

Integrated Energy System Planning at Modular Regional-user Level Based on a Two-layer Bus Structure

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Abstract—An integrated energy system (IES) planning method with modular simulation and optimization models is proposed in this paper. A two-layer bus structure is adopted in the simulation model, where the external bus structure is used for power balance while the internal bus structure simulates the fast dynamics of electricity and slow dynamics of heat network in detail. In addition, an improved self-adaptive genetic algorithm (GA) is adopted in the optimization model to solve the multi-dimension and multi-time-scales optimization problem for the regional-user level IEPS. The proposed method can improve the extension flexibility of the system optimal planning model with expected accuracy. A case study is used to verify the effectiveness of the proposed planning method.

Index Terms—Genetic algorithm (GA), heat network, integrated energy system, planning, power network, two-layer bus structure.

I. INTRODUCTION

THE large-scale integration of distributed generation, distributed energy storage, and electric vehicles creates new challenges for local distribution networks, in which the regional integrated energy system (IES) provides an important technical alternative to meet these challenges. The IEPS is an electric power centered system with a coupling of multi-energies in the form of cooling, heat, electricity, gas, etc., in conjunction with combined segments of energy production, conversion, transmission and consumption. It breaks the existing independent supply mode of electricity, heat and gas, and becomes a type of modern energy development and utilization mode to improve the comprehensive energy efficiency [1]–[3].

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The complexity of IEPS also suggests higher requirements for planning and design [4]–[6]. On the one hand, the diversity of energy types and equipment types makes system configuration schemes more flexible, which directly affects the efficiency and economy of the system. On the other hand, the characteristics of user orientation and specialized service demands are more significant for the system planning, and the system design is less replicable, which also suggests higher requirements for the generality and effectiveness of the planning method [7], [8].

The modeling of the equipment and the system is the basis of IEPS planning. However, the existing methods either do not distinguish between the characteristics of the heat and electrical system adopting unified modeling method, or do not consider the network structure using a simplified process to describe the relationship of energy flow, which cannot effectively reflect the differences between electricity and heat transfer characteristics and network losses as well, especially for those IEPS with complex networks.

An optimization of a hybrid generation systems planning model is proposed in [9], the corresponding relationship of load and generators is established which lacked an independent modeling of the intermediate conversion equipment and feature description of IEPS as a whole. The method of the network flow graph of the combined heat and power system (CHP) optimal planning model is used in [10] which is convenient to describe the energy system. However, with the increased numbers of equipment, the network flow graph will be complicated and the actual operability is weak. The bus structure of the combined cooling, heat and power (CCHP) micro-grid optimal planning and scheduling model is adopted in [4], [7], so that the bus structure can clearly reflect the cooling, heat and power transmission and conversion relationship of source, network, demand and energy storage, and can effectively simplify the network topology structure of the system at the same time. However, the bus structure also has some serious weaknesses, especially in the process of simplification, as some key information about network structure and connection equipment is lost, resulting in the decrease of the model precision, especially for complex systems.

In this paper, a dual-model optimal planning model composed of the simulation model and optimization model is constructed. The simulation model adopts a two-layer bus-

structure analysis method which considers the energy flow in the external bus and the detailed network in the internal bus, such as the power/heat relationship, while retaining the characteristics of the bus structure description. The model not only meets the precision of the respective system requirements, but also simplifies the calculation and analysis. Combined with the power/heat decoupling iteration algorithm, the dimension and complexity of the system simulation can be obviously reduced, which will be beneficial to the regional-user level IEPS joint optimal planning. In addition, an improved self-adaptive genetic algorithm (GA) is adopted in the optimization model to obtain the optimal planning scheme. The contributions of this paper are shown as follows:

- 1) A dual-model optimal planning model composed of the simulation model and optimization model is established;
- 2) The two-layer extended bus structure is introduced in which the internal bus considers complex energy flow, such as the power/heat relationship;
- 3) An improved self-adaptive GA with optimized crossover and mutation rate is adopted to avoid the shortcomings of the traditional GA.

The paper is organized as follows. Section II introduces the model of units in this regional-user level IEPS. Section III describes the dual-model planning model. Section IV formulates the solution of optimization problem. Finally, the optimization results of the case study and conclusions are presented in Section V and VI, respectively.

II. THE MATHEMATICAL MODEL OF UNITS

A. CHP Unit

The CHP unit is composed of micro-turbines (MT) and an exhaust-heat boiler. The MT consumes natural gas and provides electricity while the thermal energy is recovered by the exhaust-heat boiler. The annual fuel costs of the MT $C_{\text{gas,fuel}}$ can be calculated based on the power of MT, P_{pgu} , by the power consumption function:

$$C_{\text{gas,fuel}} = \sum_{t=1}^T \alpha + \beta P_{\text{pgu}}(t) + \gamma (P_{\text{pgu}}(t))^2 \quad (1)$$

where T is the whole scheduling period; the parameters α , β , γ of the consumption function can be chosen from the fuel consumption curve of the MT [11], [12]. The MT should also be subject to the on and off constraints:

$$U_{\text{pgu}}(t)P_{\text{pgu}}^{\min} \leq P_{\text{pgu}}(t) \leq U_{\text{pgu}}(t)P_{\text{pgu}}^{\max} \quad (2)$$

$$I_{\text{pgu}}(t) + M_{\text{pgu}}(t) \leq 1 \quad (3)$$

$$U_{\text{pgu}}(t-1) - U_{\text{pgu}}(t) + I_{\text{pgu}}(t) - M_{\text{pgu}}(t) = 0 \quad (4)$$

where U_{pgu} is the binary variable describing the state of MT; I_{pgu} represents the on state of MT; M_{pgu} represents the off state of MT; $P_{\text{pgu}}^{\min}$, $P_{\text{pgu}}^{\max}$ are the lower and upper power of MT, respectively. In addition, the recovery thermal energy H_{pgu} can be calculated as follows:

$$H_{\text{pgu}}(t) = P_{\text{pgu}}(t)\eta_{\text{wh}} \quad (5)$$

where η_{wh} is the waste heat recovery efficiency.

