \sum_{g\in G} Pin_{g,t} \times 1; \quad E_t^{\text{gas}} = \sum_{d\in D} Pin_{d,t}^{\text{cchp}} \times 1 \tag{4}$$

In this project, the constraints of power generator include capacity limits, and generation efficiency. The output of generator should be within the output limit range as seen in (5) below. It is worth to notice in (6) that, the startup characteristic is taken into consideration, $cu_{g,t}$ and $cu_{g,t-1}$ represents whether g-th generator is committed at t-th and (t-1)-th hour respectively, $y_{g,t}$ represents whether g-th generator starts up at the period t, $z_{g,t}$ represents whether g-th generator shuts down at the period t. Cold start issue is also taken into consideration in (7) and (8), and $y_{g,t}^{\text{cold}}$ represents whether g-th generator cold starts up in the period t [37].

(5) to (8) are logic constraints to describe the operation of generator start up and shut down, in which variables are binary variables.

$$\text{Cap}_{g,\min} \cdot cu_{g,t} \le Pout_{g,t} \le \text{Cap}_{g,\max} \cdot cu_{g,t} \tag{5}$$

$$cu_{g,t} - cu_{g,t-1} = y_{g,t} - z_{g,t} \tag{6}$$

$$y_{g,t}^{\text{cold}} \le y_{g,t} \tag{7}$$

$$y_{g,t}^{\text{cold}} \ge y_{g,t} - \sum_{\text{k}=\text{T}_\text{g}^{\text{off}}}^{\text{T}_\text{g}^{\text{off}}+\text{T}_\text{g}^{\text{cold}}+1} cu_{g,t-k} \tag{8}$$

In this model, generators' nonlinear efficiency is considered in (9). To meet the linear requirement of MILP model, piecewise linearization method is applied by involving auxiliary variables which satisfy special order set condition (SOS). (9) to (17) are the details of this linearization method [24]. Suppose the nonlinear efficiency curve in (9) is divided into five intervals to carry out the piecewise linearization, n_{interval} is set to be 5 and the length of each interval (l_{interval}) is calculated in (10). The breakpoints ($n_1, n_2, \ldots, n_6$) of these five intervals is obtained in (11). (12) to (17) show the efficiency constraints of generator, which build the relationship between $Pin_{g,t}$ and $Pout_{g,t}$. In these constraints, x_1, x_2, …, x_6 are non-negative continues variables and $y_1, y_2, \ldots, y_6$ are binary variables.

$$Pin_{g,t} = f(Pout_{g,t}) = \text{a}_g(Pout_{g,t})^2 + \text{b}_g Pout_{g,t} + \text{c}_g \tag{9}$$

$$l_{\text{interval}} = (\text{Cap}_{g,\max} - \text{Cap}_{g,\min})/n_{\text{interval}} \tag{10}$$

$$\begin{aligned} n_1 &= \text{Cap}_{g,\min}; \\ n_2 &= \text{Cap}_{g,\min} + l_{\text{interval}}; \\ n_3 &= \text{Cap}_{g,\min} + l_{\text{interval}} \times 2; \\ n_4 &= \text{Cap}_{g,\min} + l_{\text{interval}} \times 3; \\ n_5 &= \text{Cap}_{g,\min} + l_{\text{interval}} \times 4; \\ n_6 &= \text{Cap}_{g,\min}; \end{aligned} \tag{11}$$

$$Pout_{g,t} = n_1x_1 + n_2x_2 + n_3x_3 + n_4x_4 + n_5x_5 + n_6x_6 \tag{12}$$

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 = 1 \tag{13}$$

$$\begin{aligned} Pin_{g,t} = &f(n_1)x_1 + f(n_2)x_2 + f(n_3)x_3 + f(n_4)x_4 \\ &+ f(n_5)x_5 + f(n_6)x_6 \end{aligned} \tag{14}$$

$$x_i \le y_i, \quad i = 1, 2, 3, \ldots, 6 \tag{15}$$

$$\sum_{i=1}^{6} y_i \le 2 \tag{16}$$

$$\begin{aligned} &y_1 + y_3 \le 1; \quad y_1 + y_4 \le 1; \\ &y_1 + y_5 \le 1; \quad y_1 + y_6 \le 1; \\ &y_2 + y_4 \le 1; \quad y_2 + y_5 \le 1; \\ &y_2 + y_6 \le 1; \quad y_3 + y_5 \le 1; \\ &y_3 + y_6 \le 1; \quad y_4 + y_6 \le 1; \end{aligned} \tag{17}$$

The piecewise linearization method involves plenty of binary auxiliary variables which lead to the reduction of MILP solving speed. For this project, the nonlinear efficiency curve is divided into 5 (n_{interval}) intervals and 6 ($n_{\text{interval}} + 1$)

binary auxiliary variables ($y_1, y_2, \ldots, y_6$) are introduced. According to [36], the number of binary auxiliary variables can be reduced from ($n_{\text{interval}}+1$) to $\log_2(n_{\text{interval}}+1)$ and the reduction of binary variables number results in the reduction of MILP solving time. This simplified method is to encode the definition intervals by Gray code [36]. For this project, the number of binary auxiliary variables is set to be 3 ($\log_2 6$). The linearization constrains (15) to (17) is replaced by (18) which achieves a reduction of binary variables and constrains.

