INTELLIGENT MODELING METHOD OF ENERGY HUB BASED ON DIRECTED MULTI-GRAPH

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An energy hub (EH), consisting of a combination of electricity, heat power, cooling power, natural gas, and other energy sources, is considered a key component of the Energy Internet (EI). It requires quick and accurate optimization and control as well as a standardized and programmable model. This study proposes an intelligent modeling method based on a directed multigraph. This method starts from an input–output model and then establishes a directed multigraph in which a vertex indicates energy and an edge indicates energy conversion equipment and its parameters. Then, an adjacency matrix is obtained by processing and simplifying the directed multigraph. This adjacency matrix is searched using an intelligent algorithm to obtain the coupling matrix model of the EH. A hydrodynamic laboratory consisting of electricity, natural gas, heating, and cooling energy is used as a case study to verify the reliability and accuracy of the modeling process and to provide standardized data for deep learning uses in the EI. The obtained results show that the proposed method can quickly and effectively establish the EH model. This method is also effective when an energy storage device is added to or removed from the EH.

Key words: *Energy Internet, energy hub, intelligent algorithm, matrix model, directed multigraph*

1. Introduction

Fossil energy sources cause considerable pollution and are becoming increasingly scarce. Therefore, countries worldwide are actively developing renewable and clean energy technologies such as photovoltaic power, hydropower, wind power, tidal power, waste pressure and waste heat power, and large-scale energy storage. As a result, energy systems are becoming increasingly complex. In particular, various forms of energy such as electricity, natural gas, hydropower, wind energy, thermal energy, and cold energy are being coupled, interconverted, and used to supplement each other. Therefore, studies are focusing on how to calculate the relationship between energy sources and allocate various energy sources quickly and accurately. In addition, recent years have seen significant developments in areas such as large-scale data processing, complex network structure processing, distributed computing, and artificial intelligence. The application of such technologies to energy systems seems promising. This has led to the emergence of the concept of Energy Internet (EI). The article “Building the energy internet” in

The Economist first proposed the EI concept in 2004 [1]. Subsequently, Jeremy *et al.* proposed the ideal state of EI, that is, renewable energy is fully utilized, energy utilization rate is maximized, energy distribution is optimized, and system stability is greatly improved [2].

In the EI architecture, the basic unit is called the energy hub (EH) [3]. The EH concept has been widely used in subsequent studies [4–9]. Studies have also investigated an EH graph, that is, the topological relationships in an EI. For example, Geidl *et al.* studied an EI comprising three EHs and three types of energy [10]. In this study, the energy amount of EH was used to calculate the energy transfer between EHs, and a method for optimizing the energy distribution was proposed. Denis *et al.* used a binary tree diagram to study the energy distribution of an EI and developed a program to realize an automatic synthesis process [11]. Michele *et al.* applied a distributed control method to an EI system and decomposed the overall optimization problem of the entire system into subproblems according to the control agents [12].

However, in our project research, we found that the EH data used in the EI was not the load of the EH but the energy supply to the EH. Because the structure of each EH is different and the coupling relationship between the energy and the equipment in an EH is complicated, the energy supply to the EH will change with the load and parameters. This raises challenges in our project. Therefore, we investigated the structure of the EH. In recent years, some studies have already focused on EH modeling. The earliest model used to represent an EH is the input–output mathematic model proposed by Wassily *et al.* [13]. This model express a complex system as a set of linear equations; however, its representation is insufficiently intuitive. Geidl proposed the highly effective coupling matrix model [10] and later described this model more completely [14]. The coupling matrix model has been widely used to represent EHs because it can intuitively and clearly describe the parameter transfer relationship among multiple energy sources. Studies of the EH coupling matrix model have investigated computer programs for obtaining the coupling matrix of a complex system.

In the present study, an intelligent EH modeling method based on a directed multigraph is established. The multigraph model is built by transforming the input–output model. Then, a simplified directed multigraph without a duplicate energy vertex or loops is built by using the simplified multigraph model. Finally, the energy coupling matrix can be obtained by searching for the adjacency matrix from the simplified directed multigraph. The modeling process is described using the example of a complex system that combines electricity, fuel thermal content, cooling and heat energy.

The proposed modeling method affords the following advantages:

- It can obtain the data needed for EI research under various loads and control parameters through a unified method and procedure. Furthermore, it can be used to manage the energy flow by controlling processes such as adjustment, transformation, storage, and distribution.
- The coupling relationship and parameters between different energy types are clear owing to the form of the energy coupling matrix.
- The coupling matrix can be obtained by searching for the adjacency matrix in the form of repetition and iteration, making it suitable for computer programming in artificial intelligence research.
- The rows and columns of the adjacency matrix are expressed in terms of energy and input/output. The energy type is fixed after the topological form of the EH is determined. Therefore, the size of the adjacency matrix will not change even with new energy storage equipment or users with special needs join the EH.