B. Photovoltaic and Wind Turbine

The output power of the photovoltaic (PV) can be calculated as follows:

$$P_{\text{pv}} = P_{\text{STC}}G_{\text{AC}} \frac{[1 + k_0(T_c - T_r)]}{G_{\text{STC}}} \quad (6)$$

where P_{pv} is the output power of PV; G_{AC} is the light intensity; P_{STC} is the maximum power under standard conditions; G_{STC} is the light intensity under standard conditions; k_0 is the power temperature coefficient; T_c is the panel operating temperature; T_r is the reference temperature.

The output power of the wind turbine (WT) P_w can be calculated based on the wind speed v .

$$P_w = \begin{cases} P_{\text{wr}}(v^2 - v_{\text{cin}}^2)/(v_{\text{rat}}^2 - v_{\text{cin}}^2), & v_{\text{cin}} \leq v \leq v_{\text{rat}} \\ P_{\text{wr}}, & v_{\text{rat}} \leq v \leq v_{\text{cout}} \\ 0, & v_{\text{cout}} \leq v, v \leq v_{\text{cin}} \end{cases} \quad (7)$$

where P_{wr} , v_{cin} , v_{rat} and v_{cout} are the rated power, the cut-in wind speed, the rated wind speed and the cut-off wind speed, respectively.

C. Heat Pump

The thermal output of the heat pump can reach several times that of its own electricity energy consumption, which greatly reduces the primary energy consumption. Generally, the performance of the heat pump unit is evaluated by the coefficient of heating performance λ_{COP} :

$$Q_{\text{EHP}} = \frac{P_{\text{EHP}}}{\lambda_{\text{COP}}} \quad (8)$$

where Q_{EHP} and P_{EHP} are the thermal output and electricity power consumption of the heat pump.

D. Battery Energy Storage System

$$E(t + \Delta t) = E(t) + f_{\text{ch}}(t)P_{\text{ch}}(t)\Delta t\eta_1 - f_{\text{dis}}(t)P_{\text{dis}}(t)\Delta t/\eta_2 \quad (9)$$

$$0 \leq P_{\text{ch}}(t) \leq f_{\text{ch}}(t)P_{\text{chmax}} \quad (10)$$

$$0 \leq P_{\text{dis}}(t) \leq f_{\text{dis}}(t)P_{\text{dismax}} \quad (11)$$

$$f_{\text{ch}}(t) + f_{\text{dis}}(t) \leq 1 \quad (12)$$

$$E_{\min} \leq E(t) \leq E_{\max} \quad (13)$$

where E is the capacity of the battery; P_{ch} , P_{dis} are the battery charging and discharging power, respectively; f_{ch} and f_{dis} are the binary variables representing charging and discharging modes, respectively; P_{chmax} , P_{dismax} are the limits of charging and discharging power, respectively; η_1 , η_2 are the battery charging efficiency and discharging efficiency, respectively; $E_{\max}$, $E_{\min}$ are the upper and lower limits of the battery capacity, respectively.

E. Gas Boiler

The fuel costs of the gas boiler C_{boiler} can be calculated by the heat power H_{boiler} :

$$C_{\text{boiler}} = \sum_{t=1}^T \frac{H_{\text{boiler}}(t)}{\eta_{\text{boiler}}H_{\text{ng}}}K \quad (14)$$

where η_{boiler} is the heat efficiency of the gas boiler; H_{ng} is the heat value of the gas, which is 9.78 (kW·h)/m³; K is the price

of gas. The gas boiler should also be subject to the operational constraints:

$$H_{b,\min} f_b(t) \leq H_{\text{boiler}}(t) \leq H_{b,\max} f_b(t) \quad (15)$$

where $H_{b,\min}$ and $H_{b,\max}$ are the lower and upper limits of heat power; f_b is the binary variable describing the state of the gas boiler.

III. DUAL-MODEL PLANNING MODEL

A. Framework

Planning of the IEPS is done through comparing different system configurations (such as battery capacity configuration) to achieve a solution to optimize the system operational objectives during the whole project period. The optimization problem, as we know, is multi-factor, multi-dimensional, and nonlinear which is hard to solve. Therefore, this paper presents a framework combining the simulation model and optimization model to reduce the complexity of the optimization problem, which is shown in Fig. 1.

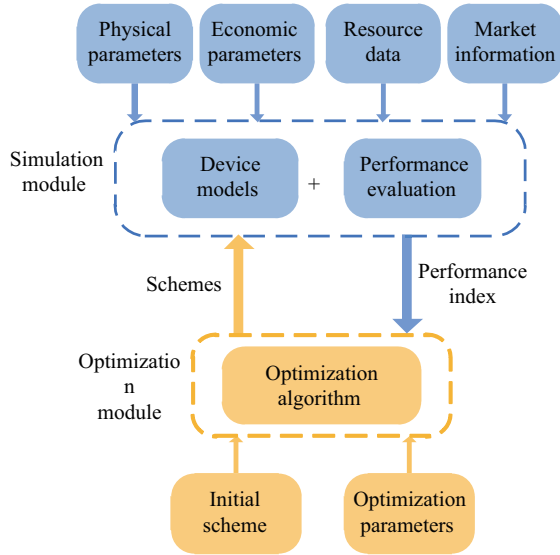


Fig. 1. Relationship graph of the planning optimization models.

In the simulation model, the technical, economic, environmental indexes or their combinations are evaluated by the system planning scheme with the operational data obtained through simulations considering the technical characteristics of the IEPS. Based on the evaluation results, the optimal planning scheme is obtained through the optimization model. Within the proposed framework, the simulation model and optimization model are the key issue and will be discussed in more detail below.

B. Two-layer Bus Structure

It is well known that the composition and structure of a regional-user level IEPS is complicated, which makes it difficult to describe all the energy flow and topology in a single graph. For example, a typical simple IEPS includes distributed generation (DG), e.g. WT, PV, CHP systems, gas boiler and

other conversion devices; the relationship of energy flow is shown in Fig. 2.

