Energy Proceedings
Vol 40, 2024

ISSN 2004-2965

Entropy State Modelling Method for Integrated Energy System based on Flow Hub Model

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ABSTRACT

Energy quality analysis is a novel method to evaluate the effectiveness of mitigation on energy crisis and carbon emission. Entropy increase, as a developing energy quality evaluation theory, quantifies the energy unavailability caused by exergy loss in transmission and uncertainty of source and load, and provides theoretical support for decision making on planning and operational optimization of Integrated Energy System (IES). This article proposes the entropy state mechanism and Flow Hub (FH) model to solve the entropy state distribution of IES. Finally, a case study verifies the effectiveness of the proposed models, discussed the entropy increase balance between source and load.

Keywords: integrated energy system; renewable energy; energy quality; entropy state; entropy increase flow; exergy flow

NONMENCLATURE

Abbreviations	
IES	Integrated Energy System
FH	Flow Hub
ES	Energy Station
EH	Energy Hub
CHP	Combined Heat and Power
GB	Gas Boiler
EB	Electric Boiler
PV	Photovoltaic
WT	Wind Turbine
Symbols	
ΔS_{th}	Traditional Thermodynamic Entropy
Δe	Exergy Loss
T_{a}	Ambient Temperature
ΔS_{info}	Informatic Equivalent Thermodynamic Entropy Increase
$W_{\mathrm{i\,nfo}}$	Generalized Information Work
p_{info}	Information Potential
f_{info}	Information Flow
ΔS	Entropy Increase Source
$\Delta S_{\mathrm{f},}$	Entropy Increase Flow
ΔS_{N}	Node Entropy Increase
e_{N}	Exergy Flow Out Of Node
e_{L}	Load Exergy
e_{f}	Exergy Flow

1. INTRODUCTION

With the continuous growth of energy demand and the increasingly serious environmental problems, integrated energy systems (IES) have attracted widespread attention as a form of energy utilization with multiple energy interconnections[1]. In the theoretical research and practical application of IES, energy quality is an important consideration factor, referring to the degree of energy availability and utilization level of energy during transmission, conversion, and utilization. Studying energy quality can provide scientific basis for system design and operation[2].

The decrease in energy availability, which is caused by the uncertainty of renewable energy, as well as energy degradation, can be measured by entropy increase[3]. Understanding the propagation laws of entropy in energy systems is of great significance for optimizing energy quality in energy systems[4]. The IES entropy state mechanism model take the network characteristic of IES and quantitatively into consideration and analyzes the energy unavailability generated during the system energy supply process, aiding to seek IES

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

planning and operation decisions that are conducive to the goal of coordinated development of quantity and quality[5].

The Energy Station (ES) determines the conversion and distribution of energy in different forms, plays the role of regulator on the quantity and quality of IES[6]. With new understanding and evaluation methods of energy quality for IES[7], traditional modelling method like Energy Hub(EH) model shows limitation on expressing the conversion and distribution characteristics of energy quality attributes during energy conversion process[8]. Flow Hub (FH) model is used in this article as it is capable to determine the internal entropy increase distribution while considering the reallocation of entropy increase at individual energy conversion equipment.

To provide a tool to evaluate energy quality of IES on the aspect of entropy increase, the entropy state mechanism model and analysis method is proposed. The entropy increase mechanism of elements in energy network is defined. With the help of FH model, the IES entropy state modelling method for IES with multiple subsystems and ES is proposed. The effectiveness of the proposed method is verified through case study.

2. ENTROPY STATE MECHANISM MODEL

2.1 Entropy increase mechanism in Integrated energy system

IES Entropy increase comes from the unavailability and uncertainty of energy, including traditional thermodynamic entropy and informatic equivalent thermodynamic entropy increase[9]. The traditional thermodynamic entropy increase ΔS_{th} is generated due to exergy loss Δe in the process of transmission and conversion of energy in IES, the relationship is as Eq.(1) shows:

$$\Delta S_{\mathrm{th}} = \frac{\Delta e}{T_{\mathrm{a}}} \tag{1}$$

Where T_{a} is the ambient temperature in K.

Note that when gas leakage is ignored and the calorific value and theoretical combustion temperature of natural gas stay constant, there is not exergy loss in the transmission of nature gas system, hence thermodynamic entropy increase in gas system is zero for steady state analysis.

