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Optimal Scheduling of Integrated Energy System Based on Model Predictive Control

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ABSTRACT

In order to realize the renewable energy consumption and multi-energy coupling, it is necessary to study the optimal dispatching strategy of the integrated energy system. This paper aims to minimize the total operating cost of the integrated energy system, considers the randomness of distributed energy and the uncertainty of load, and adopts the method of model predictive control to conduct research. The main work is as follows: A typical cogeneration microgrid is given. The basic structure and energy flow relationship are established, and the mathematical model of each part of the integrated energy system is established. The optimal scheduling and control strategy of integrated energy system based on model predictive control is introduced, and the objective function and constraints of this paper are given. Finally, taking the winter integrated energy system of a district with distributed energy as an example, the effectiveness of the model predictive control method is verified by the comparison of different operation modes.

Keywords: model predictive control, integrated energy systems, economic optimization, renewable energy generation, energy storage

1. INTRODUCTION

In order to improve energy utilization efficiency and give full play to the value of energy utilization, China will strive to achieve peak carbon dioxide emissions by 2030 and carbon neutrality by 2060[1]. At present, China's fossil energy system still accounts for more than 80% of primary energy, and the world's energy structure adjustment is imminent, breaking the independence of the original energy systems, building an energy system with unified dispatch and controlling energy system, and an integrated energy system. pregnancy.

The integrated energy system includes a variety of different forms of energy sources and various types of loads such as electrical load, heating load and cooling load, and has strong randomness and volatility. In addition, the access of distributed energy sources leads to complex operation scenarios of the integrated energy system, which brings challenges to the economical, safe and efficient operation of the integrated energy system. Reference [2] uses particle swarm optimization algorithm to solve the model for a new CCHP system with renewable energy and energy storage devices to achieve the economy of optimal operation. Reference [3] proposes a global optimization algorithm for active distribution network on a long time scale based on optimal power flow and a regional autonomous control algorithm for active distribution network on a short time scale based on power control error, which can effectively deal with the fluctuation of distributed energy.

Combining the above strategies, there are three links: active load prediction, rolling optimization and feedback correction. These three links together form a model predictive control to solve prediction errors and uncertain factors. Based on the model's prediction of the future dynamic behavior of the system, through By adding constraints to future input, output or state variables, the constraints can be expressed explicitly as a planning problem to be solved online[4]. Reference [5] adopts the MPC method, which combines forecasts and latest information to achieve real-time retail pricing. Reference [6] proposes a multi-time-scale optimization strategy based on MPC for CCHP system, which can effectively deal with the randomness of renewable energy and improve the stability of system operation through two-phase day-to-day scheduling. Reference [7] proposed an online optimization operation method based on MPC for CCHP system, and the prediction error was further reduced by rolling optimization and feedback correction, thereby alleviating the imbalance between supply and demand of various energy forms. This requires the integrated energy system to fully consider the difference between supply and demand in real life, and to correct the scheduling strategy in each time scale in real time. Therefore, model predictive control is introduced as a control algorithm for optimal scheduling in this paper.

2. INTEGRATED ENERGY SYSTEM ARCHITECTURE AND MODELING

CCHP system is the most common form of integrated energy system. It is mainly to coordinate other forms of supply and demand balance for the residual utilization value of natural gas, that is, to use equipment such as waste heat recovery devices for secondary utilization of natural gas-fueled equipment such as gas turbines. In the form of supplementing the input of the absorption chiller, the energy cascade utilization is realized. The coupling of the gas turbine and the absorption chiller is realized through the waste heat recovery unit, which can make full use of the primary energy and improve the system economy. On this basis, with the connection of energy storage system and renewable energy, it can not only realize the consumption of renewable energy through various forms of energy conversion, but also reduce energy consumption and improve the environmental protection of the system while meeting the load demand of users[8].

Based on this, this paper constructs an integrated energy system as shown in Figure 1, which mainly includes equipment such as gas turbines, absorption chillers, renewable energy generator sets, and batteries.

