

System Modeling and Optimal Dispatching of Multi-energy Microgrid with Energy Storage

Liting Tian, Lin Cheng, Jianbo Guo, and Kuihua Wu

Abstract—The coordinated operation and comprehensive utilization of multi-energy sources require systematic research. A multi-energy microgrid (MEMG) is a coupling system with multiple inputs and outputs. In this paper, a system model based on unified energy flows is proposed to describe the static relationship, and an analogue energy storage model is proposed to represent the time-dependency characteristics of energy transfer processes. Then, the optimal dispatching model of an MEMG is established as a mixed-integer linear programming (MILP) problem using piecewise linear approximation and convex relaxation. Finally, the system model and optimal dispatching method are validated in an MEMG, including district electricity, natural gas and heat supply, and renewable generation. The proposed model and method provide an effective way for the energy flow analysis and optimization of MEMGs.

Index Terms—Energy flow, energy storage, multi-energy microgrid (MEMG), optimal dispatching.

I. INTRODUCTION

MICROGRID is one of the most promising new grid paradigms for the integration of distributed renewable energy. A microgrid is a regionally limited energy system consisting of distributed energy resources, controllable loads and energy storage, etc. The optimal operation of a microgrid has been widely discussed. The balance of power generation and demand is focused in previous research. However, the energy consumed by heating/cooling system has the highest percentage among all building services and electric appliances [1]. In addition, a significant part of the electric power may be consumed for heating/cooling in a microgrid. And utilizing the flexibility of thermal demand can minimize the overall cost [2]. At the same time, multiple benefits can be achieved by the combined supply of electric and thermal energy such as combined cooling, heating and power (CCHP) generation. Interactions among electricity, gas and heating/cooling networks are increasing at the demand side [3], [4].

Therefore, the concept of microgrid should be extended beyond power grid. Recent works have been carried out on microgrids of multi-energy carriers. The designation of multi-energy microgrid (MEMG) in [5], [6] is adopted in this paper.

An MEMG can be regarded as a multi-energy system (MES)[7] at a limited level. In order to achieve a synergetic effect which is obtainable from different energy carriers, it is necessary to develop a mathematical representation of MEMG as one integrated system. Energy hub (EH) model is originally developed in [8], [9] for analyzing multi-energy conversion from the input-output perspective. The EH model is established in [10] for a small tri-generation plant in which the efficiencies of the components and dispatching factors are considered for optimal operation. References [11] and [12] describe an MEMG as an energy body via EH model, and a distributed dynamic event-triggered Newton-Raphson algorithm is proposed to realize islanded mode, network-connected mode switching in [12]. One of the limitations is that it is difficult to use the EH model to describe the internal relationships of a more complex system. An interesting development is reported in [13] by using a directed graph to model EH. Reference [14] applies the topological layering characteristic of directed acyclic graph (DAG) to describe the detailed input-output relationship of an EH. Relationship matrices can be obtained by energy flow topology represented as a directed graph [15]. It is shown that the graph theory provides a tractable method for expressing the complex topology relationships among multi-carrier energy flows and can help standardize the related matrices. However, most of the above studies assume a static and linear relationship of energy flows. To reduce the system investment and operation costs or energy consumption in the planning and operation of MEMGs, it is necessary to detailly reflect the characteristics of real energy components such as the nonlinearity of energy conversion and the dynamic characteristics of energy transmission, etc. Among these characteristics, the dynamics of energy transmission in an MEMG can not be ignored, as they form part of the flexibility of the system. For example, energy storage devices can transfer energy in a time horizon, resulting in dynamic change in energy status and time-dependency constraints. The significant differences in transmission speeds and inertias of various energy carriers also cause changes in energy flows at different time scales. In addition, the application of demand response also changes the balance between supply and demand of the system, which

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can be represented as demand-side flexibility. These issues have been discussed in the current literatures. Reference [16] presents a residential EH model to integrate energy storage and demand response, which augments the operation flexibility. A hybrid of nodal hydraulic head and thermal pipe flow equations are implemented in [17] for load flow analysis of highly coupled district energy networks. In [18], a two-stage iterative modeling method is implemented to integrate energy network constraints. Nevertheless, it still remains an open question how to describe the transfer process of total energy flow in an MEMG while ensuring the feasibility and efficiency of computation.

So far, system modeling methods lack the generality and are case-specific for the planning and operation of MEMGs. This paper aims to present a generalized modeling approach including static and dynamic characteristics and shed light on the feasibility of energy transfer process of an MEMG. For this purpose, unified energy flow is defined for the main components in MEMGs, and analogue energy storage model is proposed to describe the dynamic energy transfer process. A mixed-integer linear programming (MILP) framework is proposed for the optimization of integrated electricity, heat and gas dispatching.

Accordingly, the main contents of this paper are as follows. In Section II, each type of components in MEMGs is modeled. The system topology and limitations are described. Standard incidence matrix is defined to describe the balance of input/output energy and the continuity of energy flows. In Section III, the optimal dispatching model is proposed with the objective of minimizing the equivalent energy consumption. Then the optimal dispatching problem is transformed into the MILP problem. In Section IV, an MEMG test system is studied to verify the proposed approach. Two cases are compared, and the results and discussions are presented. Finally, Section V draws the conclusion.

II. SYSTEM MODELING OF MEMG

An MEMG can be considered as a multi-input, multi-output system. As shown in Fig. 1, the system inputs the energy in the form of electricity, natural gas and renewable energy, and outputs the energy for the demand of electric power, heating and cooling.

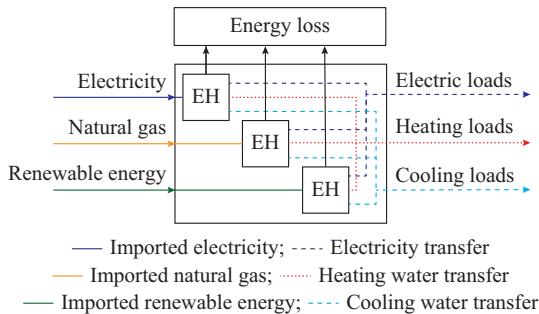


Fig. 1. Input and output black-box model for MEMG.

The input energy is converted and transferred to the energy loads. Part of the imported energy is lost and degraded in the processes. There may be multiple paths from one input

to one output of the system. The flexibility requires that the dispatching strategy should be considered when determining energy consumption and loss. For the studies of optimal dispatching, we do not focus on the distribution and variation of voltage, pressure, temperature, and other state quantities in the space horizon, but coupling energy flows in time horizon. Since there is no long-distance energy transmission in MEMGs, various forms of energy have the same dimension, which is the basis of unified modeling of an MES.

In this paper, we define the energy flow as a vector with magnitude and direction and the junctions of energy flows as nodes. According to the law of energy conservation, the algebraic sum of inflow energy is equal to the sum of outflow energy at a node. The energy flow between two nodes can be modeled as a simple directed connection shown in Fig. 2, where $\dot{f}_{ij,t}^{start}$ is the steady-state energy flow flowing out of the sending-node i at time t ; and $\dot{f}_{ij,t}^{end}$ is the steady-state energy flow flowing into the receiving-node j at time t .



Fig. 2. Diagram of energy flow.