The informatic equivalent thermodynamic entropy increase ΔS_{info} is derived from generalized information work W_{info} [4]. W_{info} is defined as the product of information potential p_{info} and information flow f_{info}, both of which can be gathered from historical energy data of source and load with uncertainty:

$$W_{\mathrm{info}} = p_{\mathrm{info}} f_{\mathrm{info}} \tag{2}$$

The information work represents the exergy loss due to uncertainty with the potential to become useful work under the control of information. When information is absent, ΔS_{info} can be used to express the exergy loss due to uncertainty:

$$\Delta S_{\mathrm{info}} = \frac{W_{\mathrm{info}}}{T_{\mathrm{a}}} \tag{3}$$

2.2 Entropy state network

The entropy state network is an analyzing model that quantifies the entropy increase property of energy media while considering the network property of IES. Similar to power system network or exergy flow network, the entropy state network includes branches and nodes. Additionally, entropy increase source is introduced to represent the two types of entropy increase mentioned in 2.1. Within the entropy state network flows the entropy increase flow as the measure of entropy increase property for exergy flow. The value of entropy increase flow is the additive result of all the entropy increase source on the path of exergy flow while several rules are applied.

2.2.1 The rule of entropy increase source

The Entropy increase source generates entropy increase to the system. When there is an entropy increase source on the path of entropy increase flow, as Fig.1 shows, the value of entropy increase flow after the source become the sum of the value of entropy increase source and the entropy increase flow before the source, as Eq.(4) shows:

$$\Delta S_{\mathrm{f},2} = \Delta S_{\mathrm{f},1} + \Delta S \tag{4}$$

Where ΔS is the entropy increase brough by the entropy increase source, $\Delta S_{\mathrm{f},1}$ and $\Delta S_{\mathrm{f},2}$ are entropy increase flow before and after the entropy increase source, respectively.

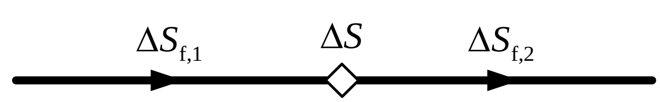

Fig. 1. Schematic diagram of entropy increase source

2.2.2 The rule of node entropy increase

The node represents the connection of different IES sections, and the node parameter of the entropy state network is the node entropy increase ΔS_{N} . ΔS_{N} is the sum of all entropy increase flow into the node, whether it is from a branch or an injection, as Eq.(5) and Fig.2 shows:

$$\Delta S_{\mathrm{N}} = \sum_{i=1}^{I} \Delta S_{\mathrm{f},i}^{\mathrm{in}} + \Delta S_{\mathrm{s}} \tag{5}$$

Where I is the total number of branches that carries entropy increase flow into the node, namely inflow branches, $\Delta S_{\mathrm{f},i}^{\mathrm{in}}$ is the entropy increase flow in i-th inflow branch, ΔS_{s} is the entropy increase flow injection outside the network.

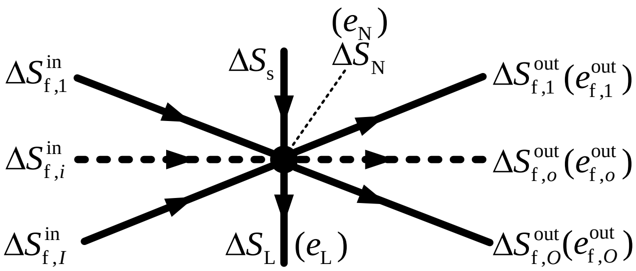

Fig. 2. Schematic diagram of node entropy increase

2.2.3 The rule of allocation at node

Considering the energy media is evenly distributed at the node, all three of flows, specifically media flow, exergy flow, entropy increase flow have the same distribution ratio at the output of the node. Outflow exergy flow ratio is chosen as the allocation coefficient of entropy state network, as Eq.(7) and Fig.2 shows:

$$e_{\mathrm{N}} = \sum_{o=1}^{O} e_{\mathrm{f},o}^{\mathrm{out}} + e_{\mathrm{L}} \tag{6}$$

$$\Delta S_{\mathrm{f},o}^{\mathrm{out}} = \Delta S_{\mathrm{N}} \frac{e_{\mathrm{f},o}^{\mathrm{out}}}{e_{\mathrm{N}}} \tag{7}$$

$$\Delta S_{\mathrm{L}} = \Delta S_{\mathrm{N}} \frac{e_{\mathrm{L}}}{e_{\mathrm{N}}} \tag{8}$$

Where e_{N} is the sum of all the output exergy flow of the node; e_{L} is exergy flow to the load that connects to the node; O is the total number of outflow branches; $e_{\mathrm{f},o}^{\mathrm{out}}$ and $\Delta S_{\mathrm{f},o}^{\mathrm{out}}$ are the exergy flow and entropy increase flow in the o-th outflow branch, respectively; ΔS_{L} is the entropy increase flow to the load.