Fig 1 Typical CCHP System Structure

Specifically, the gas turbine uses natural gas as the raw material to supply power to the grid, while the waste heat recovery unit absorbs the heat generated during the power generation process to supplement the thermal energy capacity of the system. There are three types of loads on the user side: electricity, cooling and heat. The electricity load is guaranteed by gas turbines, power grids and renewable energy generator sets. At the same time, the battery helps to balance the supply and demand of electricity and realize peak shaving and valley filling; cooling load is guaranteed by electricity. Chillers and absorption chillers are met; heat load is supplied by gas boilers and waste heat recovery units. The integrated energy system integrates the form of cold, heat and electricity, and considers the deep coupling between modules, realizes energy cascade utilization and renewable energy consumption, and improves energy utilization efficiency and system environmental protection.

2.1 Micro Gas Turbine (MT)

MT is the core equipment of CCHP system. It has many advantages such as low cost, high efficiency, less pollution, simple maintenance, and flexible operation. The mathematical model of its input and output characteristics can be expressed as

$$Q_{MT}(t) = \frac{P_{MT}(t)(1-\eta_{MT}(t)-\eta_L)}{\eta_{MT}(t)} \tag{1}$$

In the formula, $Q_{MT}(t)$ and $P_{MT}(t)$ are the thermal power and electric power of the micro-combustion turbine at time t, respectively, and $\eta_{MT}(t)$ and η_L are the power generation efficiency and heat loss coefficient of the micro-combustion turbine at time t, respectively.

2.2 Heat Recovery Device (HR)

HR is mainly in the form of waste heat recovery boilers. Micro gas turbines generate a lot of waste heat while generating electricity. Waste heat recovery boilers use the exhaust heat of micro gas turbines to supplement the capacity of the system in the form of thermal energy, and are the key equipment to realize the cascade utilization of energy in the integrated energy system. The mathematical model of its input and output characteristics can be expressed as

$$Q_{HR}(t) = Q_{MT}(t)\eta_{HR} \tag{2}$$

In the formula, $Q_{HR}(t)$ is the thermal power of the waste heat recovery boiler at time t, and η_{HR} is the heat energy absorption and conversion efficiency of the waste heat recovery boiler.

2.3 Gas Boiler (GB)

Using natural gas as the raw material, GB converts the chemical energy in the natural gas into thermal energy, heats the water in the boiler to generate superheated steam, and participates in the energy supply of the integrated energy system in the form of thermal energy. The mathematical model of its input and output characteristics can be expressed as

$$Q_{GB}(t) = F_{GB}(t)\eta_{GB} \tag{3}$$

In the formula, $Q_{GB}(t)$) is the thermal power of the gas boiler at time t, $F_{GB}(t)$ is the natural gas consumption of the gas boiler at time t, and η_{GB} is the efficiency of the gas boiler.

2.4 Absorption Chiller (AC)

Except for the heat load of the user, the heat of the system is consumed by AC for the cooling load of the user. The most common absorption chiller is a bromine chiller. The mathematical model of its input and output characteristics can be expressed as

$$Q'_{AC}(t) = Q_{AC}(t)COP_{AC} \tag{4}$$

In the formula, $Q'_{AC}(t)$ is the output cooling power of the absorption chiller at time t, $Q_{AC}(t)$ is the input thermal power of the absorption chiller at time t, and COP_{AC} is the cooling power of the absorption chiller.

2.5 Electric Chiller (EC)

EC serves as an auxiliary device for supplying cooling load, and when the output cooling power of the absorption chiller is insufficient, it supplements the cooling power of the remaining demand to achieve a balance between cooling load and supply. The mathematical model of its input and output characteristics can be expressed as

$$Q'_{EC}(t) = P_{EC}(t)COP_{EC} \tag{5}$$

In the formula, $Q'_{EC}(t)$ is the output cooling power of the electric refrigerator at time t, $P_{EC}(t)$ is the input electric power of the electric refrigerator at time t, and COP_{EC} is the cooling performance coefficient of the electric refrigerator. Electric energy conversion efficiency is much greater than thermal energy utilization efficiency, so its value is greater than the refrigeration performance coefficient of absorption refrigerators.