- When a device is added or removed, only some adjacency matrix data require modification, and the adjacency matrix need not be reestablished.

2. EH Modeling Method

2.1. Establishment of multigraph model based on an input–output model

We treat the EH as a multiple input–multiple output (MIMO) system with multiple energy sources, conversion devices, storage devices, and complex coupling. To clearly describe the types and coupling relationships of various equipment and energy sources, an EH could be represented by an input–output model as shown in Fig. 1. This EH contains a cogeneration unit (CHP) and a compression electric refrigeration unit (CERG) with four types of energy sources.

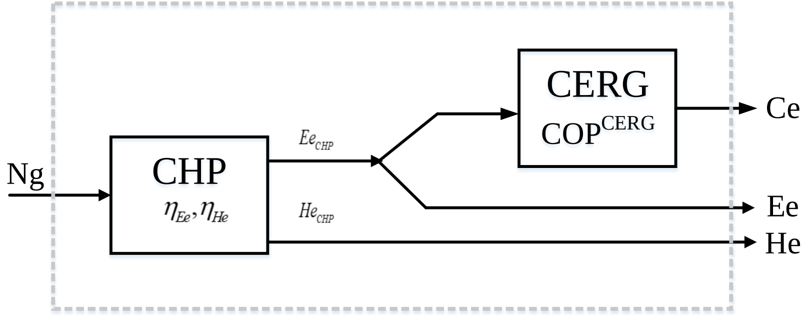


Fig. 1 Input–output model of the EH

The multigraph model is built as follows:

- Add a virtual input vertex V(I) and a virtual output vertex V(O).
- Represent all energy types of the EH as a vertex in the graph.
- Express the energy transfer relationship as an edge in the graph. The name and energy conversion efficiency of an edge that is passed must be indicated.
- When energy sources diverge to different edges, add loops with the same number of bifurcations on the corresponding vertex and assign the dispatch factor.

Accordingly, the multigraph for the given EH is established as shown in Fig. 2.

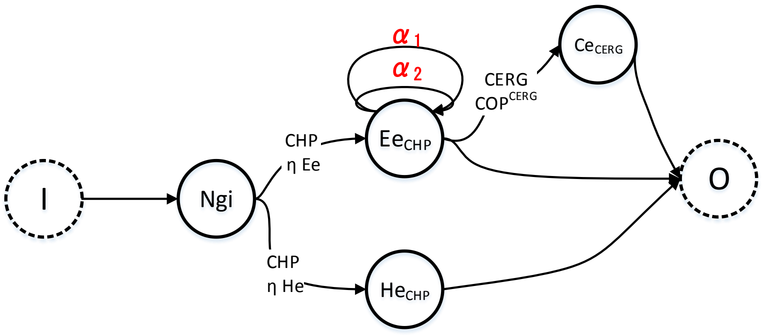


Fig. 2 EH multigraph model

2.2. Parameter flow in the multigraph model

In the EH, each energy type flows along a certain path. The energy flow involves energy conversion, efficiency change, energy loss, and other processes. This study aims to establish a coupling matrix for the EH. The parameters of each path must be found and expressed in the form of a product, meaning that the parameters on the edge could flow along the direction of energy flow, whereas the product result of the parameters on the whole path is invariant. In this manner, loops in the multigraph can be removed. For the example multigraph in Fig. 2, the parameter flow is as follows:

- Starting from the input vertex, the parameters on the edge flow along the outgoing direction of the end vertex of the edge; the parameter does not move if the end vertex of the edge has a loop. For example, as shown in Fig. 2, the parameter P(CHP, η_{He}) of edge E(Ng_i - He_{CHP}) flows to the edge E(He_{CHP} - O) to form the end vertex V(He_{CHP}). The parameter of edge E(Ng_i - Ee_{CHP}) cannot flow because the end vertex V(Ee_{CHP}) has loops.
- Owing to the number of energy bifurcations, that is, loops is same to the output of this energy vertex, the parameters of all loops on a vertex could be assigned to the output edge of this vertex. The parameters P(α1) and P(α2) of the loops of the vertex V(Ee_{CHP}) are assigned to the edge E(Ee_{CHP} - Ce_{CERG}) and E(Ee_{CHP} - O), after which the loops can be deleted.
- After the parameters are assigned, a parameter such as P(CHP-CERG), P(CHP-O) that is used to indicate the input and output devices should be added to each edge, as shown in Fig. 3.