$$\begin{aligned} x_3 &\le y_1; \\ x_1+x_5+x_6 &\le 1-y_1; \\ x_1+x_2 &\le y_2; \\ x_4+x_5+x_6 &\le 1-y_2; \\ x_1+x_2+x_3+x_4 &\le y_3; \\ x_6 &\le 1-y_3; \end{aligned} \tag{18}$$

In this article, to focus on the analysis of power system UC in transmission level, linear efficiency is chosen for energy convertors in district-level IES to reduce the calculation time. (19) to (24) are the output limits and efficiency constraints of CCHP. (25) and (26) are the output limits and efficiency of heating heat pump. (27) and (28) are the output limits and efficiency of cooling heat pump.

$$\text{Cap}_{d,\min}^{\text{cchp\_e}} \le Pout_{d,t}^{\text{cchp\_e}} \le \text{Cap}_{d,\max}^{\text{cchp\_e}} \tag{19}$$
$$Pin_{d,t}^{\text{cchp}} = \eta_d^{\text{cchp\_e}} Pout_{d,t}^{\text{cchp\_e}} \tag{20}$$
$$\text{Cap}_{d,\min}^{\text{cchp\_c}} \le Pout_{d,t}^{\text{cchp\_c}} \le \text{Cap}_{d,\max}^{\text{cchp\_c}} \tag{21}$$
$$Pin_{d,t}^{\text{cchp}} = \eta_d^{\text{cchp\_c}} Pout_{d,t}^{\text{cchp\_c}} \tag{22}$$
$$\text{Cap}_{d,\min}^{\text{cchp\_t}} \le Pout_{d,t}^{\text{cchp\_t}} \le \text{Cap}_{d,\max}^{\text{cchp\_t}} \tag{23}$$
$$Pin_{d,t}^{\text{cchp}} = \eta_d^{\text{cchp\_t}} Pout_{d,t}^{\text{cchp\_t}} \tag{24}$$
$$\text{Cap}_{d,\min}^{\text{hph}} \le Pout_{d,t}^{\text{hph}} \le \text{Cap}_{d,\max}^{\text{hph}} \tag{25}$$
$$Pin_{d,t}^{\text{hph}} = \text{COP}_d^{\text{hph}} Pout_{d,t}^{\text{hph}} \tag{26}$$
$$\text{Cap}_{d,\min}^{\text{hpc}} \le Pout_{d,t}^{\text{hpc}} \le \text{Cap}_{d,\max}^{\text{hpc}} \tag{27}$$
$$Pin_{d,t}^{\text{hpc}} = \text{COP}_d^{\text{hpc}} Pout_{d,t}^{\text{hpc}} \tag{28}$$

There are two types of storage devices mentioned in this project, which are thermal and cooling storage, and their constraints are (29) to (32) and (33) to (36) respectively. Take thermal storage as an example, (29) and (30) refer to the limits of consuming and releasing power, (31) refers to the limit of energy stored within the storage structure. (32) is the energy balance constraint between two adjacent time periods.

$$\text{Pin}_{d,\min}^{\text{cs}} \le Pin_{d,t}^{\text{cs}} \le \text{Pin}_{d,\max}^{\text{cs}} \tag{29}$$
$$\text{Pout}_{d,\min}^{\text{cs}} \le Pout_{d,t}^{\text{cs}} \le \text{Pout}_{d,\max}^{\text{cs}} \tag{30}$$
$$\text{Cap}_{d,\min}^{\text{cs}} \le Es_{d,t}^{\text{cs}} \le \text{Cap}_{d,\max}^{\text{cs}} \tag{31}$$
$$Es_{d,t}^{\text{cs}} = Es_{d,t-1}^{\text{cs}} + \eta\text{in}_d^{\text{cs}} Pin_{d,t}^{\text{cs}} - \eta\text{out}_d^{\text{cs}} Pout_{d,t}^{\text{cs}} \tag{32}$$
$$\text{Pin}_{d,\min}^{\text{ts}} \le Pin_{d,t}^{\text{ts}} \le \text{Pin}_{d,\max}^{\text{ts}} \tag{33}$$
$$\text{Pout}_{d,\min}^{\text{ts}} \le Pout_{d,t}^{\text{ts}} \le \text{Pout}_{d,\max}^{\text{ts}} \tag{34}$$
$$\text{Cap}_{d,\min}^{\text{ts}} \le Es_{d,t}^{\text{ts}} \le \text{Cap}_{d,\max}^{\text{ts}} \tag{35}$$