2.6 Energy Storage (ES)

ES equipment has different energy storage forms based on different forms of energy storage, such as batteries can be used for electrical energy storage, heat storage tanks and cold storage tanks are used for heat and cold storage respectively. Due to the similar relationship between the input and output characteristics of electric energy storage, thermal energy storage, and cold energy storage, the mathematical model is comprehensively expressed as

$$W_{ES}(t) = (1-\delta)W_{ES}(t-1) + \left[P_{ES,cha}(t)\eta_{cha} - \frac{P_{ES,dis}(t)}{\eta_{dis}}\right]\Delta t \tag{6}$$

In the formula, $W_{ES}(t)$ is the energy storage of the energy storage device at time t, $P_{ES,cha}(t)$ and $P_{ES,dis}(t)$ are the charging and discharging power of the energy storage device at time t, respectively, and δ is The self-discharge rate of the energy storage device, η_{cha} and η_{dis} are the charge and discharge efficiencies of the energy storage device, respectively.

3. OPTIMAL SCHEDULING OF INTEGRATED ENERGY SYSTEM BASED ON MODEL PREDICTIVE CONTROL

3.1 Model Predictive Control

Model predictive control is a control strategy that predicts the future dynamics of the system based on current measurement values and is repeatedly optimized for execution. Because of the prediction in a limited time domain and continuous rolling optimization, model predictive control can well cope with the randomness and Disturbing factors such as volatility and uncertainty. In other words, it is a set of solving a series of optimization problems, that is, dividing the infinite time domain into finite time domains, and repeating the following strategy in each independent finite time domain: Refresh the optimization problem with the latest measured value at each sampling instant, solve the optimization problem, and get the optimal solution to act on the system. It mainly includes three parts: prediction model, rolling optimization and feedback correction.

3.2 objective function

With the goal of minimizing the total operating cost of the integrated energy system, an objective function is established, as shown in the following formula.

$$\min f = \sum_{t=1}^{N_T}[C_{FU}(t) + C_{ME}(t) + C_{EX}(t) + C_{ST}(t) - C_{HE}(t)]\,\Delta t \tag{7}$$

In the formula, f is the total cost of the integrated energy system, N_T is the upper limit of the scheduling period in the limited time domain, $C_{FU}(t)$ is the fuel cost of the period t, mainly the fuel cost of the gas turbine.

$$C_{FU}(t) = C_{gas}\frac{P_{MT}(t)}{\eta_{MT}(t)L_{HVNG}} \tag{8}$$

In the formula, C_{gas} is the unit price of natural gas, $P_{MT}(t)$ and $\eta_{MT}(t)$ are the electric power and power generation efficiency of the micro-combustion turbine in period t, respectively; L_{HVNG} is the calorific value of natural gas, which is 9.7kW·h/m^3 .

$C_{ME}(t)$ is the maintenance cost of the period t.

$$C_{ME} = \sum_{i=1}^{6} C_{me,i}P_i(t) \tag{9}$$

In the formula, $C_{me,i}$ and P_i are the unit energy maintenance cost and output power of the above components, respectively.

$C_{EX}(t)$ is the power purchase cost of time period t,

$$C_{EX}(t) = \frac{C_{in}(t) + C_{out}(t)}{2}P_{ex}(t) + \frac{C_{in}(t) - C_{out}(t)}{2}|P_{ex}(t)| \tag{10}$$

In the formula, $C_{in}(t)$ represents the electricity purchase price in time period t, $C_{out}(t)$ represents the electricity sales price in time period t, and $P_{ex}(t)$

represents the interactive power between the integrated energy system and the large power grid in time period t.