As the direction of energy flow is consistent with the directed connection, we will not illustrate the direction of energy flow in subsequent sections. The directed connection and nodes can be used to represent energy components in MEMG. Energy loss and degradation may occur in the direction of energy flow, thus $\dot{f}_{ij,t}^{start} \neq \dot{f}_{ij,t}^{end}$. The loss and degradation can be described by energy conversion efficiency η_{ij} , which can be modeled as a function of the output energy flow and related environmental parameters:

$$\eta_{ij} = g_{ij}(\dot{f}_{ij,t}^{end}, \theta) \quad (1)$$

where θ is the related environmental parameters; and $g_{ij}(\cdot)$ is the energy conversion efficiency function.

Four basic types of components in MEMGs are categorized as below: energy conversion component, energy storage component, energy transmission component, and energy consumption component.

A. Energy Conversion Component

An energy conversion component is a set of devices which converts certain forms of energy into other forms of energy. And there may be multi-stage conversion links within the component. Sometimes, one energy flow is converted into multiple energy flows. A typical energy conversion component is a combined heat and power (CHP) plant, in which the generation of electricity is accompanied with the generation of heat. Therefore, CHP can be modeled with two outflows connected to an internal node, as shown in Fig. 3, where k and h are vertexes.

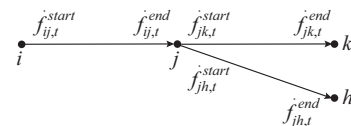


Fig. 3. Model of energy conversion component.

The input energy of fuel is divided into two parts at the internal node j . We can obtain:

$$\dot{f}_{ij,t}^{end} = \dot{f}_{jk,t}^{start} + \dot{f}_{jh,t}^{start} \quad (2)$$

where $\dot{f}_{jk,t}^{start}$ and $\dot{f}_{jh,t}^{start}$ are the split energy flows. The relationship between $\dot{f}_{jk,t}^{start}$ and $\dot{f}_{jh,t}^{start}$ can be formulated by the following equation, which represents the relationship of the split energy flows at node j :

$$g_j(\dot{f}_{jk,t}^{start}, \dot{f}_{jh,t}^{start}) = 0 \quad (3)$$

where $g_j(\cdot)$ is a function of the split energy flows.

B. Energy Storage Components

There are different types of energy storage in MEMGs such as electro-chemical energy storage, heat storage, and gas storage. In this paper, the energy storage components are divided into two categories: ① type I is to charge and discharge the energy through the same device such as a battery storage system connected to the grid via a power converter; ② type II is to charge and discharge the energy through different devices such as a heat storage electric boiler which converts and stores heat via an electric heater, but releases the heat through an exchanger connected to thermal pipes. Accordingly, two models are proposed, as illustrated in Fig. 4. The ground symbol in Fig. 4 represents the energy storage node. Although energy storage enables the decoupling between charging and discharging energy flows, it introduces temporal coupling constraints. For instance, the state of energy (SOE) of the type I component can be formulated as:

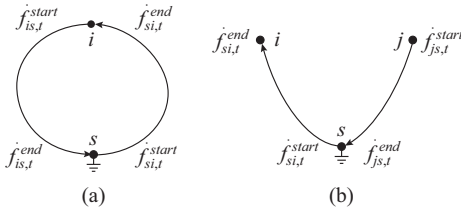


Fig. 4. Energy storage component model. (a) Type I. (b) Type II.

$$\frac{dS_{s,t}}{dt} = \dot{f}_{is,t}^{end} - \dot{f}_{si,t}^{start} - \lambda S_{s,t} \quad (4)$$

where $S_{s,t}$ is the SOE of the energy storage node s ; $\dot{f}_{is,t}^{end}$ is the charging energy flow; $\dot{f}_{si,t}^{start}$ is the discharging energy flow; and λ is the energy dissipation coefficient to the external environment. The right-hand side in (4) indicates that the loss of stored energy occurs regardless of the presence of charging/discharging energy flow.

C. Energy Transmission Component

There are significant differences in the transmission of different forms of energy. Electric power transmits at a speed close to that of light. Hydraulic processes of gas and heat pipes transmit at the speed of sound, while thermal processes transmit at the speed of mass flow. In this paper, the energy flow of electric transmission is defined as active power. And the energy flow of gas transmission is defined as the product of the mass flow and unit combustion enthalpy. Both electric and gas network can be considered stable in MEMG at the dispatching time scale (usually a few min-

utes). Thus, an energy transmission branch can be described by the basic model shown in Fig. 2, where the transient process of energy transfer is ignored. However, heat network involves a much slower transient process depending on the water flow speed in the pipe (less than a few meters per second). Therefore, the transfer delays may be obvious even with a distance of several kilometers in MEMGs.

As shown in Fig. 5, hot water flows through the supply pipeline to the receiving-end and flows back to the sending-end through the return pipeline. The mass is considered incompressible, so the mass flow rate is equal along the pipeline. Thus, we can obtain the energy flows at the sending-end and the receiving-end:

$$\dot{f}_1 = C_p \dot{m}(T_1^s - T_1^r) \quad (5)$$

$$\dot{f}_2 = C_p \dot{m}(T_2^s - T_2^r) \quad (6)$$

where $\dot{m}$ is the mass flow, $\dot{m} = \dot{m}_1^s = \dot{m}_1^r = \dot{m}_2^s = \dot{m}_2^r$; C_p is the specific heat capacity of water; and T_1^s , T_2^s , T_1^r , and T_2^r are the mass temperatures at each end, and the superscripts s, r denote the supply pipeline and the return pipeline, respectively.

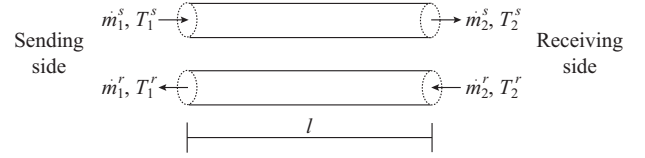


Fig. 5. Supply pipeline and return pipeline for heat transmission.

The heat energy transfer process in a pipeline can be described by a partial differential equation at time t and on the axial position x of the pipeline [19]:

$$C_p \rho A \frac{\partial T}{\partial t} + C_p \dot{m} \frac{\partial \Delta T}{\partial x} + \mu(T - 2T_0) = 0 \quad (7)$$

where A is the cross section area of the pipeline; ρ is the mass density; μ is the heat-loss factor per unit length of the pipeline; T is the sum of the average supply water temperature and the average return water temperature; ΔT is the temperature difference between the supply water and the return water; and T_0 is the surrounding temperature.

Assuming the change of temperature along the pipeline is uniform, the partial differential item $\partial \Delta T / \partial x$ can be approximated as $(T_2^s - T_2^r) - (T_1^s - T_1^r) / l$, where l is the length of the pipeline. Then, substituting (5) and (6) into (7), we can obtain:

$$C_p \rho A l \frac{dT}{dt} + \dot{f}_2 - \dot{f}_1 + \mu l(T - 2T_0) = 0 \quad (8)$$

It can be seen that (8) is similar to (4). Therefore, by defining the SOE of the pipeline as $S_p = C_p \rho A l(T - 2T_0)$, we can use the energy storage model to describe the characteristics of heating/cooling energy transfer, as shown in Fig 6.