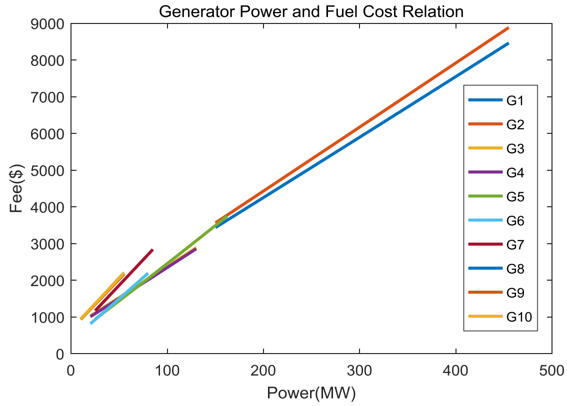

FIGURE 7. The relation curve of generators power output and cost.

$$Es_{d,t}^{\text{ts}} = Es_{d,t-1}^{\text{ts}} + \eta\text{in}_d^{\text{ts}} Pin_{d,t}^{\text{ts}} - \eta\text{out}_d^{\text{ts}} Pout_{d,t}^{\text{ts}} \tag{36}$$

As seen in Fig.3 above, the electric power balance constraint can be express as (37). The total electric power produced by generators together with the electric power output of CCHP should meet the demand of all district-level IESs including all the electric loads, the input of heating and cooling heat pumps. There are also thermal and cooling power balance constraints in each district-level IESs. As seen in (38), the sum of thermal power produced by heating heat pump and released by thermal storage device equals to the sum of thermal load and power consumed by storage device. Similar in (39), the sum of cooling power produced by cooling heat pump and released by cooling storage device equals to the sum of cooling load and power consumed by storage device. The situation that storage devices charge and discharge at the same time is prevented during the optimization progress in which the cost (fuel and O&M) is minimized.

$$\sum_{g\in G}(Pout_{g,t}) = \sum_{d\in D}(P_{d,t}^{\text{el}} + Pin_{d,t}^{\text{hpc}} + Pin_{d,t}^{\text{hph}} - Pout_{d,t}^{\text{cchp\_e}}) \tag{37}$$
$$Pout_{d,t}^{\text{cchp\_t}} + Pout_{d,t}^{\text{hph}} + Pout_{d,t}^{\text{ts}} = P_{d,t}^{\text{tl}} + Pin_{d,t}^{\text{ts}} \tag{38}$$
$$Pout_{d,t}^{\text{cchp\_c}} + Pout_{d,t}^{\text{hpc}} + Pout_{d,t}^{\text{cs}} = P_{d,t}^{\text{cl}} + Pin_{d,t}^{\text{cs}} \tag{39}$$

III. CASE STUDY

A. SETTING OF SCENARIOS

To assess the influence of IES on the UC in power system, the model in Fig.3 is developed and several cases are evaluated to provide evidence. In Case 1, the simulation time is chosen as one day which is 24 hours, and the simulation time step is chosen to be one hour. The cold start issue is not taken into consideration due to the short simulation time. However, when the simulation time is extended to one week which is 168 hours in Case 2, the generator cold start issue is considered. The improved piecewise linearization method is verified in the 168h case, since the MILP model scale in the 24h case is too small and the change may be not significant.

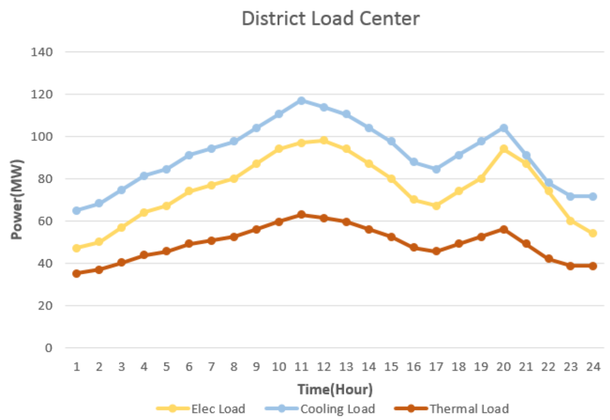

FIGURE 8. Electric, cooling and thermal power of one load center, all these ten load centers are set to have same load values to analysis the incremental effect of the increasing application level of IES.

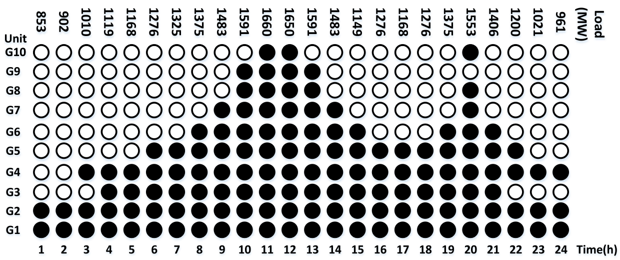

FIGURE 9. Unit commitment results of the basic electric only case.

B. MODEL INPUT

There are three parts of input information in this model.