$C_{ST}(t)$ is the start-stop cost of controllable equipment in period t.

$$C_{ST} = \sum_{j=1}^{N} \max\{0, U_j(t) - U_j(t-1)\} C_{st,j} \tag{11}$$

In the formula, $U_j(t)$ represents the start-stop state of the controllable equipment j in the period t, and $C_{st,j}$ is the single start-up cost of the controllable equipment j.

$C_{HE}(t)$ is the cost of starting and stopping the controllable equipment in period t.

$$C_{HE}(t) = C_{he} Q_{he}(t) \tag{12}$$

In the formula, C_{he} is the unit selling price of heat energy provided, and $Q_{he}(t)$ is the heat load demanded by the user during period t.

3.3 Restrictions

The constraints mainly include energy balance constraints and constraints on the characteristics of the model itself. The specific constraints are as follows:

3.3.1 Power Balance Constraints

$$\sum_{i=1}^{6} P_i(t) - P_{ES,cha}(t) + P_{ES,dis}(t) + P_{ex}(t) = P_{load}(t) + P_{EC}(t) \tag{13}$$

The left equation represents the electrical power provided by each power generation unit of the system, and the right equation represents the electricity consumption in the system and the electrical load power required by users.

$$Q_{HS,dis}(t) + Q_{HR}(t) + Q_{GB}(t) = Q_{he}(t) + Q_{HS,cha}(t) \tag{14}$$

The cooling power balance constraint relationship is similar to that of the heating power, and will not be repeated here.

3.3.2 Energy Interaction Constraint

$$0 \le |P_{ex}(t)| \le P_{line,max} \tag{15}$$

In the formula, $P_{line,max}$ represents the maximum allowable power of the line, and it must be ensured that the interactive power of the two systems at any time is lower than the maximum allowable power.

3.3.3 Model Property Constraints

$$P_{MT,min} \le P_{MT}(t) \le P_{MT,max} \tag{16}$$

In the formula, $P_{MT,min}$ and $P_{MT,max}$ represent the minimum electric power output and maximum capacity of the micro gas turbine, respectively.

Taking a micro gas turbine as an example, the ramp rate constraints of each unit are as follows:

$$K_{MT,min}\Delta t \le P_{MT}(t) - P_{MT}(t-1) \le K_{MT,max}\Delta t \tag{17}$$

In addition, the energy storage system also needs to meet certain charge and discharge power constraints in the process of adjusting the balance of power supply and demand. The specific inequality relationship is as follows:

$$\theta_{dis} P_{ES,dis} \le P_{ES}(t) \le \theta_{cha} P_{ES,cha} \tag{18}$$

In the formula, θ_{dis} and θ_{cha} represent the discharge and charge ratios of the energy storage system, respectively, and $P_{ES,cha}$ and $P_{ES,dis}$ represent the upper and lower limits of the charge and discharge of the energy storage system, respectively.

$$E_{ES}(0) = E_{ES}(N_t \Delta t) \tag{19}$$

In the formula, $E_{ES}(t)$ represents the capacity of the energy storage device in the period t.

3.4 optimization solution

Among the parameters of each part of the integrated energy system, there are two types of decision variables: 0-1 binary variables and parameters that change continuously. Since the highest degree of the item containing the decision variable in the objective function is one, and the constraints are all linear constraints, the solved model is a mixed integer linear programming problem, which can be solved by using the Yalmip toolbox. The optimal scheduling model is established in MATLAB, and then GUROBI, CPLEX and other solvers are called to solve.

CPLEX is a relatively mature solution software for solving linear programming problems. It can easily deal with problems such as linear programming, mixed integer programming, quadratic programming, quadratic constraint programming and their combinations. Therefore, the CPLEX solver is selected for the mixed integer linear programming problem to solve the optimization problem of this paper.