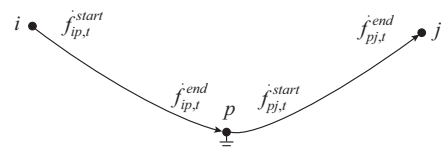


Fig. 6. Heating/cooling transmission model.

It can be seen that heat transmission process can be modeled as energy storage model of type II. With the energy flows depicted in Fig. 6, we can rewrite (8) as:

$$\frac{dS_{p,t}}{dt} = \dot{f}_{ip,t}^{end} - \dot{f}_{pj,t}^{start} - \frac{\mu}{C_p \rho A} S_{p,t} \quad (9)$$

For gas and heat pipeline, additional energy needs to be consumed to maintain a certain pressure and mass flow rate. Compared with the total energy consumption, this part of loss is relatively fixed and small, so it is not included in the model.

D. Energy Consumption Component

Considering demand response, the system can output the energy with some flexibility, which has a similar effect to energy storage and can be defined as an analogue to energy storage. For example, some electrical loads only need to meet the electricity demand in a certain period of time. In this case, the load can be considered as energy storage that is not allowed to discharge. For the heating/cooling demand of buildings, the thermal inertia of buildings can be described as an analogue to energy storage. A first-order equivalent thermal parameter (ETP) model [20] can be used to describe the thermal inertial of buildings, as shown in Fig. 7, where T_{in} and T_{out} are the indoor and outdoor temperatures, respectively; C_b is the equivalent thermal capacitance of the building; R_b is the equivalent thermal resistance; and P_b is the heat power flow into the building.

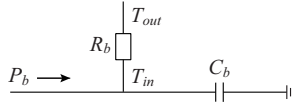


Fig. 7. First-order ETP model of buildings.

ETP model is an electrical analogy of a building, thus we can obtain:

$$C_b \frac{dT_{in}}{dt} + \frac{1}{R_b} (T_{in} - T_{out}) = P_b \quad (10)$$

Therefore, we can apply the energy storage model of type I to describe the thermal inertial of buildings, as shown in Fig. 8. In order to be consistent with the energy storage model of type I, a discharging edge with zero energy flow is added, as shown by the dashed line in Fig. 8.

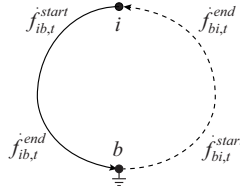


Fig. 8. Energy consumption model.

Defining SOE of the building as $S_{b,t} = C_b (T_{in} - T_{out})$, we can obtain:

$$\frac{dS_{b,t}}{dt} = \dot{f}_{ib,t}^{end} - \frac{S_{b,t}}{C_b R_b} \quad (11)$$

E. System Modeling

So far, the components in MEMGs are modeled with nodes and connections. The overall model of the system can be obtained by integrating individual components according to the relationship of the topology. And the system can be modeled as a directed graph which is equal to energy storage node set $\mathbb{S}$. $\mathbb{V}$ is the vertex (nodes other than energy storage nodes) set; and $\mathbb{E}$ is the edge (connection) set.

According to the directed graph theory, the system can be described with standardized matrices. For a graph containing n vertices and m edges, the relationship between the vertices and edges can be represented by an incidence matrix, denoted as $A = (\alpha_{ve})_{n \times m}$.

The element α_{ve} at the directed edge $e(i,j)$ (connecting node i and node j) and vertex v is given by:

$$\alpha_{ve} = \begin{cases} 1 & v=i \\ -1 & v=j \\ 0 & \text{else} \end{cases} \quad (12)$$

We extend the incidence matrix A to a n by $2m$ matrix denoted as $B = (b_{ve}, b'_{ve})_{n \times 2m}$. The element (b_{ve}, b'_{ve}) for the directed edge $e(i,j)$ is given by:

$$b_{ve} = \begin{cases} 1 & v=i \\ 0 & \text{else} \end{cases} \quad (13)$$

$$b'_{ve} = \begin{cases} -1 & v=j \\ 0 & \text{else} \end{cases} \quad (14)$$

For the energy loss occurring in the edge, we define the weight of $e(i,j)$ as w_{ij} :

$$w_{ij} = -\ln(\eta_{ij}) \quad (15)$$

where η_{ij} is the energy conversion efficiency of $e(i,j)$, $e(i,j) \in \mathbb{E}$. Then we can obtained:

$$\dot{f}_{ij,t}^{start} = e^{w_{ij}} \dot{f}_{ij,t}^{end} \quad (16)$$

In order to integrate the input and output flow of the system shown in Fig. 1, let the input vertex set be $\mathbb{K}$, $\mathbb{K} \subseteq \mathbb{V}$. Let the output vertex set be $\mathbb{H}$, $\mathbb{H} \subseteq \mathbb{V}$. For convenience, the input energy flow vectors are represented as $\dot{F}_t^{in} = [\dots, \dot{f}_{k,t}^{in}, \dots]$, $k \in \mathbb{K}$, and the output energy flow vectors are represented as $\dot{F}_t^{out} = [\dots, \dot{f}_{h,t}^{out}, \dots]$, $h \in \mathbb{H}$, where $\dot{f}_{k,t}^{in}$ is the input energy flow at vertex k , and $\dot{f}_{h,t}^{out}$ is the output energy flow at vertex h . The energy flow vector at edges are represented as $\dot{F}_t = [\dots, \dot{f}_{ij,t}^{start}, \dot{f}_{ij,t}^{end}, \dots]$, $i, j \in \mathbb{V} \cup \mathbb{S}$. Arranging the rows of matrix B as:

$$B = \begin{bmatrix} B^0 \\ B^{in} \\ B^{out} \end{bmatrix} \quad (17)$$

where B^0 includes the rows of vertices which do not belong to the input vertices or the output vertices; B^{in} includes the rows of the input vertices; and B^{out} includes the rows of the output vertices. Energy storage vertices should be processed separately because the inflow energy is not equal to the out-flow energy at these vertices.

There may be multiple paths from one of the system's input vertices to one of the system's output vertices. Let $\mathbb{P}$ be one of the paths from input vertex k to output vertex h . $\mathbb{P}$

represents the set of edges that constitutes the path. The length of $\mathbb{P}$ is defined as:

$$L = \sum_{e(i,j) \in \mathbb{P}} w_{ij} \quad (18)$$

Substituting (15) into (18), we can obtain:

$$L = -\ln \left(\prod_{e(i,j) \in \mathbb{P}} \eta_{ij} \right) \quad (19)$$

Therefore, when the system outputs the energy flow of the unit, the input energy can be expressed as e^L , and the energy loss at the path can be expressed as $e^L - 1$. Thus, when the energy flow on each edge is known, the energy flow can be decomposed into various paths to analyze the energy loss at each path.

So far, MEMG modeling based on weighted directed graph has been completed. In addition to the static relationship described by the graph model, the system dynamics, including energy storage, heat transmission delay, and building thermal inertia, are described uniformly by the ordinary differential equation (ODE) of SOE.

III. OPTIMAL DISPATCHING MODEL OF MEMG

MEMG is an MES limited to a certain range. With load forecasting, the energy demand is determined, and the day-ahead energy management [21] can be implemented. In this subsection, the optimal dispatching model is established based on the proposed system model.