The technical parameters of equipment mentioned above includes input and output limits, efficiency and storage limits. The economic parameters are about the equipment operation cost and the fuel price. The value of energy sources and energy loads is also an important part of input information. The value of parameters is obtained from [25] (district-level IES part) and [26] (power system unit commitment part). To simplify the calculation and comparison, the measure units in this article are converted to electrical units which power is described by megawatt(MW) and energy is described by megawatt hour(MWh).

In the initial case, the total capacity of these ten generators in power system is 1662MW. In each load district, a 150MW cooling heat pump as well as a 100MW heating pump is equipped as shown in Fig.6. After a district is converted to an IES as seen in Fig.4, a CCHP which contains 78MW gas turbine is applied. The CCHP also has a capacity of 110MW (cooling) and 90MW (heating). In the proposed IES, the capacity of thermal and cooling storage is 80MWh and 140MWh respectively. The choice of IES capacity in this article consults a real project in Guangdong Province, China. In that project, two 78MW gas turbine is used to build a CCHP system and service a university town with 10 universities, 3.5 million m^2 building and around 240 thousand people as mentioned in [28]. It is obvious that if all the districts are converted to be IES, the total capacity of distribute level components would have a significant effect to the 1662MW transmission level power system.

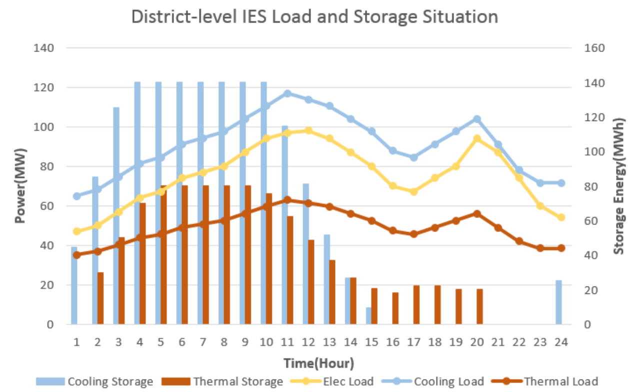

FIGURE 10. District-level IES load and storage situation for the situation that all load centers are equipped with thermal and cooling storage devices.

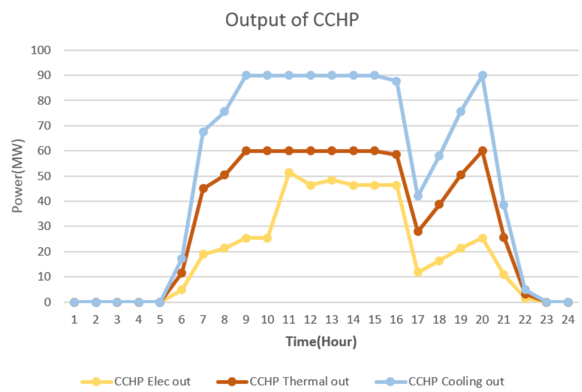

FIGURE 11. The output of a CCHP for the condition that all load centers are equipped with CCHP.

In this project, a laptop with intel core i7, 2.5GHz processor and 8G memory is used for simulation work and GUROBI is chosen to solve the MILP problem.

IV. RESULTS AND ANALYSIS

A. CASE 1: 24h SCENARIO

Initially, all storage devices and CCHPs in the IESs are disabled to model a basic case, which is a simple ten generators' unit commitment problem. The generators' fuel cost functions in quadratic form are drawn in Fig.7 below, these small capacity generators have a low economic efficiency, for example G9 and G10. On the other hand, high capacity generators like G1 and G2 have a high economic efficiency. The UC result is listed in Fig.9 below. The load mentioned in Fig.9 means the electric power needs to satisfy electric, cooling and thermal loads in all ten district-level load centers, whose detail loads is shown in Fig.8. Black dots in Fig.9 represent the generator is on at a certain time. During the peak time which is 11 and 12 o'clock, all ten generators are committed to meet the demand.