2.2.4 The entropy state modelling method of a subsystem

With steady state exergy flow model of a subsystem of IES, the thermodynamic entropy increase of all the branches is acquirable. And given the historical data of renewable energy generation and load, the informatic equivalent thermodynamic entropy increase of the system can be determined.

Renewable energy generation is regarded as entropy increase injection brought by an informatic equivalent thermodynamic entropy increase source. Load with uncertainty needs supplementary load node and branches to form load entropy state model, which will be demonstrated in case study. The entropy increase of load consists of entropy increase from the energy network and the informatic equivalent thermodynamic entropy increase brought by the uncertainty of load. Heat load is assigned with a node that takes the entropy increase flow from the sending network, part of it is sent to load and the remaining back to the returning network. The ratio depends on the exergy flow ratio.

According to the modelling rules mentioned in 2.2.1-2.2.3, the entropy state model for all the individual subsystem could be generated only if the entropy increase flows from the ES were given. The FH model is used in this article to determine the output entropy increase flow of ES.

2.3 Flow Hub model

Entropy state network is capable to quantify the entropy increase distribution in an energy transmission or distribution network, but lack of the ability to model the link of multi-energy coupling with energy conversion equipment. To obtain the entropy increase flow distribution of the multi-coupling link, the flow hub model(FH) is developed with the aid of graph theory[6,8,10]. Note that flow hub is capable of model multiple flow distribution of an ES, but this article only focuses on entropy increase flow modelling of FH.

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2.3.1 The composition and expression of a Flow Hub

The structural composition of a FH consists of the followings:

1. Generalized source/resistor: Each equipment is regarded as a generalized source/resistor;
2. Node: each connection section is regarded as node, the input and output of the ES are considered as a special kind of ports.
3. Port: The input and output of generalized source/resistor and node are regarded as ports.
4. Branch: Each link between ports is defined as a branch.

The branch-port entropy increase flow model can be formed with elements defined above. Based on the structure of the flow hub model, a linear equation expression for entropy increase flow distribution can be formed, as Eq(9). shows:

$$\begin{bmatrix} \boldsymbol{X}_{\mathrm{U}} \\ \boldsymbol{X}_{\mathrm{I}} \\ \boldsymbol{X}_{\mathrm{O}} \\ \boldsymbol{X}_{\mathrm{N}} \end{bmatrix} \boldsymbol{V}_{\mathrm{B}} = \begin{bmatrix} \boldsymbol{V}_{\mathrm{U}} \\ \boldsymbol{V}_{\mathrm{I}} \\ \boldsymbol{V}_{\mathrm{O}} \\ \boldsymbol{V}_{\mathrm{N}} \end{bmatrix} \tag{9}$$

Where $\boldsymbol{V}_{\mathrm{B}}$ is the vector of branch flow, formed by the flows of all branches; $\boldsymbol{X}_{\mathrm{U}}$ is the generalized source/resistor – branch coupling matrix, describes flow characteristic of the equipment and the connection relationship between branches and the ports of generalized source/resistor, ; $\boldsymbol{V}_{\mathrm{U}}$ is the vector of generalized source/resistor, formed by value of each generalized source/resistor; $\boldsymbol{X}_{\mathrm{I}}$ and $\boldsymbol{X}_{\mathrm{O}}$ are the input and output – branch coupling matrix, respectively; $\boldsymbol{V}_{\mathrm{I}}$ and $\boldsymbol{V}_{\mathrm{O}}$ are the input and output flow vector, respectively; $\boldsymbol{X}_{\mathrm{N}}$ is the node – branch coupling matrix, describes flow dispatch ratio and the connection relationship between branch and ports of node; $\boldsymbol{V}_{\mathrm{N}}$ is node balance vector, formed by zeros.