2.3. Merging of duplicate energy vertices in the multigraph

The proposed modeling method establishes a coupling matrix between different energy sources. However, the same energy type may be obtained from different devices in an EH; for example, heat energy is output from both the CHP and the auxiliary heat boiler equipment (AB). Duplicate energy vertices must be merged into one vertex.

During the merging process, all vertices with the same energy type are immediately merged into one new vertex, and all edges connected to these vertices are connected to the new vertex because no loops exist and no edges are connected between vertices of the same energy type.

The simplified directed multigraph shown in Fig. 3 can be obtained after duplicate energy vertices are merged in the multigraph.

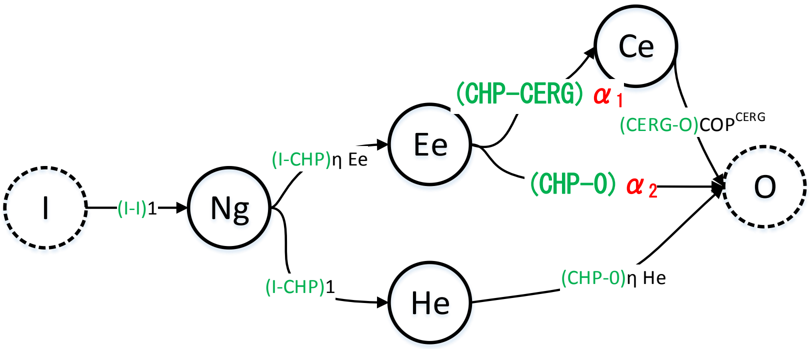


Fig. 3 Simplified directed multigraph

2.4. Adjacency matrix of the directed multigraph

The adjacency matrix clearly shows the direct energy conversion relationship. The corresponding elements in the adjacency matrix are the energy conversion equipment and their parameters. The adjacency matrix is obtained from the directed multigraph as follows:

- Assume that there exists an EH continuing n types of energy sources, a virtual input, and a virtual output. Then, a matrix with size (n + 2) × (n + 2) can be obtained. In this matrix, the first row and column represent the input, the last row and column represent the output, and the n rows and n columns in the middle represent the n types of energy sources in the same order. For example, the EH shown in Fig. 3 contains four types of energy sources. Therefore, the adjacency matrix is a matrix with six rows and six columns named $C_{I\text{-}O}$, where the order of energy sources is I, Ee, Ng, He, Ce, and O.

- The parameters on each edge in the corresponding position in the adjacency matrix are marked. For example, the parameter of edge E(I - Ng_i) is P((I-I)1); therefore, "(I-I)1" is marked in the first row and third column of the adjacency matrix, that is, $C_{I\text{-}O}$(I,Ng). Similarly, the parameter corresponding to $C_{I\text{-}O}$(He,O) is P((CHP - O)η_{He}). The element is P(0) when no edge exists between energy vertices. The adjacency matrix is $C_{I\text{-}O}$, as given by Eq. (1).

$$\underbrace{\left[\begin{array}{c|cccccc} & I & Ee & Ng & He & Ce & O \\ \hline I & 0 & 0 & (I-I)1 & 0 & 0 & 0 \\ Ee & 0 & 0 & 0 & 0 & (CHP-CERG)\alpha 1 & (CHP-O)\alpha 2 \\ Ng & 0 & (I-CHP)\eta_{Ee} & 0 & (I-CHP)1 & 0 & 0 \\ He & 0 & 0 & 0 & 0 & 0 & (CHP-O)\eta_{He} \\ Ce & 0 & 0 & 0 & 0 & 0 & (CERG-O)COP^{CERG} \\ O & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right]}_{C_{I-O}} \tag{1}$$

2.5. Energy flow path obtained by searching adjacency matrix $C_{I\text{-}O}$

After the adjacency matrix is established, an intelligent algorithm obtains the coupling matrix model consisting of the energy flow path by searching the adjacency matrix as follows:

- Start from the first row of the adjacency matrix and search from left to right. When nonzero elements are found, mark the energy conversion form, record the input and output devices and parameters, and record the position of this nonzero element as the current position. For example, as given by Eq. (1), the first nonzero element is in the first row and second column; therefore, the current position is $C_{I\text{-}O}$(I,Ng), the input is "I," the output is "I," and the parameter is "1." Then, the energy conversion process is given by Eq. (2).

$$\mathrm{I}\xrightarrow[1]{I-I} Ng \tag{2}$$

- Use the column number of the current position as the row number of the new iteration. Then, search for the element from the leftmost position in the new row for which the input device is the same as the output device of the current location. Record the position of the searched element as the new current position and mark the energy conversion form, and record the input and output devices and parameters similarly. For the above example, search left to right from the third row (Ng) because the current position is $C_{I\text{-}O}$(I,Ng). The input of $C_{I\text{-}O}$(Ng,Ee) is "I"; this is the same as the output of $C_{I\text{-}O}$(I,Ng), and therefore, the current position changes to $C_{I\text{-}O}$(Ng,Ee). The energy conversion process is given by Eq. (3).