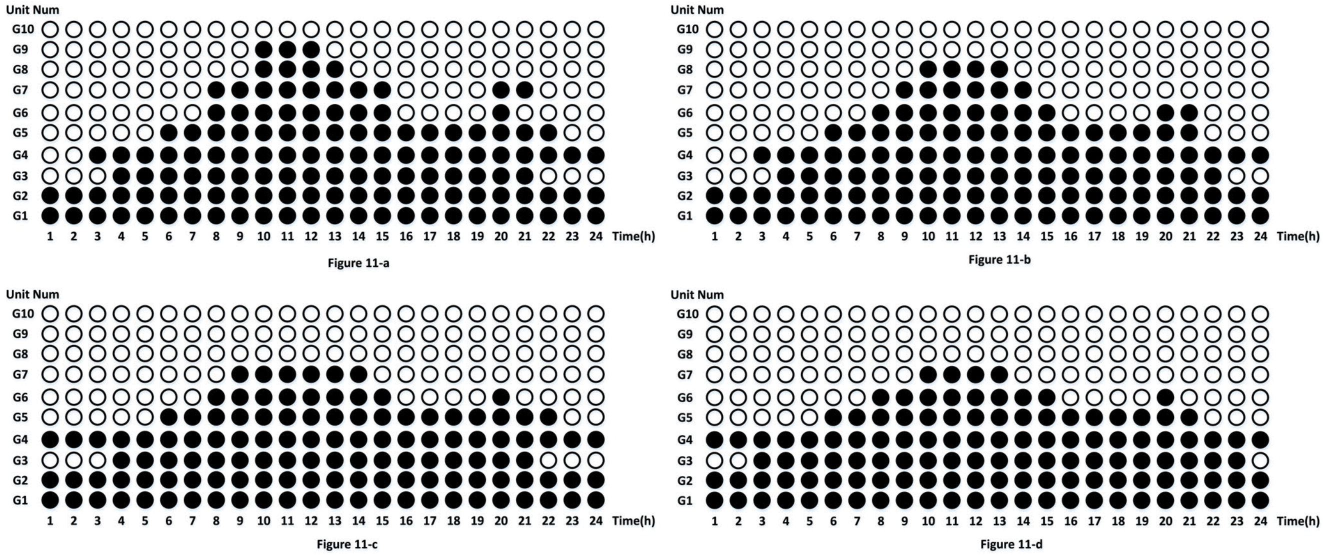

FIGURE 12. Unit commitment results for the case that thermal and cooling storage are applied, (a) is the UC result that 20% districts apply storage devices, (b) is the UC result that 40% districts apply storage devices, (c) is the UC result that 70% districts apply storage devices, (d) is the UC result that 100% districts apply storage devices.

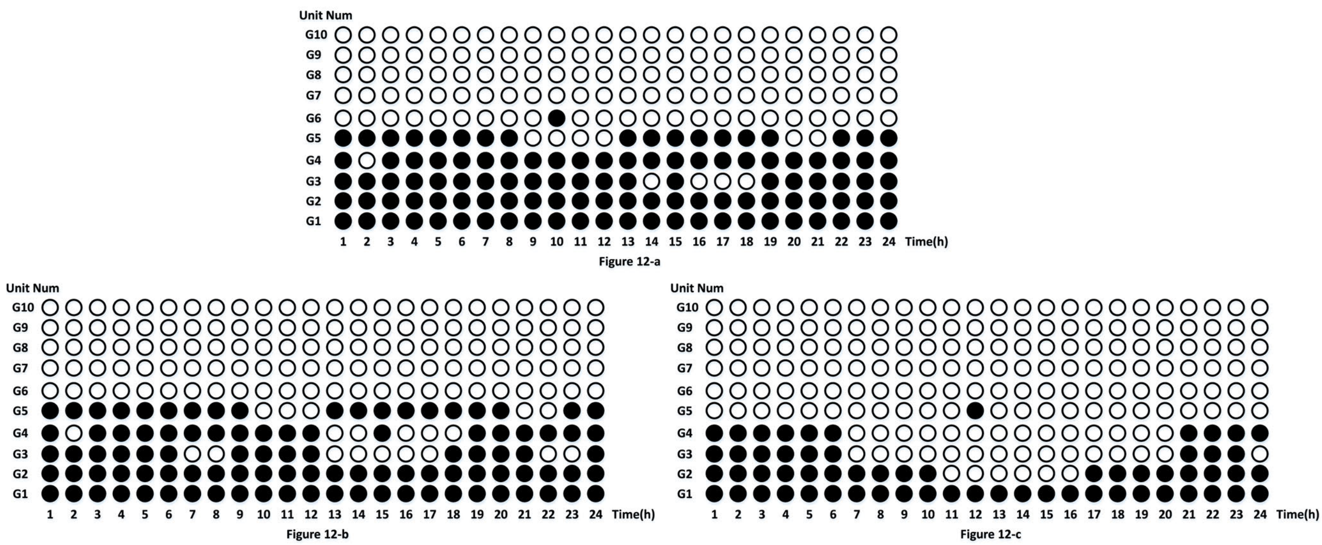

FIGURE 13. Unit commitment results for the case that CCHP are applied, (a) is the UC result that 20% districts apply CCHP, (b) is the UC result that 30% districts apply CCHP, (c) is the UC result that 100% districts apply CCHP.

First, to observe the influence caused by multiple forms of storage devices. These ten district-level load centers are equipped with thermal and cooling storage devices one by one. For each center, a 140MWh cooling storage device and an 80MWh thermal storage device are applied. The UC results are noted in Fig.12 below.