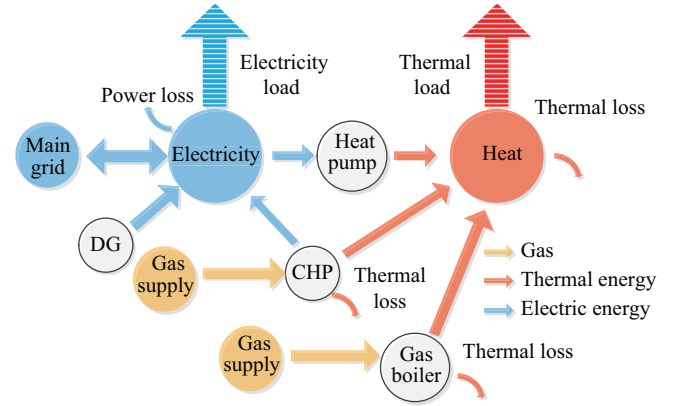


Fig. 2. Energy flow diagram of a simple IEPS.

The single-layer bus structure primarily describes the connection mode and coupling relationship of the main equipment. The energy transmission between different mediums is described in a simplified way, as shown in Fig. 3 [13].

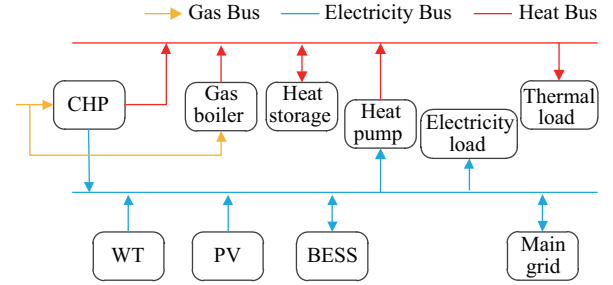


Fig. 3. The single-layer bus-structure diagram of the typical IEPS.

The system energy balance equation and equipment constraints for different energy supplies, such as electricity, heat, energy storage and heat-power conversion devices are easily listed according to the single-layer bus structure [14]–[16]. All these devices can be modeled independently, but the network transmission characteristics are simplified. Therefore, by simplifying the grid to a single-layer electric bus and heat bus, the different transmission characteristics and network losses of electricity and heat cannot be well analyzed, which makes it difficult to meet the precision requirements of the model.

The two-layer bus structure can be expanded based on the single-layer bus structure to model the electric and heat systems separately but to optimize jointly, as shown in Fig. 4. Thermoelectric decoupling plays an important role in IEPS optimization planning. Taking the electric network as an example, the power loss of the intermediate transmission and conversion can be considered by adding the topology structure to the internal layer. The two-layer bus structure can describe the system more precisely because of the consideration of the transmission losses between different devices and the AC/DC conversion losses. Similarly, the heat bus can also be extended to more complex topological structures and network

relationships, which fully reflect the operation characteristics of the power and heat decoupled systems.

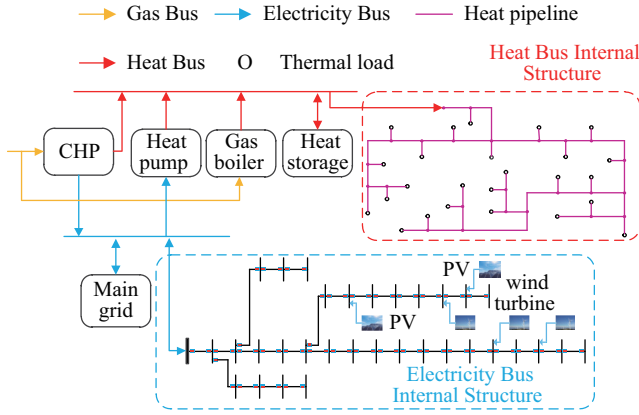


Fig. 4. Topology of a simple IEPS.

C. Thermo-electric Decoupling Method

1) The Balance Equation of the External Electric Bus

According to the two-layer bus structure of the IEPS shown in Fig. 4, the balance equation of the external electric bus is as follows:

$$P_{\text{grid}}(t) + P_{\text{pv}}(t) + P_w(t) + P_{\text{pgu}}(t) + P_{\text{es}}(t) + L_e(t) + P_{\text{EHP}}(t) + P_{\text{loss}}(t) = 0 \quad (16)$$

where P_{grid} represents the grid exchange power; P_{pv} , P_w , P_{pgu} represent the power of PV, WT and CHP unit; L_e is the electrical load, P_{es} is the energy storage power; P_{EHP} is the consumption power of the heat pump; P_{loss} is the network loss of the internal electric bus with the initial value of zero; Within the balance equation of the electric bus, the power flow into the bus is defined as positive and the outflow is negative.

Similarly, the balance equation of the heat bus is shown as (17):

$$H_{\text{pgu}} + H_{\text{boiler}} + L_{\text{heat}} + H_{\text{es,heat}} + H_{\text{loss}} = 0 \quad (17)$$

where L_{heat} is the heat demand; $H_{\text{es,heat}}$ is the heat consumption of the storage device; H_{loss} represents the heat loss inside the heat bus.

2) Internal Bus Model of the Electricity Bus With Fast Dynamics

The calculation model of the internal network of the electric bus is based on the power flow equation which is shown as (18)–(21), in which the power injection of each device is taken as the initial inputs. In this section, a traditional radial distribution network is shown in Fig. 5, and Dist-Flow [17] is used to describe the complex power flow.

$$P_{i+1}(t) = P_i(t) - \frac{r_i(P_i^2(t) + Q_i^2(t))}{V_i^2(t)} - p_{i+1,l}(t) + p_{i+1,g}(t) \quad (18)$$

$$Q_{i+1}(t) = Q_i(t) - \frac{x_i(P_i^2(t) + Q_i^2(t))}{V_i^2(t)} - q_{i+1,l}(t) + q_{i+1,g}(t) \quad (19)$$

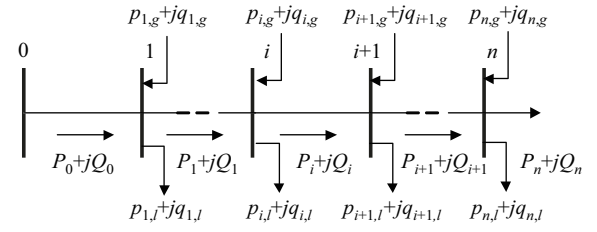


Fig. 5. The radial distribution network.