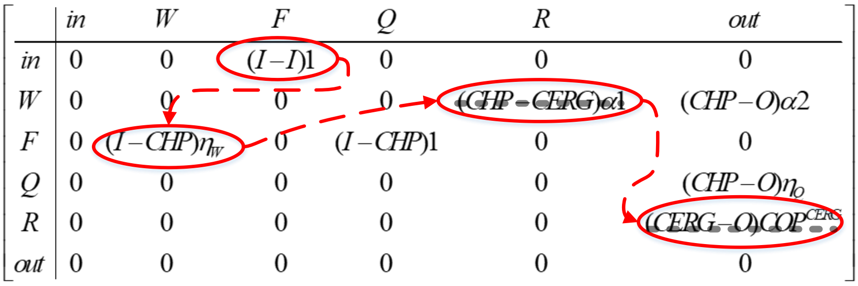
$$Ng \xrightarrow[\eta_{Ee}]{I-CHP} Ee \tag{3}$$

- Repeat the aforementioned process until the output of the current position is “O.” The entire energy flow path is obtained by connecting all energy conversion endways as given by Eq. (4).

$$\text{Path1:I} \xrightarrow[1]{I-I} Ng \xrightarrow[\eta_{Ee}]{I-CHP} Ee \xrightarrow[\alpha 1]{CHP-CERG} Ce \xrightarrow[COP^{CERG}]{CERG-O} \text{O} \tag{4}$$

- Check whether an element of the path should be deleted when the adjacency matrix is updated. If the output (input) of an element on the path is the same as the input (output) of an element outside the path in the row (column) corresponding to the column (row) of the element on the path, this element on the path remains in the new adjacency matrix; otherwise, it is set to “0” in the new adjacency matrix.

For the example above, along path1, the parameter of element $C_{I\text{-}O}$(I,Ng) is P((I-I)1). Therefore, whether the output in column “I” or the input in row “Ng” is “I” outside path1 is checked. The input of $C_{I\text{-}O}$(Ng,Ee) is “I”; then, the parameter P((I-I)1) of $C_{I\text{-}O}$(I,Ng) remains in the new adjacency matrix. With regard to the parameter P((CHP-CERG)α1) of $C_{I\text{-}O}$(Ee,Ce), the output in column “Ce” is not “CHP” and the input in row “Ce” is “CERG” outside path1. Therefore, the parameter of $C_{I\text{-}O}$(Ee,Ce) is P(0) in the new adjacency matrix. After all elements along path1 are processed in this manner, a new adjacency matrix is obtained for the next path. As shown in Fig. 4, by using the new adjacency matrix to repeat the path search process, a new energy flow path is obtained until all elements of the adjacency matrix are P(0). The other two paths in the example are given by Eqs. (5) and (6).



$$\left[\begin{array}{c|cccccc} & in & W & F & Q & R & out \\ \hline in & 0 & 0 & (I-I)1 & 0 & 0 & 0 \\ W & 0 & 0 & 0 & 0 & (CHP-CERG)\alpha 1 & (CHP-O)\alpha 2 \\ F & 0 & (I-CHP)\eta_W & 0 & (I-CHP)1 & 0 & 0 \\ Q & 0 & 0 & 0 & 0 & 0 & (CHP-O)\eta_Q \\ R & 0 & 0 & 0 & 0 & 0 & (CERG-O)COP^{CERG} \\ out & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

Fig. 4 Path1 and adjacency matrix update

$$\text{Path2:I} \xrightarrow[1]{I-I} Ng \xrightarrow[\eta_{Ee}]{I-CHP} Ee \xrightarrow[\alpha 2]{CHP-O} \text{O} \tag{5}$$

$$\text{Path3:I} \xrightarrow[1]{I-I} Ng \xrightarrow[1]{I-CHP} He \xrightarrow[\eta_{He}]{CHP-O} \text{O} \tag{6}$$