When two load centers are equipped with storage devices, nine generators are committed, as seen from Fig.12(a), generator G10 is outage at all time. When four load centers are equipped with storage devices, eight generators are committed, both G9 and G10 are outage for 24 hours, as shown in Fig.12(b). When seven load centers are equipped with storage devices, only seven generators are committed, as seen from Fig.12(c), generator G10, G9, G8 are outage at all time. And Fig.12(d) is the final case that all centers are equipped with storage devices. For this situation, the storage devices' working condition in each load centers are shown in Fig.10 below. The cooling and thermal storage devices absorb energy to their maximum storage capacity during valley load time and release these energy during peak time. From Fig.12(a) to Fig.12(d), three high-cost generators are de-committed, and the total cost of the whole system (Fig.4) reduces form \$5.966 $\times 10^5$ to \$5.634 $\times 10^5$.

Results in above section show that applying thermal and cooling storage devices leads to the reduction of committed generators quantity and the service cost of the whole system

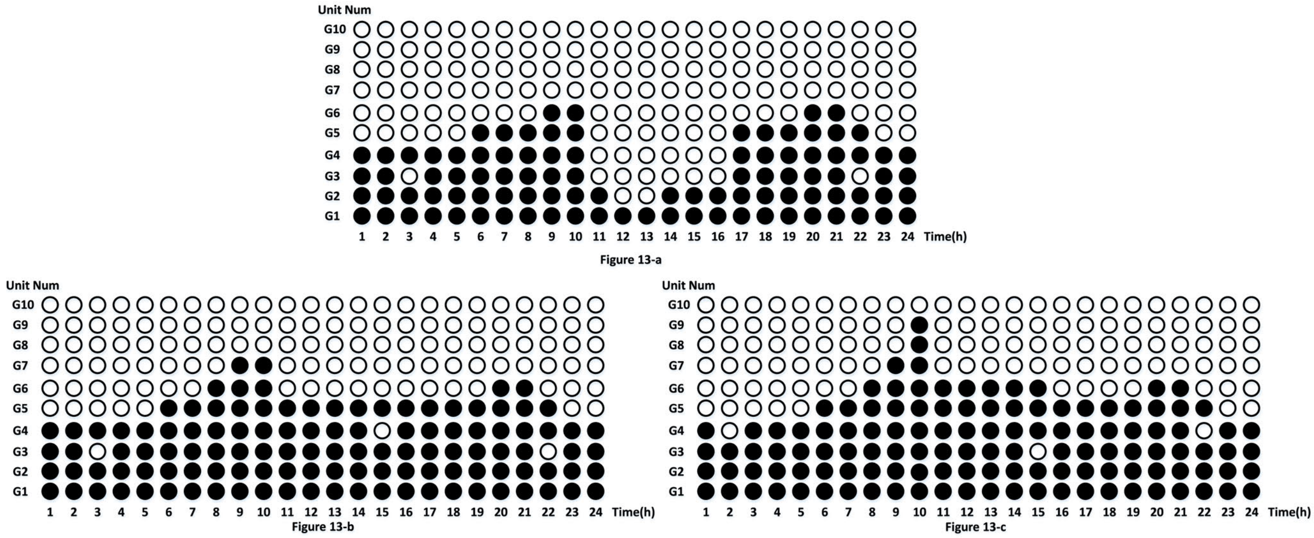

FIGURE 14. Unit commitment results for the case that CCHP are applied and natural gas price varies, (a) is the UC result that NG price is 0.21\$/m^3, (b) is the UC result that NG price is 0.29\$/m^3, (c) is the UC result that NG price is 0.43\$/m^3.

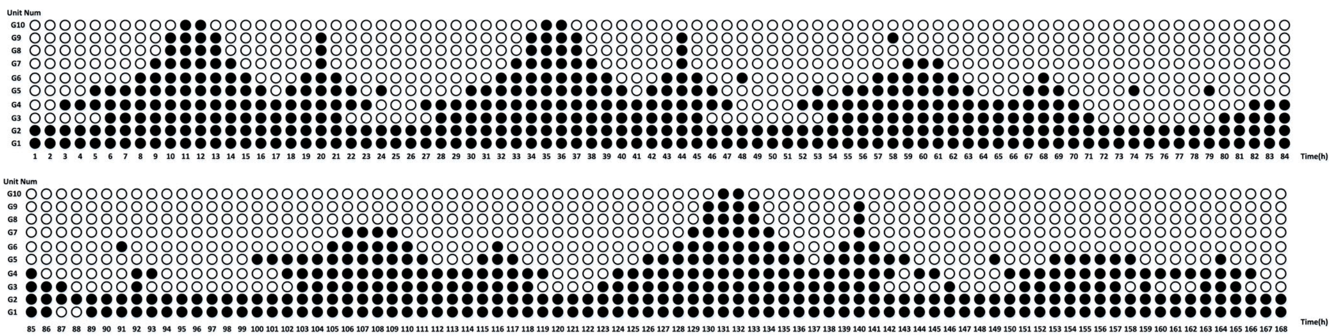

FIGURE 15. Unit commitment results of the basic electrical supply mode case in 168 hours.