$$V_{i+1}^2(t) = V_i^2(t) - 2(r_i P_i(t) + x_i Q_i(t)) + \frac{(r_i^2 + x_i^2)(P_i^2(t) + Q_i^2(t))}{V_i^2(t)} \quad (20)$$

$$V_i^{\min} \leq V_i(t) \leq V_i^{\max} \quad (21)$$

where i represents the node in the distribution network; P_i , Q_i are the active and reactive power of the line from node i to $i+1$, respectively; $p_{i,g}$, $q_{i,g}$ are the active and reactive power of the generation of node i , respectively; $p_{i,l}$, $q_{i,l}$ are the active and reactive load of node i , respectively; r_i , x_i are the resistance and reactance between node i and $i+1$, respectively; V_i is the voltage of node i . $V_i^{\min}$ and $V_i^{\max}$ are the lower and upper limits of voltage, respectively. Therefore, the internal bus power flow and network loss can be accurately calculated.

3) Internal Bus Model of the Heat Bus With Slow Dynamics

The internal bus model of the heat bus is based on the water flow in the heat supply pipelines. Due to the lack of control devices, most of the heat networks are operated with constant flow and variable temperatures [18]. It is assumed that this operational mode is also utilized in this paper, where the mass flow rate is always constant, and the hydraulic conditions always are kept stable. Then, the thermodynamic model of the pipeline network is simplified by eliminating the nonlinear hydraulic model.

A single pipeline in the heat network is shown in Fig. 6. The thermal conduction in each pipeline, including heat loss and temperature time delays, can be modeled by a partial differential equation [19], [20] as follows:

$$\frac{\partial T_{p,k,t}^x}{\partial t} + \frac{G_{p,k,t}^x}{\pi \rho_w R_{p,k}^2} \cdot \frac{\partial T_{p,k,t}^x}{\partial x} + \frac{2\mu_{p,k}}{c_w \rho_w R_{p,k}} (T_{p,k,t}^x - T_{p,k,t}^{\text{soil}}) = 0 \quad (22)$$

where p is the subscript which represent the heat pipelines; k is the number of pipelines; $T_{p,k,t}^{\text{in}}$ and $T_{p,k,t}^{\text{out}}$ are the water temperatures at the inlet and outlet of the pipeline at the time t ; $T_{p,k,t}^x$ are the water temperatures at a length of x from the inlet of the pipeline; the delay time $\Delta\tau_{p,k}$ represents the water flowing time from the inlet to the outlet of the pipeline; $\mu_{p,k}$

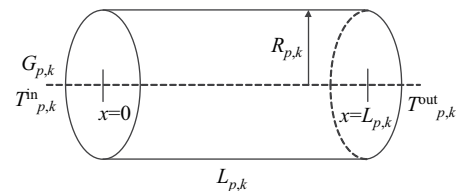


Fig. 6. Single pipeline in the heat network.

is the thermal loss coefficient; c_w and ρ_w are the specific heat capacity and density of water; $R_{p,k}$ is the radius of pipeline k ; $G_{p,k,t}^x$ is the flow rate of pipeline k . The solution of (22) can be obtained in [20], [21]:

$$T_{p,k,t+\Delta\tau_{p,k}}^{\text{out}} = T_{p,k,t}^{\text{soil}} + (T_{p,k,t}^x - T_{p,k,t}^{\text{soil}}) \exp\left(-\frac{2\mu_{p,k}}{c_w\rho_w R_{p,k}}\Delta\tau_{p,k}\right) \quad (23)$$

Since the mass flow rate is constant in this paper, $\Delta\tau_{p,k}$ is defined as:

$$\Delta\tau_{p,k} = \frac{\pi\rho_w L_{p,k} R_{p,k}^2}{G_{p,k}} \quad (24)$$

where $L_{p,k}$ is the length of pipeline k . However, $\Delta\tau_{p,k}$ should be integer times of the scheduling interval Δt in the scheduling problem. Therefore, $\Delta\tau_{p,k}$ is processed by the new auxiliary variable $\lambda_{p,k}$ and (25), (26).

$$T_{p,k,t+\lambda_{p,k}}^{\text{out}} = T_{p,k,t}^{\text{soil}} + (T_{p,k,t}^x - T_{p,k,t}^{\text{soil}}) \exp\left(-\frac{2\mu_{p,k}\lambda_{p,k}}{c_w\rho_w R_{p,k}}\Delta t\right) \quad (25)$$

$$\lambda_{p,k} = \text{round}\left(\frac{\Delta\tau_{p,k}}{\Delta t}\right) \quad (26)$$

In addition, the heat network constraints also include the relationship between heat power and water temperatures, supply and return water temperature limits and node temperature characteristics.

$$q_{p,k,t}^{\text{in}} = c_w G_{p,k} T_{p,k,t}^{\text{in}} \quad (27)$$

$$q_{p,k,t}^{\text{out}} = c_w G_{p,k} T_{p,k,t}^{\text{out}} \quad (28)$$

$$T_{ps}^{\text{min}} \leq T_{p,k,t}^{\text{in}} \leq T_{ps}^{\text{max}}, T_{ps}^{\text{min}} \leq T_{p,k,t}^{\text{out}} \leq T_{ps}^{\text{max}} \quad (29)$$

$$T_{pr}^{\text{min}} \leq T_{p,k,t}^{\text{in}} \leq T_{pr}^{\text{max}}, T_{pr}^{\text{min}} \leq T_{p,k,t}^{\text{out}} \leq T_{pr}^{\text{max}} \quad (30)$$

$$\sum_{k \in S_{\text{pipe,out},n}} (c_w G_{p,k} T_{p,k,t}^{\text{out}}) = c_w T_{\text{mix},n} \sum_{k \in S_{\text{pipe,out},n}} G_{p,k} \quad (31)$$

where $q_{p,k,t}^{\text{in}}$ and $q_{p,k,t}^{\text{out}}$ are heat power corresponding to water flow with temperatures $T_{p,k,t}^{\text{in}}$ and $T_{p,k,t}^{\text{out}}$; T_{ps}^{min} and T_{ps}^{max} are the lower and upper limits of the water temperatures in the supply network; T_{pr}^{min} and T_{pr}^{max} are the lower and upper limits of the water temperatures in return network; n is the node in the heat network; $S_{\text{pipe,out},n}$ is the set of pipelines in which water flows into node n ; $T_{\text{mix},n}$ is the temperature of water flowing out from node n .