2.6. Coupling matrix obtained using search for all paths

The parameter of one path is obtained by multiplying all parameters on that path. This parameter is used as the parameter of the corresponding position in the coupling matrix. For example, the parameter of path1 as mentioned above is $\eta_{Ee} \cdot \alpha 1 \cdot COP^{CERG}$. The corresponding energy conversion process is from “Ng” to “Ce”; therefore, the parameter of path1 is indicated in column “Ng” and row

“Ce,” and the coupling matrix of path1 (Hpath1) can be obtained as given by Eq. (7). The coupling matrix of the EH can be obtained by adding all coupling matrices of the path, as given by Eq. (8).

$$H_{Path1}=\begin{array}{cccc|c} Ee & Ng & He & Ce & \\ \hline 0 & 0 & 0 & 0 & Ee \\ 0 & 0 & 0 & 0 & Ng \\ 0 & 0 & 0 & 0 & He \\ 0 & \eta_{Ee}\cdot\alpha 1\cdot COP^{CERG} & 0 & 0 & Ce \end{array} \tag{7}$$

$$H=\underbrace{\left[\begin{array}{cccc|c} Ee & Ng & He & Ce & \\ \hline 0 & 0 & 0 & 0 & Ee \\ 0 & 0 & 0 & 0 & Ng \\ 0 & 0 & 0 & 0 & He \\ 0 & \eta_{Ee}\cdot\alpha 1\cdot COP^{CERG} & 0 & 0 & Ce \end{array}\right]}_{H_{Path1}}+\underbrace{\left[\begin{array}{cccc|c} Ee & F & He & Ce & \\ \hline 0 & \eta_{Ee}\cdot\alpha 2 & 0 & 0 & Ee \\ 0 & 0 & 0 & 0 & Ng \\ 0 & 0 & 0 & 0 & He \\ 0 & 0 & 0 & 0 & Ce \end{array}\right]}_{H_{Path2}}+\underbrace{\left[\begin{array}{cccc|c} Ee & Ng & He & Ce & \\ \hline 0 & 0 & 0 & 0 & Ee \\ 0 & 0 & 0 & 0 & Ng \\ 0 & \eta_{He} & 0 & 0 & He \\ 0 & 0 & 0 & 0 & Ce \end{array}\right]}_{H_{Path3}}$$

$$=\left[\begin{array}{cccc|c} Ee & Ng & He & Ce & \\ \hline 0 & \eta_{Ee}\cdot\alpha 2 & 0 & 0 & Ee \\ 0 & 0 & 0 & 0 & Ng \\ 0 & \eta_{He} & 0 & 0 & He \\ 0 & \eta_{Ee}\cdot\alpha 1\cdot COP^{CERG} & 0 & 0 & Ce \end{array}\right] \tag{8}$$

This procedure starts from the input–output model. The adjacency matrix of the EH is obtained after establishing and simplifying the multigraph, and then, the coupling matrix is obtained using the intelligent algorithm. The input–output model and parameters used in this process can be directly obtained through the software configuration. The program used for this method was written using MATLAB R2017b edition. The computer hardware used was an Intel i7-7700HQ 2.8-GHz central processing unit (CPU) with 8 GB of memory. Calculating the EH model shown in Fig. 3 required 0.294802 s.

3. Case Study

3.1. Case introduction

We used the Hydrodynamic Laboratory of the Xi’an Intelligent Energy Key Laboratory to conduct the case study in this project. The laboratory was considered an EH in our EI, as shown in Fig. 5. This laboratory includes a CHP, AB, CERG, and circulating water refrigeration unit (WARG); its structural block diagram is shown in Fig. 6. In this EH, we studied the coupling of four energy types: electricity, natural gas, heating energy, and cooling energy. Therefore, the data format was $[Ee_S,Ng_S,He_S,Ce_S]$. Four system parameters were used: energy conversion coefficient (η), energy efficiency ratio (COP), storage rate (φ), and energy distribution coefficient (α). These parameters change with the external environment. The EH load also includes the four aforementioned energy sources. Its data format was $[Ee_L,Ng_L,He_L,Ce_L]$. It was established using EnergyPlus software [15]. Load data for 12 months were obtained using simulation models, as shown in Table.