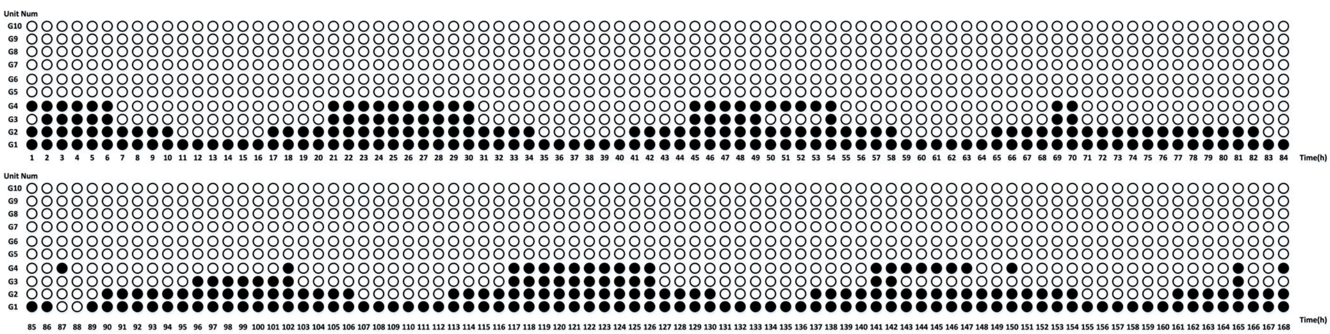

FIGURE 16. Unit commitment results of the case that all load centers are equipped with thermal and cooling storage devices as well as CCHP in 168 hours.

is also reduced. As the capacity of storage devices increases, these effects become more noticeable.

After the influences of multiple forms of storage devices are evaluated, the influence of CCHP is discussed. For each load center, a CCHP with a 78MW gas turbine is equipped to integrate with gas system. The case shown in Fig.12(d) are chosen as the basic case in this part, all load centers have cooling and thermal storage devices, and no CCHP is applied. Similar to above section, CCHPs are equipped to these centers one by one, and the changes of unit commitment result are presented in Fig.13.

When two centers are equipped with CCHP, six generators are committed during these 24 hours as shown in Fig.13(a). When three centers have CCHP, five generators are committed as seen from Fig.13(b). Fig.13(c) shows the UC result for the situation that all these ten load centers are equipped with CCHP, and the whole service cost are reduced from $5.634 × 10^5 to $4.747 × 10^5. At this time, the working condition of CCHP is presented in Fig.11 below, during the peak time, CCHP reach its capacity to serve maximum loads.

It is obvious that the application of CCHP can reduce the commitment of these high cost power units.

However, the key factor which affects the usage of natural gas related technology is the natural gas price. As for countries which need to import large amount of natural gas, the large price fluctuation is considered as a risk which constrains the development of NG industry [28]. The simulation case in Fig.13 set the NG price to be 0.14$/m^3 and as the price increases, the UC results is going to change. The UC result change is presented in Fig.14(a), Fig.14(b) and Fig.14(c), which the NG price increases to 0.21$/m^3, 0.29$/m^3 and 0.43$/m^3 respectively. It is worth to notice that NG price strongly influence the results of UC, when the price reaches to a certain level, CCHP is unable to present the above-mentioned influence on UC and fail to reduce the total service fee for the whole system.

B. CASE 2: 168h SCENARIO

Since the load varies in cycle of a week in real life, the simulation time of the model in this section is extended to a week (168 hours). Fig.15 shows the UC result of the basic case in which the electrical supply mode is used to satisfy all kinds of loads. All these ten generators are involved to serve the loads and the total service fee is $3.561 × 10^6.

After thermal and cooling storage devices, CCHPs are applied to these ten load centers, the UC results are presented in Fig.16 and the service fee reduces to $2.949 × 10^6. In this situation, only four high efficiency generators are committed during the week.

The service fee is different from seven times of 24-hour scenario fee duo to the consideration of generator cold start factor and the daily variation of loads.

In this 168h case, the modified piecewise linearization method is tested to verify the improvement of MILP solving speed. The results are listed in TABLE 1 below. For electrical supply mode, the simulation time reduces from 139s to 71s, and for the IES mode, the simulation time reduces from 25s to 21s. Compared with the original linearization method expressed in (15)-(17), the modified method in (18) reduces the number of variables, binary variables and constraints in MILP models. These reduction leads to the improvement of MILP solving speed and achieves a shorter solving time. It is worth to notice that the IES mode has a quite shorter solving time compared with the electrical supply mode. The reason for this difference is that there are less number of committed power plants in IES mode and this makes the MILP solver reaching convergence rapidly. There may be a further explanation in mathematics which could be a meaningful research topic in the future.

TABLE 1. Comparison between original piecewise linearization method and modified piecewise linearization method.