4) Iteratively Solving Method

Based on the thermo-electric decoupling, individual modeling and iterative solving are proceeded afterwards. The flowchart is shown in Fig. 7 and the main steps are as follows:

Step 1: Establish the electrical and thermal balance equation. With the consideration of the difference of the internal bus model, P_{loss} , H_{loss} are added to represent the network loss with the initial value of zero;

Step 2: Combined with the external bus balance equations and scheduling strategy, calculate the output power of each device and the transmission power between different buses, where the scheduling strategy can be selected according to the requirements for the heuristic strategy or optimization strategy;

Step 3: Put the power injection, which is determined by the external layer, into the equations with detailed internal network

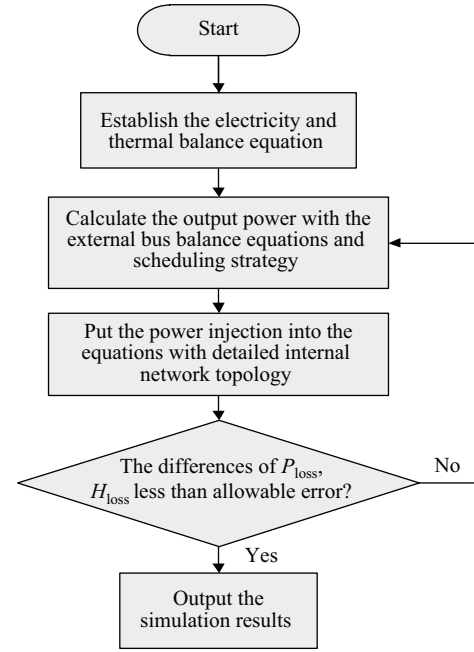


Fig. 7. Flowchart of the iterative solving process of the simulation model.

topology. Additional accurate energy flow relationships and network losses can be obtained through simulations;

Step 4: Compare the values of P_{loss} , H_{loss} before and after the calculation, if the differences are less than the allowable error range, go to Step 5; otherwise, take the internal network loss value as the transmission loss of each bus, and go to Step 2;

Step 5: Stop the iteration, and output the simulation results, such as device power and network losses.

It should be noted that for Step 2, usually a heuristic strategy or optimization strategy can be chosen as the dispatch strategy, while the optimization strategy can be divided into the static optimization and dynamic optimization [22]. This paper focuses on the planning model, both the heuristic strategy and optimization strategy can be used as the internal strategy to calculate and determine the device output without affecting the application of the proposed method.

In this paper, the method of thermo-electric decoupling is used so that the heat and power system could be modeled individually according to their own characteristics. Furthermore, the accuracy of each system can also be guaranteed. At the same time, the decoupling method can effectively reflect the differences between the heat and electrical transmission characteristics and can effectively reduce the dimension and complexity of the system simulation.

IV. SOLUTION OF THE OPTIMIZATION MODEL

A. Establishment of the Optimization Model

The economy of the planning system is usually selected as the objective of regional-user level IEPS optimization, including the investment costs, electricity purchasing costs, system operation and maintenance costs, and the electricity sale income, etc. As a long-term planning problem, the elec-

tricity market transaction is therefore neglected. The specific calculation formula is explained as follows:

1) Net Present Value

The net present value is generally used to measure the benefit of the investment. The smaller the total cost of the investment plan in the life cycle of the project, the better the scheme is. The net present value of the total cost is calculated as shown in (32):

$$C_{NPV} = \frac{C_{ann,s}}{K_{CRF}(r, T_{pro})} \quad (32)$$

where C_{NPV} represents the net present value for the total project cost, $C_{ann,s}$ is the total annual cash flow, $K_{CRF}(r, T_{pro})$ is the capital recovery factor for the project period which is used to calculate the present value of the average annual cash flow, while r is the interest rate, T_{pro} is the project period. K_{CRF} can be calculated as shown in (33):

$$K_{CRF}(r, T_{pro}) = \frac{r(r+1)^{T_{pro}}}{(r+1)^{T_{pro}} - 1} \quad (33)$$

2) Cost-Benefit Model

In the case of a regional-user level IEPS, the main purpose is to reduce the cost of the electricity purchase, and the total net present value is chosen for analysis. The calculation formula is as follows:

$$C_{ann,s} = C_{ann,cap} + C_{ann,rep} + C_{ann,om} + C_{ann,ele} + C_{ann,bas} - B_{sel} - B_{sub} \quad (34)$$

where $C_{ann,cap}$ represents the annual capital cost, $C_{ann,rep}$ represents the annual replacement cost, $C_{ann,om}$ represents the annual maintenance cost, $C_{ann,ele}$ represents the annual electricity energy cost, $C_{ann,bas}$ represents the annual basic electric power costs, B_{sel} represents the annual sale of electricity income, B_{sub} represents the subsidy income. $C_{ann,om}$, $C_{ann,ele}$, B_{sel} and B_{sub} are related to the operation of the system, which needs to be calculated with the simulation model.

The calculation of the annual capital cost $C_{ann,om}$ is as follows:

$$C_{ann,cap} = C_{cap} K_{CRF}(r, T_{pro}) \quad (35)$$

where C_{cap} is the initial capital cost of all equipment.

The annual replacement cost of the project $C_{ann,rep}$ is the replacement cost of each equipment throughout the project minus the residual cost at the end of the project, it can be expressed as (36):

$$C_{ann,rep} = C_{rep} K_{SF}(r, T_{com}) - C_{rep} \frac{T_{sur}}{T_{com}} K_{SF}(r, T_{pro}) \quad (36)$$

where C_{rep} is the replacement cost at one time, T_{com} is the equipment lifespan, T_{sur} is the residual time of the element at the end of the project, $K_{SF}(r, T_{com})$ and $K_{SF}(r, T_{pro})$ are the sinking fund factor of T_{com} and T_{pro} , respectively.