4. CASE ANALYSIS

4.1 Basic data and example description

In this paper, the typical CCHP system structure shown in Figure 1 is selected as the research object, and an integrated energy system with distributed power generation equipment in a district in winter is taken as an example. The integrated energy system includes distributed power generation equipment (such as wind turbines and photovoltaic cells), micro gas turbines, waste heat recovery units, absorption chillers, electric chillers, and energy storage devices such as batteries and heat storage tanks to solve this example to analyze the effectiveness of the model predictive control method proposed in this paper. In the model parameters, the length of the time period of the total scheduling is set to 24 hours, and the length of the time period for each update of the scheduling strategy is 1 hour, that is, the optimal scheduling strategy should be updated 24 times according to the real-time nature of the integrated energy system in each scheduling period. . In addition, due to the power interaction between the microgrid and the large power grid and the different peak and trough electricity prices of electricity consumption, the electricity purchase and sale and the electricity price of each unit at different time periods are not static, so the regulations are subject to the formulation standard of the time-of-use electricity price.

The parameters of the controllable equipment in the integrated energy system are shown in Table 1. Since the maximum and minimum adjustment space for the output of wind turbines and photovoltaic cells in the integrated energy system is small, coupled with the non-centralized and small-scale distributed generator sets, the energy provided by them accounts for a small amount of the total system, so the distribution can be ignored. Climbing constraints for type power generation equipment.

Tab 1 Equipment operating parameters

Unit	$P_{MT,min}$ $/kW$	$P_{MT,max}$ $/kW$	K_{min} $/(\mathrm{kW}/min)$	K_{max} $/(\mathrm{kW}/min)$
MT	15	65	5	10
AC	15	65	5	10
EC	0	15	—	—
GB	0	55	3	5
EB	0	50	3	5
WT	0	40	—	—
PV	0	30	—	—
MG	-60	60	—	—

Considering the time-of-use electricity price, the grid division and electricity price of each time period are shown in Table 2

Tab 2 Time-of-use tariff

Period	Time /h		Purchase /(kW·h)	Selling /(kW·h)
Valley	0-7	23-24	0.17	0.13
Normal	7-10	15-18 21-23	0.49	0.38
Peak	10-15	18-21	0.83	0.65

In the constraints, the continuity of the starting point value and the end point value of the energy storage device is specified. Further, the initial state of the energy storage device is set as the charging state of the load nature, that is, the initial capacity is the lower limit of the maximum allowable capacity, and its parameters are shown in Table 3 shown.

Tab 3 Energy storage device parameters

Type	η_{cha}	η_{dis}	δ	θ_{cha}	θ_{dis}	$E_{ES}(0)$
ES	0.9	0.9	0.001	0.25	0.25	30
HS	0.9	0.9	0.01	0.25	0.25	0

The output forecast and load forecast of the distributed energy power generation equipment of the integrated energy system are shown in Figure 2 and Figure 3.

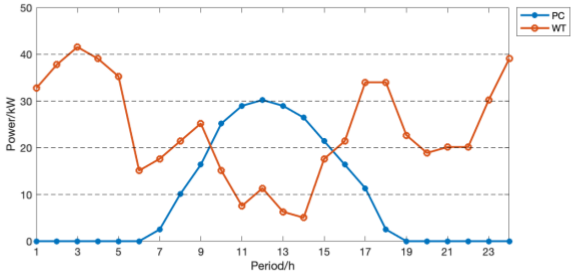

Fig 2 Distributed energy generation equipment forecast curve

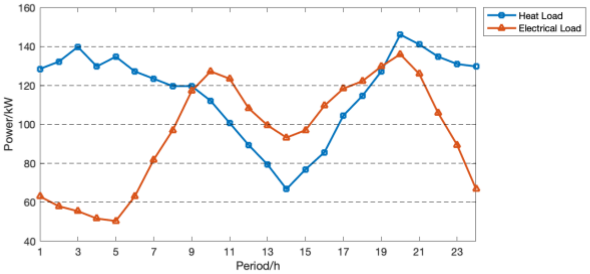

Fig 3 Load forecast curve

In order to evaluate the effectiveness of the optimal dispatch strategy for integrated energy systems based on model predictive control, this paper is divided into three operating modes for discussion and analysis:

(1) The integrated energy system scheduling strategy when the output of distributed energy equipment is constant. The output power of photovoltaic cells is set to be 15 kW in the period of 7-18, and no power is output in other periods. The output power of the fan is 25 kW throughout the period, and the load adopts Figure 3 Prediction curve value;

(2) The integrated energy system scheduling strategy when the user load is constant, set the electric load demand power as 100 kW, the thermal load demand power as 110 kW, and the distributed energy generation equipment adopts the predicted curve value in Figure 2;

(3) The optimal dispatching strategy of the integrated energy system based on model predictive control, the above-mentioned predicted curve values are used for distributed generation equipment and loads.

4.2 Result analysis

The optimal scheduling strategy proposed in this paper adopts Mode 3, and its electrical load balance and thermal load balance state are shown in Figure 4 and Figure 5. See Figures A1 to A4 in Appendix A for schematic diagrams of electrical load balance and thermal load balance for Mode 1 and Mode 2.

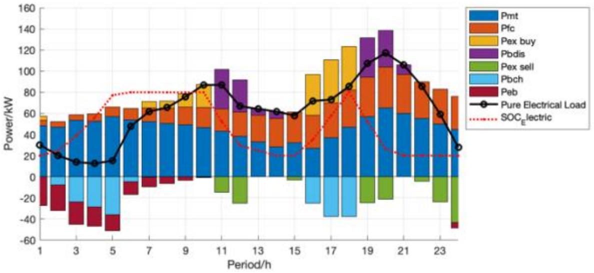

Fig 4 Power balance optimization scheduling results in mode 3

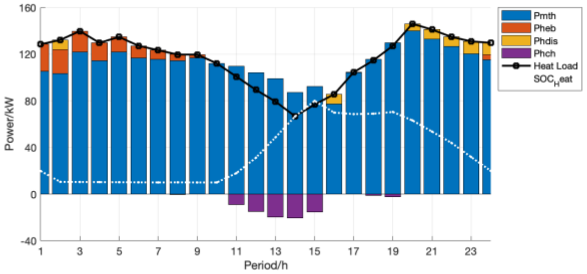

Fig 5 Heat balance optimization scheduling results in mode 3

The total operating cost of the integrated energy system of the three modes is shown in Table 4.

Tab 4 The total operating cost of the system in 3 modes

Mode	Total *operating* cost /¥
1	1118.6
2	1103.6
3	1008.3

Distributed power generation equipment includes wind turbines and photovoltaic cells, and photovoltaic cells do not work at night (i.e. 1-6 period). Only the wind turbine is in working state, so the output power of the distributed power generation equipment during this period is low. In addition, the night is the valley period of electricity consumption, and the battery is in the charging state in the form of load, so that when the power supply exceeds the demand, it can reach the Balance of supply and demand of electrical energy.

During the peak period (i.e. 10-15 period), the demand for electricity load gradually increases, but since the electricity price during this period is the highest, purchasing electricity from the power grid will result in a large electricity purchase cost, so the strategy adopted is that the battery will The stored energy is provided to the microgrid in the form of discharge, and the photovoltaic cells participate in the distributed energy generation output, so that the power supply of the microgrid is slightly greater than the electricity demand at this time, and the excess electricity is sold to the large grid at the highest electricity selling price. , this part can effectively reduce the operating cost of the system as a benefit.

During the normal period (i.e. 15-18 period), the capacity of the battery is not enough to provide electricity to the microgrid as a power supply device, and the electricity purchase price at this time is within an acceptable range, so the microgrid purchases electricity from the large grid, so that the electricity Energy balance can be achieved when supply is in short supply. At the same time, the battery is in a state of charge in the form of a load, in order to cope with the power supply during the peak period of the next period. The introduction of the battery breaks the time isolation of electric energy demand, can fully adjust the peak-to-valley difference of the electric load, realizes the function of electric energy peak-shaving and valley-filling, and reduces the total operating cost of the system.