$\boldsymbol{X}_{\mathrm{U}}$ and $\boldsymbol{V}_{\mathrm{U}}$ are the key variables of generalized source/resistor that describe 3 main flow characteristics of energy conversion equipment, that is efficiency, dispatch and increment/decrement. A simple ES with one general energy conversion equipment is set up as an example to demonstrate the calculation procedure. The FH model of this ES is as Fig.3 shows with all the branches, ports labelled.

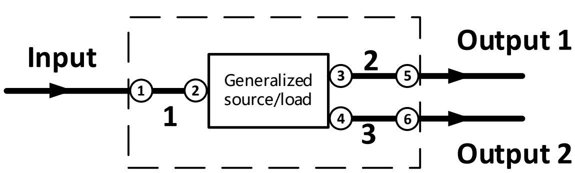

Fig. 3. Schematic diagram of example flow hub model

The equipment has one input v_{in} and two output $v_{\mathrm{out},1}$ and $v_{\mathrm{out},2}$. The energy efficiency for the outputs are η_1^{en} and η_2^{en}, indicating that the energy dispatch ratio is $(\eta_1^{\mathrm{en}} : \eta_2^{\mathrm{en}})$. Since the total energy efficiency of the equipment is $(\eta_1^{\mathrm{en}} + \eta_2^{\mathrm{en}})$, $(1 - \eta_1^{\mathrm{en}} - \eta_2^{\mathrm{en}})$ of input energy contributes to the energy decrement of the generalized source/resistor. For comparison, the energy flow expression for this individual equipment is as Eq.(10) shows:

$$\begin{cases} -\dfrac{1}{\eta_1^{\mathrm{en}}} v_{\mathrm{out},1}^{\mathrm{en}} + v_{\mathrm{in}}^{\mathrm{en}} = 0 \\ -\dfrac{1}{\eta_2^{\mathrm{en}}} v_{\mathrm{out},2}^{\mathrm{en}} + v_{\mathrm{in}}^{\mathrm{en}} = 0 \end{cases} \tag{10}$$

Where $v_{\mathrm{out},1}^{\mathrm{en}}$ and $v_{\mathrm{out},2}^{\mathrm{en}}$ are the energy outputs of the energy conversion equipment; $v_{\mathrm{in}}^{\mathrm{en}}$ is the energy input of the energy conversion equipment.

In similar form, the entropy increase flow expression for this equipment can also be derived, but a few more parameter is needed. The output distribution of entropy increase flow follows the output exergy flow ratio. With the help of Energy Quality Coefficient(EQC), the exergy flow ratio can be determined. EQC sates the amount of exergy within an energy form for a unit of energy, as Eq.(11) shows:

$$\lambda = \frac{E_{\mathrm{x}}}{Q} \tag{11}$$

Where λ is EQC of an energy form; E_{x} is the exergy contained in this energy form; Q is the energy contained in this energy form.

Hence, the output exergy efficiency of the equipment can be calculated when given the EQC of input and output, as Eq.(12)-(13) shows:

$$\eta_1^{\mathrm{ex}} = \eta_1^{\mathrm{en}} \frac{\lambda_1}{\lambda_{\mathrm{in}}} \tag{12}$$

$$\eta_2^{\mathrm{ex}} = \eta_2^{\mathrm{en}} \frac{\lambda_2}{\lambda_{\mathrm{in}}} \tag{13}$$

Where η_1^{ex} and η_2^{ex} are the output exergy efficiency of the equipment, respectively; λ_1 and λ_2 are the EQC of the output energy forms, respectively; λ_{in} is the EQC of the output energy form.

Then, the output exergy ratio, equaling to the entropy increase flow distribution ratio, can be derived as Eq. shows:

$$\eta_1^{\mathrm{s}} = \frac{\eta_1^{\mathrm{ex}}}{\eta_1^{\mathrm{ex}} + \eta_2^{\mathrm{ex}}} \tag{14}$$

$$\eta_2^{\mathrm{s}} = \frac{\eta_2^{\mathrm{ex}}}{\eta_1^{\mathrm{ex}} + \eta_2^{\mathrm{ex}}} \tag{15}$$

Finally, the entropy increase of the equipment can be determined as Eq.(1), the entropy increase flow expression for this equipment can also be formed:

$$\begin{cases} -\dfrac{1}{\eta_1^{s}} v_{\text{out},1}^{s} + v_{\text{in}}^{s} = V_{\text{U}}^{s} \\ -\dfrac{1}{\eta_2^{s}} v_{\text{out},2}^{s} + v_{\text{in}}^{s} = V_{\text{U}}^{s} \end{cases} \tag{16}$$