Supply Mode	Indicators	Original Method	Modified Method
Electrical Supply Mode	Variable number	32760	27732
	Binary variable number	16800	11760
	Constraint number	47376	28908
	Solving time	139s	71s
	Result	$3.550×10^6	$3.561×10^6
IES Mode	Variable number	34272	29249
	Binary variable number	16800	11760
	Constraint number	49896	31433
	Solving time	25s	21s
	Result	$2.972×10^6	$2.949×10^6

V. DISCUSSION

Two scenarios in this article show that IES has a positive impact on the power system generator operation. In the 24-hour case, two types of key equipment are analyzed which are storage devices and CCHP. For the aspect of storage devices, thermal and cooling storage are applied in the model. As the capacity of these storage devices increases, the number of committed generators decrease, inefficient high-cost small capacity generators are de-committed for the whole time. These storage devices consume energy when the heating or cooling load is low, and release these energy during the peak time to reduce the consumption of electricity and to prevent the commitment of high-cost generators.

On the other hand, CCHP also has the similar influence as mentioned above. During peak time, CCHP provides a plenty of electric, heating and cooling power to reduce the high cost energy bought from power system, which leads to the reduction of high cost generators' commitment. As mentioned above, NG system is different from power system that gas generation power is not required to be equals to the consumption power at the same time, it can release the burden of power system during peak time. It is worth to notice that, these benefits brought from CCHP are sensitive to the price of natural gas. If the NG price is high, CCHP will not be used to serve, although it has high energy conversion efficiency. And this is an unneglectable problem in a lot of developing countries who are short of NG resources and has to import large amount of NG through pipe or LNG from abroad.

The above benefits brought by district-level IES are the results of peak-load shifting. Storage as well as CCHP are the key devices in IES to achieve this peak shaving function.

The 168-hours case also concludes the same result obtained from 24-hours case. The reason for applying a 168-hours case is that it can reflect the actual situation better, that load varies in cycles of a week, and cold start of generator is taken into consideration.

As for the modified piecewise linearization method, it achieves the reduction of additional binary auxiliary variables. MILP is solved by branch and cut algorithm, reducing integer variables in the model leads to reducing the number of branch nodes that need to be processed in the process of branch cutting plane. So, the MILP solving speed is improved as shown in the result in 168h case.

IESs may have a varying objective function during operation due to the different ownership of power system. These district energy distributers aim to reduce the cost of their own districts and their objective function does not contains power system aspect including the startup cost of power generators as expressed in (40)-(42). To make sure that the object of these IESs will not have negative effect on the object of the whole system, power and gas system operators may guide these distributers to revise their operation objective functions by setting a reasonable peak-valley energy price mechanism. A Stackelberg game model can describe these relationships and be used to calculate the most suitable price mechanism for this situation, which could be a future research direction.

$$C_d^{\text{total}} = C_d^{\text{fuel}} + C_d^{\text{o\&m}} \tag{40}$$

$$C_d^{\text{fuel}} = \sum_{t\in T} (c_{d,t}^{\text{elec}} E_{d,t}^{\text{elec}} + c_{d,t}^{\text{gas}} E_{d,t}^{\text{gas}}) \tag{41}$$

$$\begin{aligned} C_d^{\text{o\&m}} = \sum_{t\in T} (&c^{\text{cchp\_e}} Pout_{d,t}^{\text{cchp\_e}} + c^{\text{cchp\_c}} Pout_{d,t}^{\text{cchp\_c}} \\ &+ c^{\text{cchp\_t}} Pout_{d,t}^{\text{cchp\_t}} + c^{\text{hpc}} Pout_{d,t}^{\text{hpc}} + c^{\text{hph}} Pout_{d,t}^{\text{hph}} \\ &+ c^{\text{cs}} Pout_{d,t}^{\text{cs}} + c^{\text{ts}} Pout_{d,t}^{\text{ts}}) \end{aligned} \tag{42}$$

VI. CONCLUSION

This article mainly focuses on the incremental influence of the increasing number and scale of IESs on conventional unit commitment in power system. Plenty of pioneer works mentioned the benefits brought from IES technologies, their model treats power system as an infinite bus. The model built in this project demonstrate a process that as the application of district-level IESs becomes more and more popular, the incremental effect to transmission level power system accumulates, UC problem is affected and cannot be neglected.

As seen from UC result, the increasing application of IESs can reduce the commitment of high cost generators and reduce the whole system service cost, which provide an economic way to satisfy a certain load. Thermal and cooling storage as well as CCHP with a reasonable NG price in the district-level IES are the reasons for above mentioned benefits and act a role of electric peak-load shifting.

In this article, the commonly used piecewise linearization method is modified to reduce the number of auxiliary binary variables in MILP model. The number of additional binary variables is reduced from $(n_{\text{interval}} + 1)$ to $\log_2(n_{\text{interval}} + 1)$. In the meantime, according to the result comparison in the 168h case, the MILP solving time is reduced as it expected, which prove the validity of this improved piecewise linearization method.

Future research works could relate to the influence of NG system linepack on UC in power system, as power and gas system are integrated tighter due to the increasing scale of CCHP. Also, applying game theory to analysis interaction between district-level IES and transmission level energy system as mentioned in the above discussion part is another meaningful research direction.

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