It can be seen from Figure 5 that at night (i.e. the 1-6 period and the 20-24 period), the heat load demand of users in winter is relatively large. When the electricity purchase price is low (such as the 3-6 period), the electric boiler is used to make the electric energy participate in the thermal energy dispatch; in the period with the higher electricity purchase price (such as the 18-20 period), the waste heat recovery unit is fully utilized to realize the For the cascade utilization of thermal energy, electric boilers stop running to reduce the operating cost; in normal periods (such as 21-23 period), give full play to the role of the heat storage tank to reduce the electrical output of the micro-combustion engine, so that thermal energy participates in the dispatch of electrical energy .

During the daytime, the heat load demand is low. At this time, the heat energy of the system absorbs heat in the form of load through the heat storage tank, so as to achieve a heat balance state, and the stored heat energy is used for heat release in the subsequent period, realizing the energy transfer across time.

Horizontal comparison, from the perspective of the total operating cost of the system in Table 4 the model predictive control method in Mode 3 can more accurately track the output and real-time load demand of distributed generation equipment, and can give full play to the advantages of each equipment through reasonable scheduling. Unnecessary loss and waste of resources are eliminated, and the objective function is optimized (that is, the total operating cost of the system is minimized). However, method 1 does not consider the impact of the uncertainty of distributed energy output, and method 2 does not consider the impact of user load demand fluctuations, resulting in a high total system operating cost.

APPENDIX A

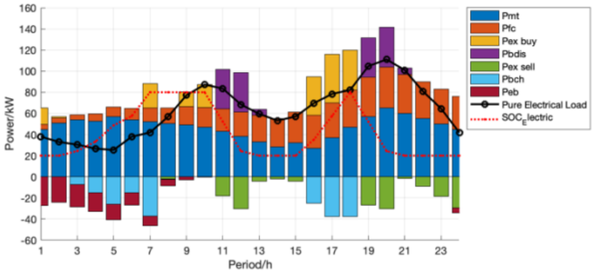

Fig 6 Power balance optimization scheduling results in mode 1

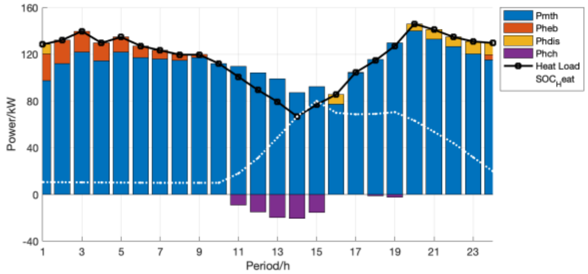

Fig 7 Heat balance optimization scheduling results in mode 1

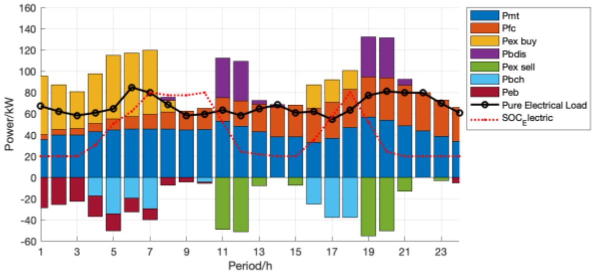

Fig 8 Power balance optimization scheduling results in mode 2

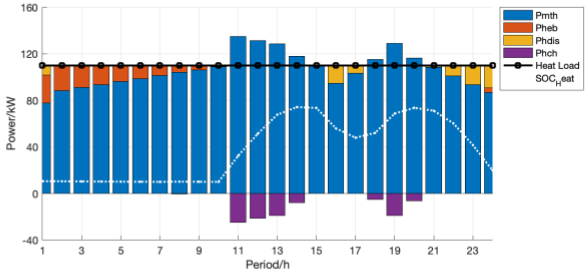

Fig 9 Heat balance optimization scheduling results in mode 2

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