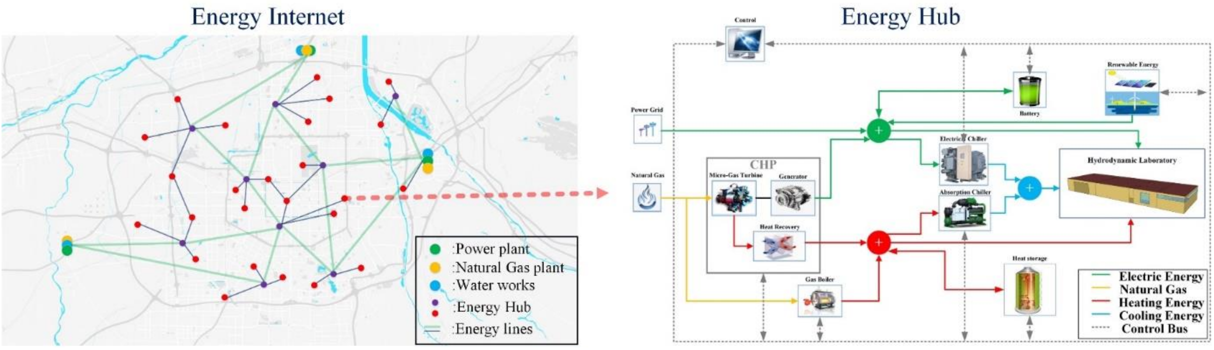


Fig. 5 Hydrodynamic Laboratory as EH in EI

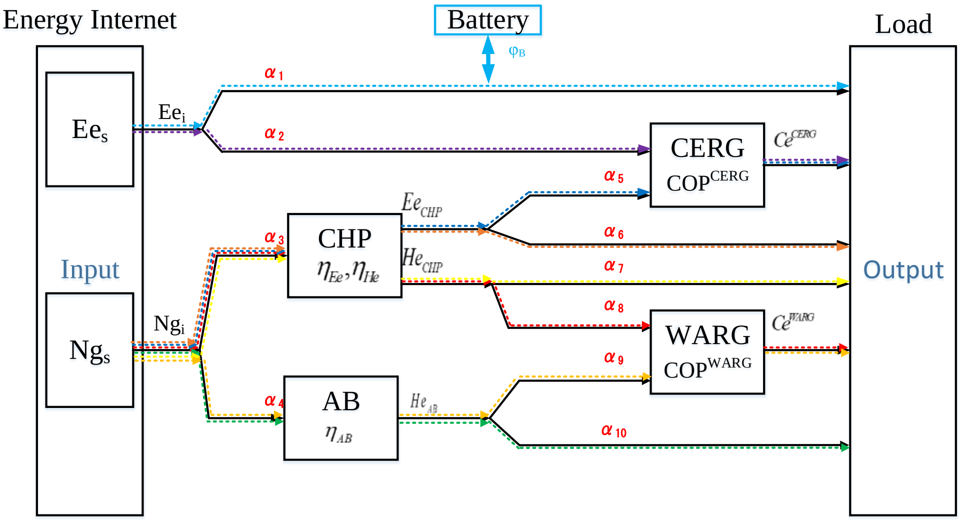


Fig. 6 Block diagram of the Hydrodynamic Laboratory

3.2. Modeling process

- The multigraph model of the EH was established using the proposed method. Then, the multigraph was simplified into a simple directed graph based on the parameter flow and merging of duplicate energy vertices. Fig. 7 shows the simple directed multigraph.
- The adjacency matrix of the simple directed multigraph was obtained, as shown in Fig. 8.
- The energy flow path was obtained by searching the adjacency matrix. The parameter of each path was obtained using Eqs. (9)–(16).

$$\text{Path1:I}\xrightarrow[1]{I-I}Ee\xrightarrow[\alpha 2]{I-CERG}Ce\xrightarrow[COP^{1}]{CERG-O}\text{O} \tag{9}$$

$$\text{Path2:I}\xrightarrow[1]{I-I}Ee\xrightarrow[\alpha 1(1-\varphi_B)]{I-O}\text{O} \tag{10}$$

$$\text{Path3:I}\xrightarrow[1]{I-I}Ng\xrightarrow[\alpha 3\eta_1^{CHP}]{I-CHP}Ee\xrightarrow[\alpha 5]{CHP-CERG}Ce\xrightarrow[COP^{1}]{CERG-O}\text{O} \tag{11}$$

$$\text{Path4:I}\xrightarrow[1]{I-I}Ng\xrightarrow[\alpha 3\eta_1^{CHP}]{I-CHP}Ee\xrightarrow[\alpha 6]{CHP-O}\text{O} \tag{12}$$

$$\text{Path5:I}\xrightarrow[1]{I-I}Ng\xrightarrow[\alpha 3\eta_2^{CHP}]{I-CHP}He\xrightarrow[\alpha 8]{CHP-WARG}Ce\xrightarrow[COP^2]{WARG-O}\text{O} \tag{13}$$

$$\text{Path6:I}\xrightarrow[1]{I-I}Ng\xrightarrow[\alpha 3\eta_2^{CHP}]{I-CHP}He\xrightarrow[\alpha 7]{CHP-O}\text{O} \tag{14}$$

$$\text{Path7:I}\xrightarrow[1]{I-I}Ng\xrightarrow[\alpha 4\eta_1^{AB}]{I-AB}He\xrightarrow[\alpha 9]{AB-WARG}Ce\xrightarrow[COP^2]{WARG-O}\text{O} \tag{15}$$

$$\text{Path8:I}\xrightarrow[1]{I-I}Ng\xrightarrow[\alpha 4\eta_1^{AB}]{I-AB}He\xrightarrow[\alpha 10]{AB-O}\text{O} \tag{16}$$