The annual total cost of electricity $C_{ann,ele}$ represents the annual total cost of the IEPS actually purchased electricity from the grid, it can be calculated as:

$$C_{ann,ele} = \sum_s^{8760} W_{pur,s} c_{pur,s} \quad (37)$$

where $W_{pur,s}$ is the s th hour electricity purchased from the power grid, $c_{pur,s}$ is the electricity price in the s th hours.

The annual basic electricity cost $C_{ann,bas}$ is used to represent the basic capacity fee that a large industrial paid according to the two-part electricity price, which can be calculated based on the monthly maximum load demand:

$$C_{bas} = \sum_j^{12} P_{max,j} c_{bas} \quad (38)$$

where $P_{max,j}$ is the average maximum load capacity for the month j , and c_{bas} stands for a monthly charge of the basic electricity price in the two-part electricity price.

The annual sale income of electricity B_{sel} is used to indicate that when the IEPS sells the surplus electricity to the grid, the calculation formula is shown as (39):

$$B_{sel} = \sum_s^{8760} W_{sel,s} c_{sel} \quad (39)$$

where $W_{sel,s}$ is the sellback electricity to the grid for the s th hour. c_{sel} is the sellback price. The subsidy income B_{sub} is primarily the power generation subsidy for the distributed generation.

B. Optimization Method

An improved self-adaptive GA is used in the optimization model [23], the general process flow is shown in Fig. 8.

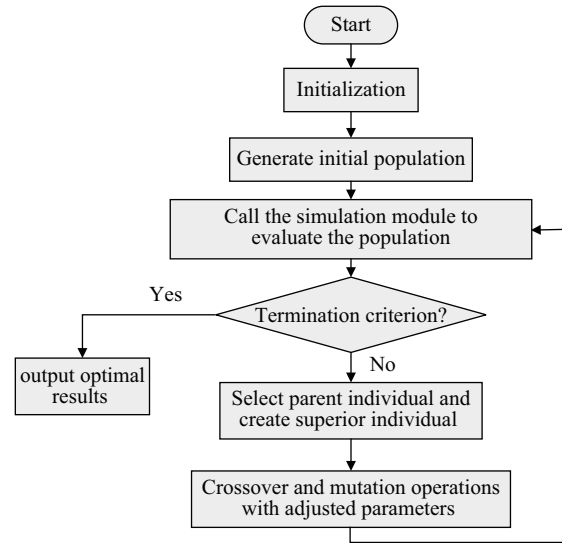


Fig. 8. Flowchart of the optimization model.

Step 1: Initialization. Input system composition and structure parameters, device parameters and optimization parameters of GA;

Step 2: Generate initial population according to GA. Each individual of the initial population is corresponding to one planning scheme in the project period;

Step 3: Call the simulation model to evaluate the population to obtain the fitness value, if the generation number reaches the set value, output the final optimal planning results; otherwise, go to Step 4;

Step 4: Select parent individual and create superior individual to do subsequent optimization.

Step 5: Crossover and mutation operations with adjusted parameters according to the population fitness. The crossover and mutation rates are adjusted as follows:

$$R_c = \begin{cases} R_{c1} - \frac{(R_{c1} - R_{c2})(f_{\max} - f')}{f_{\max} - f_{\text{avg}}} & f \geq f_{\text{avg}} \\ R_{c1} & f < f_{\text{avg}} \end{cases} \quad (40)$$

$$R_m = \begin{cases} R_{m1} - \frac{(R_{m1} - R_{m2})(f_{\max} - f)}{f_{\max} - f_{\text{avg}}} & f \geq f_{\text{avg}} \\ R_{m1} & f < f_{\text{avg}} \end{cases} \quad (41)$$

where R_c and R_m are the crossover and mutation rates, respectively. R_{c1} , R_{c2} , R_{m1} , and R_{m2} are the adjustment factors. f' is the larger fitness between the two individuals involved in the mutation. f is the fitness of the crossover individual. $f_{\max}$ and f_{avg} are the maximum fitness and average fitness of the population, respectively.

V. CASE STUDY

In this paper, a practical IEPS is chosen to demonstrate the developed model and method, within which WT, MT, gas boiler, PV, battery and heat pump system are selected. The system structure diagram of the chosen equipment is shown in Fig. 9.

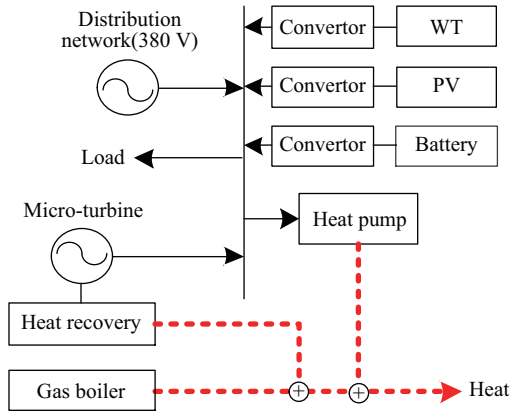


Fig. 9. System structure diagram of the chosen IEPS.

For the GA algorithm, the population size is 60, evolutionary generations are 300, crossover probability is 0.9, and mutation probability is 0.1. For the system analysis, a life time of 20 years and interest rate of 0.06 were assumed for this project. The economic parameters and performance parameters of these equipment are presented in Table I and Table II. The electricity price and load are shown in Fig. 10 and Fig. 11.