A. Equivalent Multi-energy Consumption

From a holistic perspective, the total input energy consumption reflects the energy utilization level of the system. Although the total amount of input energy can be obtained by summarizing the input energy flows, it is not possible to distinguish various forms of energy in terms of price, quality, etc. Therefore, a common basis for the comparison is necessary. The equivalent multi-energy consumption (EMEC) [22] during a certain time interval is defined as:

$$EMEC_t = \sum_{k \in \mathbb{K}} \alpha_k \dot{f}_{k,t}^{in} \Delta t \quad (20)$$

where $\dot{f}_{k,t}^{in}$ is the input energy flow of vertex k at time t ; Δt is the length of the time interval; and α_k is the transform coefficient of the input energy at vertex k , which provides a unified basis for the consumption of various energy forms.

B. Formulation of Optimal Dispatching Problem

Assuming the output energy flows of the system are known, the elements in the vector $\dot{\mathbf{F}}_t$ become the variables to be solved at each time interval.

According to the graph model presented in Section II, similar to Kirchhoff's law of current, we can obtain the balancing equation of the system as:

$$\begin{bmatrix} \mathbf{B}^0 \\ \mathbf{B}^{in} \\ \mathbf{B}^{out} \end{bmatrix} \dot{\mathbf{F}}_t = \begin{bmatrix} \mathbf{0} \\ \dot{\mathbf{F}}_t^{in} \\ \dot{\mathbf{F}}_t^{out} \end{bmatrix} \quad (21)$$

The objective is to minimize the daily EMEC. With the equation $\dot{\mathbf{F}}_t^{in} = \mathbf{B}^{in} \dot{\mathbf{F}}_t$, the objective of the dispatching prob-

lem can be expressed as:

$$\min \sum_{t=1}^N EMEC_t = \sum_{t=1}^N \mathbf{a} \mathbf{B}^{in} \dot{\mathbf{F}}_t \Delta t \quad (22)$$

where N is the number of time intervals during the dispatching period; and $\mathbf{a}$ is the transform coefficient vector, $\mathbf{a} = [\dots, \alpha_k, \dots]$, $k \in \mathbb{K}$.

In addition to the balancing constraint in (21), the constraints of the optimization problem include the performance of the conversion, transmission and storage components, which are described as follows.

Firstly, the energy flows at each edge must vary between a minimum value and a maximum value:

$$\beta_{ij} c_{ij}^{\min} \leq \dot{f}_{ij,t}^{\text{end}} \leq \beta_{ij} c_{ij}^{\max} \quad (23)$$

where $c_{ij}^{\min}$ and $c_{ij}^{\max}$ are the minimum and maximum of energy flow from vertex i to vertex j , respectively. $i, j \in \mathbb{V} \cup \mathbb{S}$; and $\beta_{ij} \in \{0, 1\}$ is the binary variable, which indicates whether the component presented as $e(i, j)$ is available.

The ramp-up/ramp-down limitations of the energy flows can be expressed as:

$$r_{ij}^{\text{lower}} \leq \dot{f}_{ij,t}^{\text{end}} - \dot{f}_{ij,t-1}^{\text{end}} \leq r_{ij}^{\text{upper}} \quad (24)$$

where r_{ij}^{lower} is the ramp-down limitation; and r_{ij}^{upper} is the ramp-up limitation.

Note that only the energy flow at the receiving-node of an edge is constrained. The energy flow at the sending-node can be limited by (1). Since η_{ij} is not constant, (1) is nonlinear. When multiple energy flows are divided at a vertex, the vertex is called a split vertex. Additional constraints should be considered between the split energy flows as given in (3). A more generalized expression is given by:

$$g_j(\dots, \dot{f}_{jk,t}^{\text{start}}, \dots) = 0 \quad (25)$$

where $j \in \mathbb{M}$, $e(j, k) \in \mathbb{E}$, and $\mathbb{M}$ is the set of split vertices.

Energy storage vertices should be processed separately. ODEs in (4), (9) and (11) can be transformed into a difference form as:

$$S_{s,t+1} - S_{s,t} = \dot{f}_{is,t}^{\text{end}} \Delta t - \dot{f}_{sj,t}^{\text{start}} \Delta t - \gamma_s S_{s,t} \Delta t \quad (26)$$

where $i, j \in \mathbb{V} \cup \mathbb{S}$; $S_{s,t}$ is SOE at energy storage node s at time t , $s \in \mathbb{S}$; and γ_s is the energy dissipation coefficient to the environment. Equation (26) can be seen as a state transfer function of the energy storage.

SOE must vary within the limits of energy storage:

$$S_s^{\min} \leq S_{s,t} \leq S_s^{\max} \quad (27)$$

where $S_s^{\min}$ and $S_s^{\max}$ are the minimum and maximum of SOE at vertex s , respectively.

For the energy storage model of type I, there is $i=j$, i.e., both charging and discharging processes are via a common device, thus the following constraint should be considered:

$$\dot{f}_{is,t}^{\text{end}} \dot{f}_{sj,t}^{\text{start}} = 0 \quad i=j \in \mathbb{V} \quad (28)$$

Sometimes, energy storage needs to be restored to the initial state at the end of the dispatching period:

$$S_{s,0} = S_{s,N} \quad (29)$$

where $S_{s,0}$ is the initial energy state at node s .

Finally, (21) and (23)-(29) constitute the constraints of the optimal problem in (22).

C. Model Linearization

Note that the objective function in (22) and the constraints in (21), (23), (24), (26), (27), (29) are linear, but the constraints in (16), (25) and (28) are nonlinear. Thus, the proposed optimal dispatching model should be regarded as a mixed-integer nonlinear programming problem. To reduce the computation burdens and improve the solution quality, the above nonlinear problem will be linearized into MILP.

In (16), the efficiency is defined as the ratio of output energy flow with respect to input energy flow. In fact, the efficiency of most energy conversion processes depends on the part-load rating of the device [23]. As a result, nominal or average efficiency values can lead to poor representative models for the efficiency increase and decrease across the operation range. Piece-wise linear (PWL) approximation can be implemented to capture the part-load efficiency of the variable. For example, the power generation efficiency of an internal combustion engine is illustrated in Fig. 9. The model in Fig. 2 is used to represent the energy conversion process of the engine. As shown in Fig. 9, a set of $Z+1$ values at the points $\{f_{ij}^{end,1}, f_{ij}^{end,2}, \dots, f_{ij}^{end,Z+1}\}$ and the corresponding efficiency values $\{\eta_{ij}^1, \eta_{ij}^2, \dots, \eta_{ij}^{Z+1}\}$ are selected. Segment z is the linear segment from $f_{ij}^{end,z-1}$ to $f_{ij}^{end,z}$, where η_{ij}^{z-1} is set as the constant efficiency for the segment.

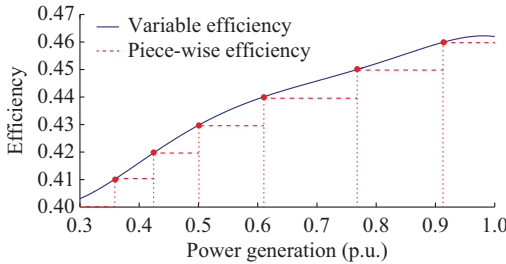


Fig. 9. PWL approximation of energy conversion efficiency.