Where $v_{\text{out},1}^{s}$ and $v_{\text{out},2}^{s}$ are the output entropy increase flows of the equipment, respectively; v_{in}^{s} is the input entropy increase flow of the equipment; V_{U}^{s} is opposite number of the entropy increase of the equipment.

$$\begin{bmatrix} 1 & -\dfrac{1}{\eta_1^{s}} & 0 \\ 1 & 0 & -\dfrac{1}{\eta_2^{s}} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{\text{in}}^{s} \\ v_{\text{out},1}^{s} \\ v_{\text{out},2}^{s} \end{bmatrix} = \begin{bmatrix} V_{\text{U}}^{s} \\ V_{\text{U}}^{s} \\ V_{\text{in}} \\ V_{\text{out},1} \\ V_{\text{out},2} \end{bmatrix} \tag{17}$$

In the entropy increase flow hub model of this ES, $-1/\eta_1^{s}$ and $-1/\eta_2^{s}$ can be found at respective location in $\boldsymbol{X}_{\text{U}}$; and V_{U}^{s} at respective rows in $\boldsymbol{V}_{\text{U}}$, v_{in}^{s}, $v_{\text{out},1}^{s}$, and $v_{\text{out},2}^{s}$ are unknown variables in $\boldsymbol{V}_{\text{B}}$. The complete linear equation for this model is as shown in Eq.(17). Where V_{in} is the input entropy increase flow of the ES; $V_{\text{out},1}$ and $V_{\text{out},2}$ are the output entropy increase flows of the ES, respectively.

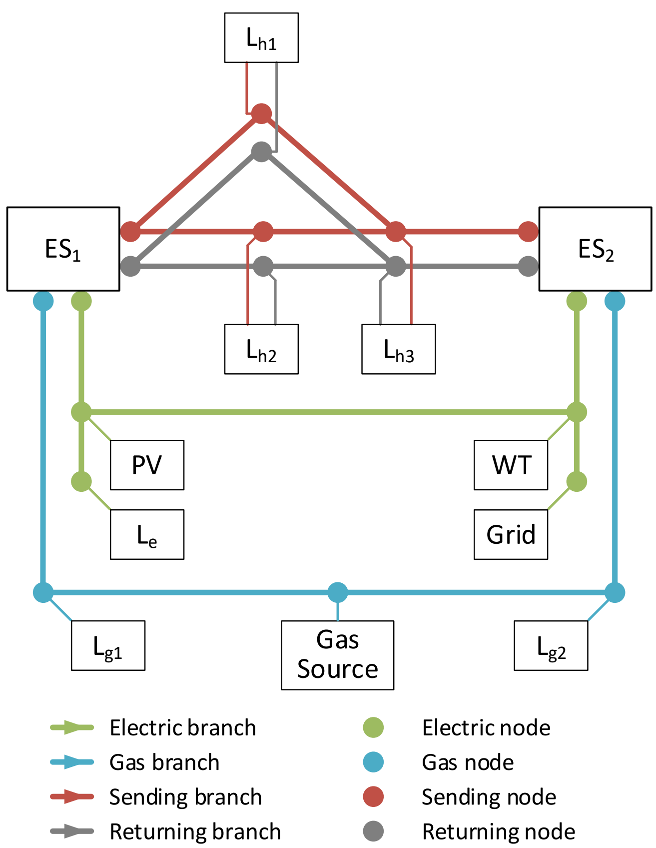

Fig. 4. Schematic diagram of case study IES

This linear equation can be solved using Gaussian Elimination method, which has been thoroughly discussed in Ref[6].

3. CASE STUDY

This article constructs a typical IES based example testing system, as shown in Fig.4, with steady state exergy flow model solution, as shown in Fig.5. The system consists of three subsystems: a 6-node electric system, a 5-node natural gas system, and a 5-node thermal system[11-13]. To take into account the impact of energy conversion on the entropy distribution of the system, it is equipped with two ESs, as shown in Fig.6-7. The ambient temperature is set to 10 ℃.