With the economy as the objective function, the optimization result of the system is shown in Table III. Three schemes are introduced where the total cost of scheme I is minimum, the operation cost of scheme II is minimum, and the investment cost of scheme III is minimum. In scheme II, every unit is used to obtain the most profits, but the investment cost is also high, correspondingly. In scheme III, electricity load is met only by purchasing electricity from the main

TABLE I
THE ECONOMIC PARAMETERS OF THE FACILITIES IN THE IEPS

Equipment	Fixed initial investment (Yuan)	Variable initial investment (kW/Yuan)	Fixed maintenance price (kW/Yuan)	Variable maintenance ((kW·h)/Yuan)
Gas Boiler	0	400	2.5	—
Micro-turbine	—	12800	0	0.1
Heat pump	0	4000	2	—
Battery	0	2000	0.8	—
WT	0	800	0.8	—
PV	0	12000	1.8	—

TABLE II
ELECTRICITY AND NATURAL GAS PRICES

Equipment	Type
Gas boiler (MW)	160, 165
Micro-turbine (MW)	1.5, 2
Heat pump (MW)	3, 5
Battery (MW)	0, 0.5, 1
WT (MW)	0, 1, 2
PV (MW)	0, 0.5, 1

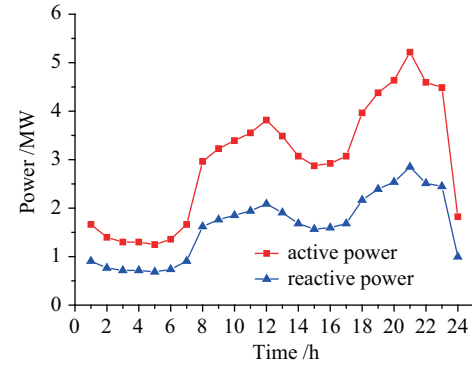


Fig. 10. 10 Forecasted hourly total load.

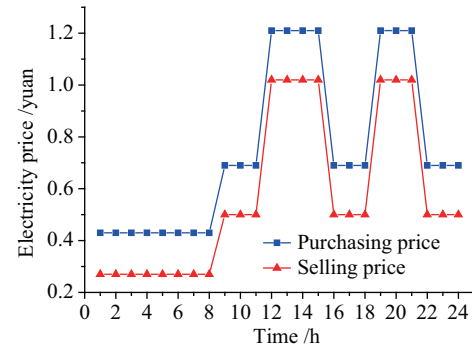


Fig. 11. Electricity price.

grid, which leads to a lower investment cost. However, the renewable energy cannot be absorbed without PV and WT, and the battery is not used to obtain more profits according to the electricity price difference. Considering the operational cost and investment cost, scheme I is the most economical scheme. In scheme I, PV is not configured because of the high investment cost, and the capacity of the battery and WT is maximum in which the most benefits are obtained by wind energy and price arbitrage. In addition, the micro-turbines can

supply heat and electricity when the higher capacity of MT is selected, and at the same time, the capacity of the pump can also be reduced compared to scheme II.

TABLE III
THE SCHEME OF DISTRIBUTED ENERGY SYSTEM

Scheme	Scheme I	Scheme II	Scheme III
Gas Boiler	165	165	160
Micro-turbine	2	2	1.5
Heat pump	3	5	3
Battery	1	1	0
WT	2	2	0
PV	0	1	0
Operation cost ($\times 10^8$ yuan)	1.37	1.34	1.53
Investment cost ($\times 10^8$ yuan)	0.17	0.36	0.13
Total cost ($\times 10^8$ yuan)	1.54	1.70	1.66
Net present value	0.134	0.148	0.1447

The operational results of scheme I are shown in Figs. 12–15. As shown in Fig. 12, the battery is charged during the low electricity period and discharged during the high electricity price (12:00–16:00, 19:00–22:00). On the other hand, the WT and MT also generate electricity and according to Fig. 13 the redundant electricity is transferred to the main grid to obtain more profits. The temperature of pipelines 1~6 is described in Fig. 14, and the distribution of the temperature in different pipelines have different time delays because of the water flow. For the heat supply source, the MT and heat pump supply heat for consumers at the same time which is depicted in Fig. 15.

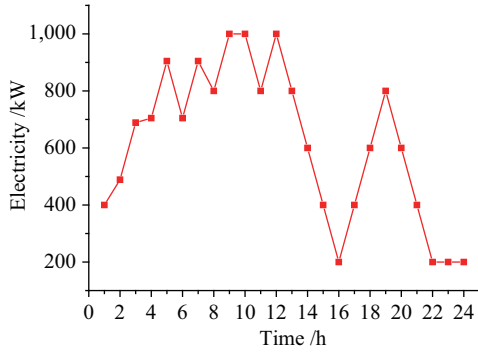


Fig. 12. The capacity of battery.

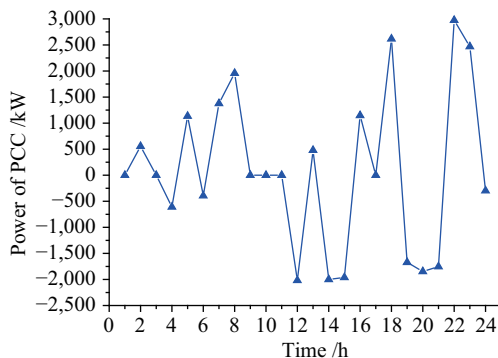


Fig. 13. The power of PCC.

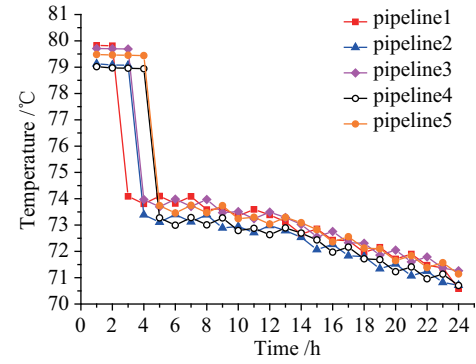


Fig. 14. The outlet temperature of pipelines.

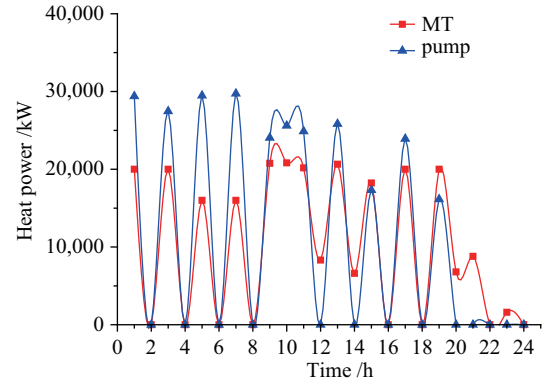


Fig. 15. The heat power of MT and pump.