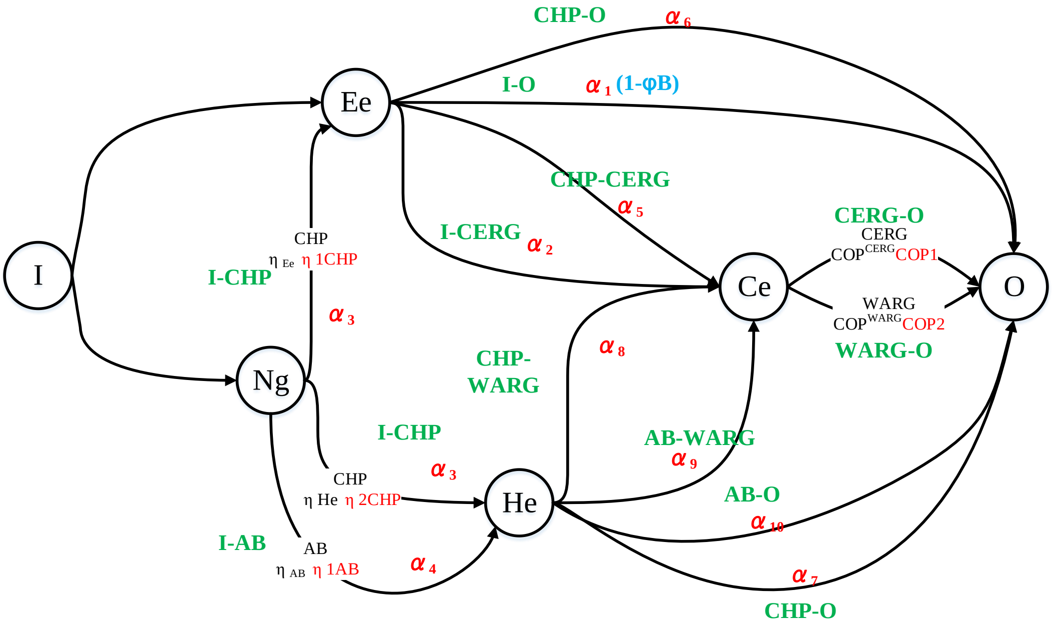


Fig. 7 Simple directed graph of EH

$$\left[\begin{array}{ccccccc}
 & I & Ee & Ng & He & Ce & O \\
I & 0 & (I-I)1 & (I-I)1 & 0 & 0 & 0 \\
Ee & 0 & 0 & 0 & 0 & (I-CERG)\alpha_2,(CHP-CERG)\alpha_5 & (CHP-O)\alpha_6,(I-O)\alpha_1(1-\varphi_B) \\
Ng & 0 & (I-CHP)\alpha_3\eta_1^{CHP} & 0 & (I-CHP)\alpha_3\eta_2^{CHP},(I-AB)\alpha_4\eta_1^{AB} & 0 & 0 \\
He & 0 & 0 & 0 & 0 & (CHP-WARG)\alpha_8,(AB-WARG)\alpha_9 & (CHP-O)\alpha_7,(AB-O)\alpha_{10} \\
Ce & 0 & 0 & 0 & 0 & 0 & (CERG-O)COP^1,(WARG-O)COP^2 \\
O & 0 & 0 & 0 & 0 & 0 & 0
\end{array}\right]$$

Fig. 8 Adjacency matrix of EH

4. Results

The case shows that the proposed method can be applied to the modeling of an EH and has the characteristics of programmability, rapidity, strong applicability, and flexibility. The present study thus makes important contributions to the use of mathematical models in the design, optimization, and control of an EH. The proposed method affords several advantages.

(1) The proposed modeling process is realized using a simple MATLAB program that can quickly perform the modeling in only 3.3 s on a computer with an Intel Core i7-7700HQ 2.8-GHz CPU with 8 GB random-access memory.