Thus, at each time t , PWL approximation of (16) can be defined as:

$$f_{ij,t}^{start} = \sum_{z=1}^{Z+1} \frac{\bar{\omega}_{ij}^z}{\eta_{ij}^z} f_{ij,t}^{end,z} \quad (30)$$

where $\sum_{z=1}^{Z+1} \bar{\omega}_{ij}^z = 1$, $\bar{\omega}_{ij}^z \geq 0$ for $z = 1, 2, \dots, Z+1$. Defining binary adjacency variables $\chi_{ij}^z \in \{0, 1\}$ for $z = 1, 2, \dots, Z+1$, $\sum_{z=1}^{Z+1} \chi_{ij}^z = 1$, we can obtain:

$$\bar{\omega}_{ij}^1 \leq \chi_{ij}^1, \bar{\omega}_{ij}^2 \leq \chi_{ij}^1 + \chi_{ij}^2, \dots, \bar{\omega}_{ij}^z \leq \chi_{ij}^{z-1} + \chi_{ij}^z, \dots, \bar{\omega}_{ij}^{Z+1} \leq \chi_{ij}^{Z+1} \quad (31)$$

PWL approximation can also be implemented to describe the nonlinear relationship of the split energy flows in (25). For example, a CCHP plant consists of a micro-turbine, a heat recovery unit and an absorption chiller. The micro-turbine generates the electric power by burning the mixture of natural gas and compressed air, and the exhaust gases are further fed into the heat recovery unit or the absorption chiller to provide heating or cooling energy. Thus, part of the energy is transformed to shaft horsepower to electric power, and the other part is transformed into heat. The relation-

ship between the output electric power and heat is illustrated in Fig. 10.

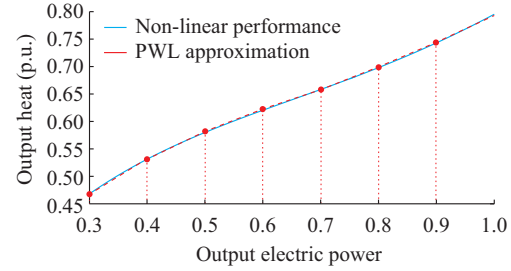


Fig. 10. PWL approximation of split energy flow.

CCHP can be represented by the model in Fig. 3. According to the nonlinear relationship between output power and heat, Y segments are set. Segment y is the linear approximation of the relationship between $f_{jk}^{start,y}$ and $f_{jh}^{start,y}$ with κ_j^y defined as the slope. Thus, at each time t , the PWL approximation of (25) can be obtained as:

$$\dot{f}_{jh,t}^{start} - \sum_{y=1}^{Y+1} \kappa_j^y \bar{\omega}_j^y f_{jk,t}^{end,y} = 0 \quad (32)$$

And the additional constraint is:

$$\bar{\omega}_j^1 \leq \chi_j^1, \bar{\omega}_j^2 \leq \chi_j^1 + \chi_j^2, \dots, \bar{\omega}_j^y \leq \chi_j^{y-1} + \chi_j^y, \dots, \bar{\omega}_j^{Y+1} \leq \chi_j^{Y+1} \quad (33)$$

where $\sum_{y=1}^{Y+1} \bar{\omega}_j^y = 1$; $\bar{\omega}_j^y \geq 0$; $\chi_j^y \in \{0, 1\}$; $\sum_{z=1}^{Z+1} \chi_{ij}^z = 1$; and $y = 1, 2, \dots, Y+1$.

The constraint of energy charging and discharging in (28) is nonlinear and nonconvex. In fact, with a goal of minimizing energy consumption, charging and discharging at the same time is clearly not the optimal solution because it results in additional energy losses. That is, the global optimum of the optimal dispatching problem can be obtained after convex relaxation, i.e., the constraint in (28) can be ignored. In order to make the proof process more concise, the constraints related to the charging and discharging energy flows in Fig. 4(a) at time t are rewritten as:

$$\sum_{k \neq s, e(k,i) \in \mathbb{E}} \dot{f}_{ki,t}^{end} + \dot{f}_{si,t}^{end} - \dot{f}_{is,t}^{start} - \sum_{h \neq s, e(i,h) \in \mathbb{E}} \dot{f}_{ih,t}^{start} = 0 \quad (34)$$

$$\dot{f}_{is,t}^{start} \geq 0 \quad (35)$$

$$\dot{f}_{sl,t}^{end} \geq 0 \quad (36)$$

$$S_{s,t} \Delta t^{-1} + \dot{f}_{is,t}^{start} \eta_{is} - \dot{f}_{si,t}^{end} \eta_{si}^{-1} - \gamma_s S_{s,t} \Delta t^{-1} - S_s^{\min} \Delta t^{-1} \geq 0 \quad (37)$$

$$-S_{s,t} \Delta t^{-1} - \dot{f}_{is,t}^{start} \eta_{is} + \dot{f}_{si,t}^{end} \eta_{si}^{-1} + \gamma_s S_{s,t} \Delta t^{-1} + S_s^{\max} \Delta t^{-1} \geq 0 \quad (38)$$

where $\sum_{k \neq s, e(k,i) \in \mathbb{E}} \dot{f}_{ki,t}^{end}$ is the sum of energy flows injected into vertex i in addition to the discharging flow; and $\sum_{h \neq s, e(i,h) \in \mathbb{E}} \dot{f}_{ih,t}^{start}$ is the sum of energy flows out of vertex i in addition to the charging flow.

Denote the Lagrangian function for $EMEC_t$ in (20) as L and the Lagrangian multipliers for (34)-(38) as $\theta_1, \theta_2, \theta_3, \theta_4$, and θ_s , respectively. The Karush-Kuhn-Tucker (KKT) conditions for determining the optimum charging and discharging energy flows are:

$$\frac{\partial L}{\partial \dot{f}_{is,t}^{start}} = -\theta_1 + \theta_2 + (\theta_4 - \theta_5)\eta_{is} = 0 \quad (39)$$

$$\frac{\partial L}{\partial \dot{f}_{si,t}^{end}} = \theta_1 + \theta_3 - (\theta_4 - \theta_5)(\eta_{si})^{-1} = 0 \quad (40)$$

$$\theta_2 \dot{f}_{is,t}^{start} = 0 \quad (41)$$

$$\theta_3 \dot{f}_{si,t}^{end} = 0 \quad (42)$$

If $\dot{f}_{is,t}^{start} \dot{f}_{si,t}^{end} \neq 0$, according to (41) and (42), it yields $\theta_2 = 0$ and $\theta_3 = 0$. Further, substituting $\theta_2 = 0$ and $\theta_3 = 0$ into (39) and (40), it can be derived that:

$$(\theta_4 - \theta_5)\eta_{is}^{-1} = (\theta_4 - \theta_5)\eta_{si} \quad (43)$$

Obviously, (43) is not possible, since the charging and discharging efficiency is always less than 1.0.

Thus, the assumption $\dot{f}_{is,t}^{start} \dot{f}_{si,t}^{end} \neq 0$ can not hold. The proof by contradiction means that $\dot{f}_{is,t}^{start} \dot{f}_{si,t}^{end} = 0$ is a necessary condition for the optimum solution, i.e., the convex constraint in (28) can be ignored. The exact convex relaxation is obtained.