VI. CONCLUSION

In this paper, a modular planning framework for a regional-user level IEPS is established, the simulation and optimization models proceed in turn to achieve the optimal solution. A two-layer bus structure simulation method is proposed, which can ensure fast dynamics of the power network and slow dynamics of the heat network separately. By taking full account of the coupling relationship between the different devices, the flexibility of the composition of the system and the accuracy of the simulation calculations are also preserved. In this paper, the optimal planning model of the IEPS is established, and the two-layer optimization method of the heat and power network is put forward. A simple IEPS example is given to exhibit and prove the correctness of the proposed method, which can also be applied to a complex IEPS with large-scaled power and heat networks.

REFERENCES

- [1] X. D. Xu, H. J. Jia, D. Wang, D. C. Yu, and H. D. Chiang, "Hierarchical energy management system for multi-source multi-product microgrids," *Renewable Energy*, vol. 78, pp. 621–630, Jun. 2015.
- [2] Y. Hu, Z. H. Bie, T. Ding, and Y. L. Lin, "An NSGA-II based multi-objective optimization for combined gas and electricity network expansion planning," *Applied Energy*, vol. 167, pp. 280–293, Apr. 2016.
- [3] W. Gu, J. Wang, S. Lu, Z. Luo, and C. Y. Wu, "Optimal operation for integrated energy system considering thermal inertia of district heating network and buildings," *Applied Energy*, vol. 199, pp. 234–246, Aug. 2017.
- [4] L. Guo, W. J. Liu, J. J. Cai, B. W. Hong, and C. S. Wang, "A two-stage optimal planning and design method for combined cooling, heat

and power microgrid system,” *Energy Conversion and Management*, vol. 74, pp. 433–445, Oct. 2013.

- [5] X. Liu and Z. Y. Li, “False data attacks against AC state estimation with incomplete network information,” *IEEE Transactions on Smart Grid*, vol. 8, no. 5, pp. 2239–2248, Sep. 2017.
- [6] X. Liu, Z. Y. Li and Z. Y. Li, “Optimal protection strategy against false data injection attacks in power systems,” *IEEE Transactions on Smart Grid*, vol. 8, no. 4, pp. 1802–1810, Jul. 2017.
- [7] C. S. Wang, B. W. Hong, L. Guo, D. J. Zhang, and W. J. Liu, “General modeling method for optimal dispatch of combined cooling, heating and power microgrid,” *Proceedings of the CSEE*, vol. 33, no. 31, pp. 26–33, Nov. 2013.
- [8] X. P. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, “Optimal expansion planning of energy hub with multiple energy infrastructures,” *IEEE Transactions on Smart Grid*, vol. 6, no. 5, pp. 2302–2311, Jan. 2015.
- [9] H. B. Ren and W. J. Gao, “A MILP model for integrated plan and evaluation of distributed energy systems,” *Applied Energy*, vol. 87, no. 3, pp. 1001–1014, Mar. 2010.
- [10] H. Cho, P. J. Mago, R. Luck, and L. M. Chamra, “Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme,” *Applied Energy*, vol. 86, no. 12, pp. 2540–2549, Dec. 2009.
- [11] Y. Liu, S. Gao, X. Zhao, C. Zhang, and N. Y. Zhang, “Coordinated operation and control of combined electricity and natural gas systems with thermal storage,” *Energies*, vol. 10, no. 7, pp. 917, Jul. 2017.
- [12] M. Kalantar and G. S. M. Mousavi, “Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage,” *Applied Energy*, vol. 87, no. 10, pp. 3051–3064, Oct. 2010.
- [13] B. W. Hong and Z. H. Zheng, “Stochastic multi-objective dynamic optimal dispatch for combined heat and power microgrid,” in *Proceedings of 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference*, 2016.
- [14] S. Abedi, A. Alimardani, G. B. Gharehpetian, G. H. Riahy, and S. H. Hosseini, “A comprehensive method for optimal power management and design of hybrid RES-based autonomous energy systems,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 3, pp. 1577–1587, Apr. 2012.
- [15] B. W. Hong, L. Guo, C. S. Wang, B. Q. Jiao, and W. J. Liu, “Model and method of dynamic multi-objective optimal dispatch for microgrid,” *Electric Power Automation Equipment*, vol. 33, no. 3, pp. 100–107, Mar. 2013.
- [16] R. Wang, W. Gu, and Z. Wu, “Economic and optimal operation of a combined heat and power microgrid with renewable energy resources,” *Automation of Electric Power Systems*, vol. 35, no. 8, pp. 22–27, May 2011.
- [17] M. E. Baran and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing,” *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1401–1407, May 1989.
- [18] P. Li, H. X. Wang, Q. Lv, and W. D. Li, “Combined heat and power dispatch considering heat storage of both buildings and pipelines in district heating system for wind power integration,” *Energies*, vol. 10, no. 7, pp. 893, Jun. 2017.
- [19] Z. G. Li, W. C. Wu, M. Shahidehpour, J. H. Wang, and B. M. Zhang, “Combined heat and power dispatch considering pipeline energy storage of district heating network,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, pp. 12–22, Jan. 2016.
- [20] G. Sandou, S. Font, S. Tebbani, A. Hiret, C. Mondon, S. Tebbani, A. Hiret, and C. Mondon, “Predictive control of a complex district heating network,” in *Proceedings of the 44th IEEE Conference on Decision and Control, 2005 and 2005 European Control Conference*, Seville, Spain, 2005, pp. 7372–7377.
- [21] L. Arvastson, “Stochastic Modeling and Operational Optimization in District Heating Systems,” Ph. D. dissertation, Lund Institute of Technology, Lund, Sweden, 2001.
- [22] B. W. Hong, W. W. Miao, and D. J. Zhang, “A dual-module method for energy-internet-oriented distributed energy system planning,” in *Proceedings of 2017 IEEE Conference on Energy Internet and Energy System Integration*, Beijing, China, 2017.
- [23] L. Wang and D. B. Tang, “An improved adaptive genetic algorithm based on hormone modulation mechanism for job-shop scheduling problem,” *Expert Systems with Applications*, vol. 38, no. 6, pp. 7243–7250, Jun. 2011.



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