Other researchers have also proposed effective programmatic modeling methods for EH, among which the more representative ones are as follows:

(a) Chicco and Mancarella proposed a comprehensive input–output matrix modeling method [16]. Their programmatic search method uses graph theory, and it replaces each device with a matrix model. However, the matrix model is very large, and the modeling speed is greatly reduced for an EH with more equipment.

(b) Wang *et al.* proposed an automatic and linearized modeling method [17]. This method is applicable to EHs similar to the one considered in the present case study. Its modeling method is also programmable but requires multiple iterations to determine variables; therefore, the programming difficulty and modeling time are increased. On a computer with a Intel Core I5 2.7-GHz CPU with 8 GB of 1867-MHz DDR3 memory, the program implementation time was more than 1000 s.

(2) The proposed method focuses on the connection relationships between the equipment in the EH and the connection and conversion relationships among the energy sources. These relationships are used as a type of data in the modeling method. This clearly shows the structure of the EH more clearly and is more conducive to the realization of control methods.

(a) The two aforementioned modeling methods [16,17] lack a manifestation of the energy relationship. Therefore, when their control strategy is established, an energy relationship equation must be established to satisfy the constraint conditions.

(b) By contrast, some modeling methods, such as the integrated modeling of EH proposed by Wasilewski [18], focus too much on the energy relationship and ignore the connection relationship of the equipment. This method established active and reactive power models of the electric energy in the EH but did not consider the influence of other equipment in the CHP on the electric energy.

(3) The proposed modeling method focuses on the flexibility of the model. When equipment is added to or removed from the EH, the equipment data is updated accordingly. Therefore, the modeling method and procedure need not be changed. This allows our modeling method to be applied to more scenarios, and the program is easier to maintain compared with previous methods.

(a) The aforementioned modeling methods [16–18] do not have the flexibility of our proposed method. When the structure of the EH changes, their modeling methods and procedures must be changed.

(b) Regarding flexibility, some studies have used an uncertainty modeling method [19]. They have performed modeling based on the probability of equipment being added or lost. This approach somewhat improves the model flexibility but greatly compromises the accuracy of data and modeling.

Through this comparison, the result shown in Fig. 9 is obtained. Compared with currently available methods, the proposed modeling method affords obvious advantages.

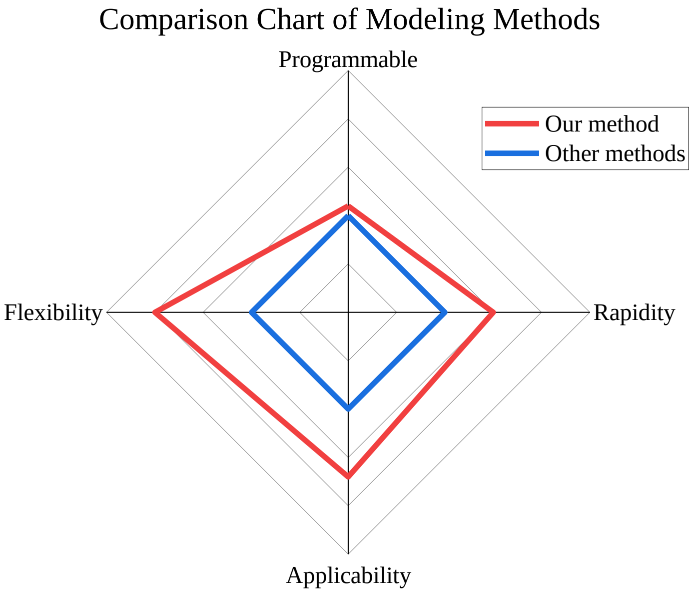


Fig. 9 Comparison of modeling methods

5. Conclusion

This study proposes a method to develop an EH model and to obtain EH data for deep learning of the EI. This method obtains the adjacency matrix by using a directed multigraph and then automatically finds the coupling matrix of the EH by using an intelligent search algorithm.

The proposed method was applied to a hydrodynamic laboratory as a case study. The results shows that the model dimension and program structure are not changed when energy storage is added or removed. This method can be used as a standardized computer modeling method for an EH. It can quickly and accurately establish an EH model, and the required source data can be obtained from the load data.

Nomenclature

AB – auxiliary boiler
$C_{I\text{-}O}$ – energy adjacency matrix
CERG – compression electric refrigerator group
Ce – heating energy [kW]
CHP – combined heat and power
COP – coefficient of performance [–]
Ee – electrical energy[kW]
He – cooling energy (refrigeration) energy [kW]
Ng – natural gas energy [kW]
WARG – water absorption refrigerator group

Greek symbols:

α – dispatch factor
η – efficiency factor
λ – storage efficiency
φ – energy storage rate

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