D. Solution Method

With PWL approximation and convex relaxation, the optimal dispatching problem can be transformed into an MILP problem. Due to high performance, commercial solvers like CPLEX can be employed to solve the MILP problem. A representation of the modeling approach is shown in Fig. 11. Network and device data are required to establish the topology and constraint of the system. And demand profiles and meteorological data are used to predict energy demand and renewable energy generation in the system.

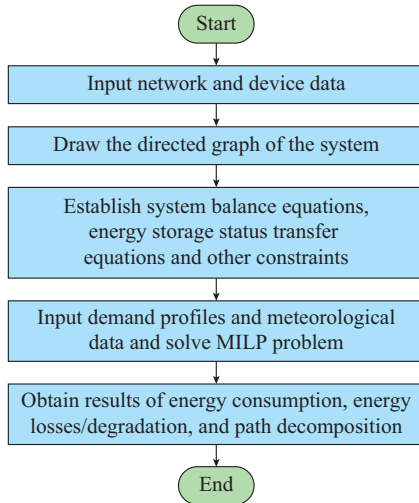


Fig. 11. Flow chart of optimal dispatching of MEMG.

IV. CASE STUDIES

To illustrate the graph model and employ it to the optimal dispatching problem, an MEMG test system is used to demonstrate the proposed approach. MEMG consists of a distribution-level transformer, a photovoltaic (PV) generation system, a wind turbine (WT) generation system, a battery energy storage system (BESS), a gas boiler (GB), an electric boiler (EB), a CHP plant, a ground source heat pump (HP) and heating, electric loads in a building, as shown in Fig.

12. Local gas, electric utilities and solar, wind resources are the energy sources of MEMG.

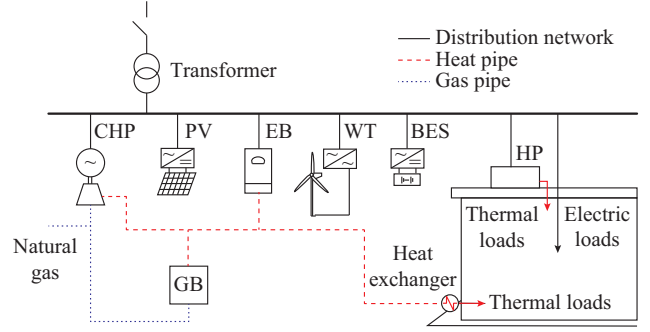


Fig. 12. Layout of test system for MEMG.

The directed graph representation of MEMG is illustrated in Fig. 13, where V_1 , V_2 , and V_3 , and V_4 are the input nodes representing the electric power, natural gas, solar radiation and wind inputs of the system, respectively; and V_{15} and V_{16} are the output nodes for electric and thermal loads, respectively. The energy storage nodes V_{17} , V_{18} , and V_{19} are used to represent BES, the analogue of the heat pipe, the analogue of the building respectively, which are deduced in Section II. The system has 19 vertices and 23 edges in total.

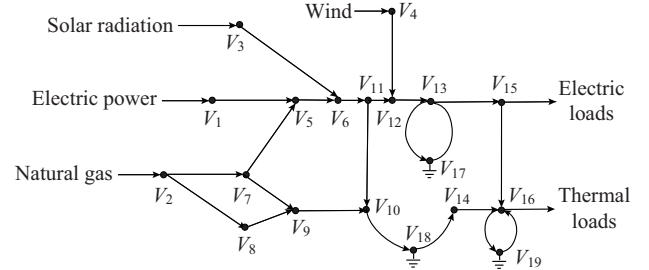


Fig. 13. Diagram of MEMG test system modeled by directed graph.

The optimal dispatching is conducted in the 24-hour horizon with a unit scheduling interval of 5 min. Energy flows on each edge are considered as schedulable variables with all constraints.

A. Data Input

The input and output energy flows, including input solar radiation, wind power as well as the electric/thermal loads can be obtained by forecasting. The daily solar radiation and wind power are shown in Fig. 14. The input solar radiation power is the total irradiation power on the tilt surfaces of the installed PV panels, and the input wind power is the total air kinetic energy that flows through installed WTs per unit of time. The data are obtained from [24] and modified with practical considerations. The base power is 1000 kW. The load profiles of the system are shown in Fig. 15. Note that the heating loads of the building are included in the energy storage model at V_{19} . As a result, the thermal loads in Fig. 15 include only the loads other than heating such as domestic hot water. The heating demand for maintaining an indoor temperature of 21 °C of the building is also shown in Fig. 15.

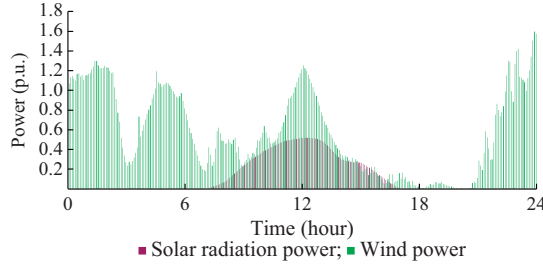


Fig. 14. Predicted solar radiation and wind power.

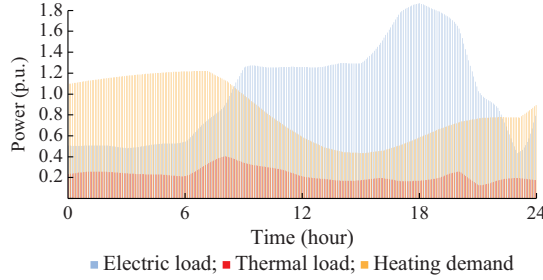


Fig. 15. Predicted load profiles.

The efficiencies, operation range and ramp rates of each edge are listed in Table I. The efficiencies are variable within a certain range obtained from [25]. When losses are ignored, the efficiencies are set to be 1, e.g., the efficiency at $e(2, 8)$, $e(5, 6)$, etc. The efficiency at $e(15, 16)$ represents the coefficient of performance (COP) of the ground source HP which absorbs the heat from the ground. Because the energy in the environment is not included in the proposed model, the efficiency is greater than 1. In Table I, all the energy flows are referenced at 1000 kW and NA means there is no constraint on the item.

V_7 is a split vertex representing the combined power and heat generation of CHP, the relationship of the split energy flows can be referred to [23]. As aforementioned, γ_s is the energy loss factor for the environment. For the BES vertex V_{17} , γ_{17} is the self-discharging rate of the batteries which is usually very low. And $\gamma_{17} = 0$ is given in this paper. The initial SOE of BES is set to be 1.8 MWh, and the upper and lower bounds are set to be 0.36 MWh and 3.6 MWh. The vertex V_{18} represents the energy storage analogue of the heat pipelines, and the related parameters are referred to [19]. The temperature of the supply water flow is set between 78 °C and 105 °C with an initial value of 86 °C. The vertex V_{19} represents the energy storage analogue of the building, where the related parameters are referred to [20]. The indoor temperature is set to be 21 °C.

The case study considers the equivalent fossil energy consumption as EMEC. The input energy of the studied system involves electricity, natural gas, solar radiation and wind. And the transform coefficient of each energy source to EMEC needs to be given. The coefficients in (20) are set as 2.5 considering that the power generation efficiency of the power supply from the grid is 0.4. The transform coefficient of solar radiation is set to 0, so the system also maximizes the use of renewable energy sources, since the consumption of renewable energy is not included in the objective.

TABLE I
RELATED PARAMETERS FOR EACH EDGE

Edge	Efficiency	Maximum output (p.u.)	Minimum output (p.u.)	Ramp-up rate (p.u. per min)	Ramp-down rate (p.u. per min)
$e(1, 5)$	0.972-0.973	2.50	-2.50	NA	NA
$e(2, 7)$	0.898-0.951	2.60	0.78	0.26	0.26
$e(7, 5)$	0.856	1.20	0.36	0.12	0.12
$e(7, 9)$	0.932	1.40	0	0.14	0.14
$e(2, 8)$	1.000	NA	NA	NA	NA
$e(8, 9)$	0.468-0.982	0.78	0.16	0.08	0.08
$e(5, 6)$	1	NA	NA	NA	NA
$e(3, 6)$	0-0.139	1.20	0	NA	NA
$e(6, 11)$	1	NA	NA	NA	NA
$e(11, 10)$	0.468-0.983	0.80	0	0.16	0.16
$e(9, 10)$	1	NA	NA	NA	NA
$e(11, 12)$	1	NA	NA	NA	NA
$e(4, 12)$	0-0.482	1.50	0	NA	NA
$e(12, 13)$	1	NA	NA	NA	NA
$e(13, 17)$	0.884-0.908	1.25	0	1.25	1.25
$e(17, 13)$	0.884-0.890	1.25	0	NA	NA
$e(10, 18)$	1	1.60	0	NA	NA
$e(18, 14)$	1	1.60	0	NA	NA
$e(13, 15)$	1	NA	NA	NA	NA
$e(14, 16)$	0.980	1.60	0	NA	NA
$e(15, 16)$	2.610-4.340	0.80	0.16	0.24	0.24
$e(16, 19)$	1	1.60	0	NA	NA
$e(19, 16)$	1	0	0	NA	NA

For EMEC, the case study considers the equivalent fossil energy consumption. The input energy of the case system involves electricity, natural gas, solar radiation and wind, considering that the power generation efficiency of the power supply from the grid is 0.4, so α_k in (20) are set to be 2.5, 1, 0, 0, for $k = 1, 2, 3, 4$, respectively. Therefore, the system maximizes the use of renewable energy sources, since the consumption of renewable energy is not included in the objective.

B. Optimal Dispatching Results

To verify the feasibility of the proposed method, two cases for the dispatching problem are compared in this paper. Case 1: BES and energy storage effect of the pipelines and buildings are not utilized, i.e., SOEs remain at its initial value. Case 2: energy storage and similar effects are all utilized, i.e., the SOEs are allowed to change between the upper and lower bounds.

All the units in MEMG are assumed to be available before the dispatching. The optimal dispatching problem is solved by CPLEX 12.6. The calculation is run on an Intel (R) CORE(TM) i7-8550U 1.90 GHz personal computer with 16 GB memory.

Figures 16 and 17 show the electric and heat dispatching results for Case 1. The electric load of the system is provided by CHP, PV, WT and TR. EB and HP consume electricity

to provide heat and become additional loads. During peak power period, when renewable energy generation is low, CHP outputs electricity at its maximum power; renewable energy output is low; and TR provides other electric loads. At midday and night, some kinds of renewable energy generation are curtailed because they are not allowed to be reversed to the grid. EB operates intermittently to compensate for heat at a certain time.

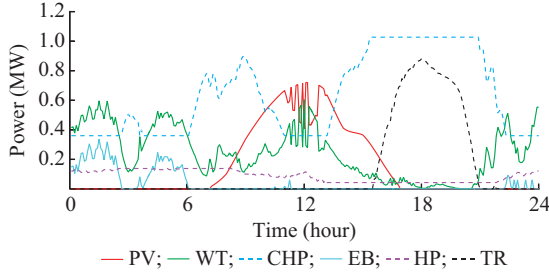


Fig. 16. Daily electric dispatching results for Case 1.

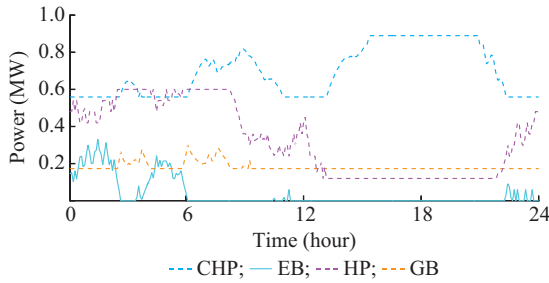


Fig. 17. Daily heat dispatching results for Case 1.

Figures 18 and 19 show the electric and heat dispatching results for Case 2. There are not any curtailments of renewable energy in Case 2. Comparing Fig. 16 with Fig. 14, the power provided by TR is significantly reduced in Case 2. As shown in Fig. 19, EB is out of work during the day. HP outputs at its maximum power during the early hours of the morning. And GB outputs the heat at its minimum power throughout the day.

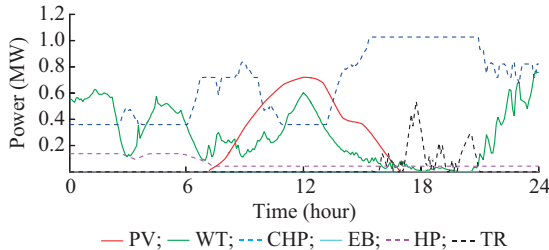


Fig. 18. Daily electric dispatching results for Case 2.

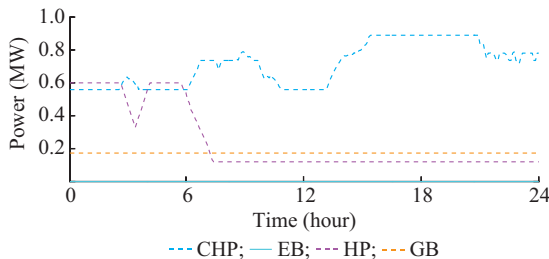


Fig. 19. Daily heat dispatching results for Case 2.

In Case 2, BES and the energy storage effect of the heat pipelines and the building are utilized. SOE and the charging and discharging power of BES are illustrated in Fig. 20. BES discharges during peak load and is charged when the renewable energy is sufficient at noon and night.

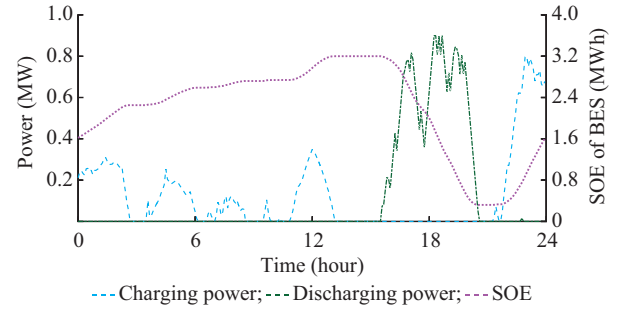


Fig. 20. SOE and charging and discharging power of BES.

For the heat pipelines, corresponding to the energy flows of $e(10, 18)$ and $e(18, 14)$, the heat exchange power at the source side and the load side are shown in Fig. 21. The power difference between the two sides causes SOE of the pipelines to change, which is reflected in fluctuations in the temperature differences of the supply and return water.

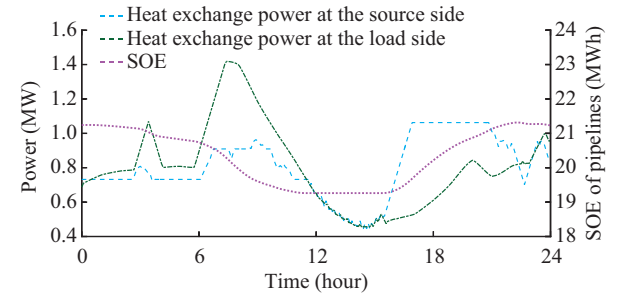


Fig. 21. SOE and heat exchange power of pipelines.

The heating demand of the building is supplied by both the district heat pipelines and HP. As illustrated in Fig. 22, the heating demand varies with the temperature of the outdoor environment. When the building absorbs more heat than the amount of heat, it transmitted to the environment. Then, the room temperature of the building increases. It can be seen that in order to reduce energy consumption, for most of the time, the indoor temperature is maintained at its minimum temperature of 20 °C, and the indoor temperature rises to about 23 °C during some time intervals.

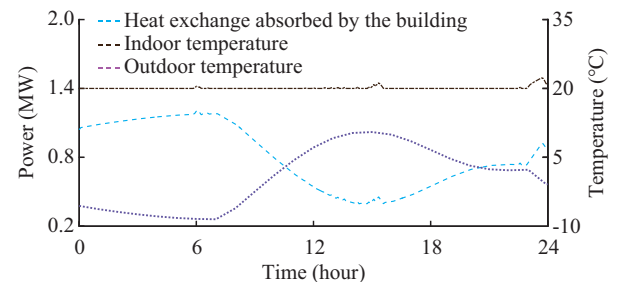


Fig. 22. Indoor temperature and absorbed heat power.

Table II compares the dispatching results of Case 1 with Case 2. EMEC is reduced by 5.64 MWh in Case 2. By dispatching charging and discharging power of BES and utilizing the water temperature change of the pipelines and the thermal inertia of the building, the renewable energy curtailment is avoided. The disposal of CHP waste heat is reduced. And both the electricity and heat consumption are saved. These are the main reasons for the reduction of EMEC.

TABLE II
RESULTS COMPARISON OF CASE 1 AND CASE 2

Case	EMEC (MWh)	Curtailed renewable energy (MWh)	Curtailed heat (MWh)	Electric consumption (MWh)	Heat consumption (MWh)
1	53.36	3.45	3.76	28.12	25.69
2	47.23	0	1.77	26.70	24.78

C. Analysis of Energy Flow Paths

To learn more about how each input energy flow is utilized, the energy flow paths in the system are traced. Based on the topology of the graph model, all the feasible paths from any input vertex to any output vertex can be obtained. Note that the existence of energy storage model of type I makes the system graph cyclic. A total of 34 paths are searched. By input and output vertices, the paths are divided into 8 subsets, as shown in Table III. Since the paths are independent of each other, the energy flows decomposed in each path can be calculated using the continuity and additivity of energy flows. However, the allocation result is not unique because the number of the corresponding equations is less than that of energy flows to be allocated. For a higher energy efficiency, the power supply from the grid is always supposed to provide as much electric load as possible. Hence, among the feasible allocation solutions, the one which maximizes the total input energy flow in the path subset $\mathbb{L}_1$ is selected as the allocation result. The allocated energy flows along each path are calculated, and the total input energy consumption of each path subset during the dispatching period is given in Table III. In Case 1 and Case 2, all power supply is used for electric loads, while the energy of natural gas is used for both heat and electric loads. Part of the renewable generation is transferred to the heat loads. It can be seen that Case 2 consumes more natural gas, and more renewable energy is used for the electric loads.

TABLE III
PATH SET AND INPUT ENERGY ALLOCATION

Path subset	Input vertex	Output vertex	No. of path	Input energy (MWh)	
				Case 1	Case 2
$\mathbb{L}_1$	V_1	V_{15}	2	3.39	0.75
$\mathbb{L}_2$	V_1	V_{16}	6	0	0
$\mathbb{L}_3$	V_2	V_{15}	2	17.01	18.67
$\mathbb{L}_4$	V_2	V_{16}	10	20.57	20.15
$\mathbb{L}_5$	V_3	V_{15}	2	19.51	24.52
$\mathbb{L}_6$	V_3	V_{16}	6	7.34	4.16
$\mathbb{L}_7$	V_4	V_{15}	2	10.79	12.68
$\mathbb{L}_8$	V_4	V_{16}	4	1.16	1.10

D. Analysis of Energy Loss and Degradation

In addition to the amount of imported energy, energy loss and degradation are also important factors in energy consumption research. Energy degradation can be expressed as the loss of exergy. And the exergy of energy carriers such as renewable energy, natural gas, electricity and hot water can be referred to [24]. With the decomposed energy flows, energy loss and degradation can be clearly reflected. As mentioned in Section II, the energy losses along a path can be obtained by path length calculation. Table IV shows the cumulative energy and exergy losses of the path subsets during the dispatch period for Case 1 and Case 2.

TABLE IV
ENERGY LOSS AND EXERGY LOSS

Path subset	Energy loss (MWh)		Exergy loss (MWh)	
	Case 1	Case 2	Case 1	Case 2
$\mathbb{L}_1$	0.09	0.08	0.09	0.08
$\mathbb{L}_2$	0	0	0	0
$\mathbb{L}_3$	3.16	3.61	3.16	3.61
$\mathbb{L}_4$	3.22	4.02	19.77	19.41
$\mathbb{L}_5$	16.79	21.22	15.80	20.03
$\mathbb{L}_6$	4.74	2.35	6.92	3.84
$\mathbb{L}_7$	5.59	6.65	1.99	2.42
$\mathbb{L}_8$	-0.94	-0.59	0.64	0.59

As HP absorbs the energy from the environment, negative energy loss occurs in the subset $\mathbb{L}_8$. The total energy losses in Case 1 and Case 2 are 32.67 MWh and 37.34 MWh, respectively. And the total exergy losses in Case 1 and Case 2 are 48.44 MWh and 49.99 MWh, respectively. In general, the energy charging and discharging process will result in additional losses. However, with the nonlinearity performance, the components can work in a more efficient way due to the change of energy flow brought by energy storage components, thus the overall system losses can also be reduced. In order to reduce EMEC and energy loss simultaneously, it is necessary to consider the corresponding objectives in the dispatch model. This will be carried out in the future research.

V. CONCLUSION

This paper presents a generalized system modeling and optimal dispatching method for MEMG considering energy storage. The steady-state multi-carrier energy flows are focused in the study and the dynamics of heat transmission and thermal flexibility are included. It is found that the heat transmission and thermal inertia have a similar effect to energy storage, and they are defined as analogues to energy storage. The system is modeled by weighted directed cyclic graph and state transfer functions of energy storage. The system model is applied in the optimal dispatching problem which is established as an MILP problem by PWL approximation and convex relaxation. It is verified that the proposed model and approach are reasonable for a meaningful MEMG system and an effective way is provided for the analysis of energy consumption. In the future work, more applications

in the optimal planning and operation of MEMG will be explored.

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