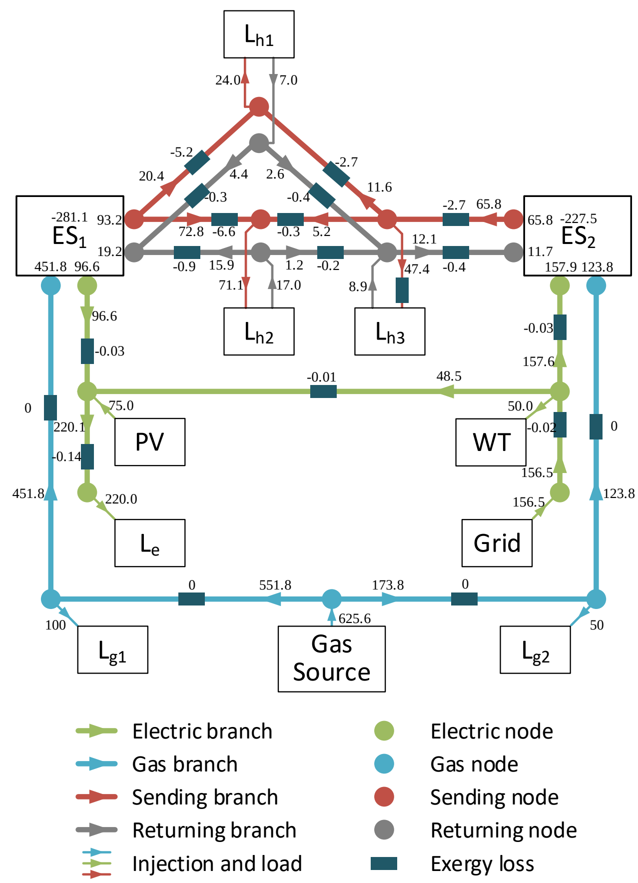

Fig. 5. Schematic diagram of exergy flow model for case study IES

The electric system is built based on the IEEE33 node system, with a voltage level of 12.66kV. Distributed Photovoltaic (PV) and Wind Turbine (WT) are connected to electric system to consider the impact of informatic equivalent thermodynamic entropy increase caused by renewable energy uncertainty.

The gas source pressure of the natural gas system is 0.5MPa, and the calorific value and theoretical combustion temperature of natural gas are 45.75MJ/m3 and 1973 ℃, respectively. The relevant parameters of the heat system are modified based on typical system data. Two ESs provide thermal energy for the heat

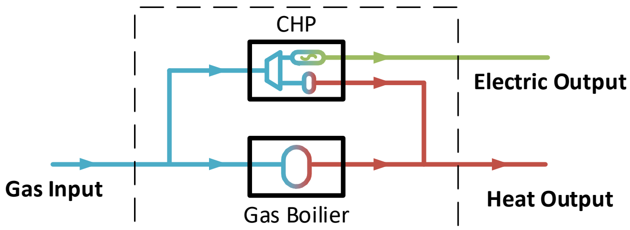

Fig. 6. Schematic diagram of energy station 1

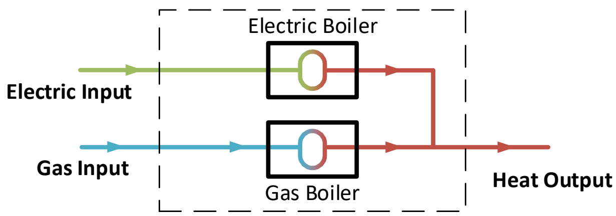

Fig. 7. Schematic diagram of energy station 2

system, with the outlet temperature of the heat source set at 100 ℃ and the outlet temperature of the load set at 50 ℃.

Among the two typical ES configured in the example, ES1 is equipped with one Combined Heat and Power unit (CHP) and one Gas Boiler (GB), with energy conversion efficiency of $\eta_{\mathrm{g2e}}^{\mathrm{CHP}}=0.3$, $\eta_{\mathrm{g2h}}^{\mathrm{CHP}}=0.4$ and $\eta_{\mathrm{g2h}}^{\mathrm{GB}}=0.85$, respectively[14].

The input end of ES1 is connected to electric network and natural gas network, while the output end is connected to thermal network, providing thermal and electrical energy for both the heat and power systems. ES2 is equipped with one GB and one Electric Boiler (EB), with energy conversion efficiency of $\eta_{\mathrm{g2h}}^{\mathrm{GB}}=0.85$ and $\eta_{\mathrm{e2h}}^{\mathrm{EB}}=0.95$, respectively.

$$\begin{bmatrix} \boldsymbol{X}_{\mathrm{U},1}^{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{I},1}^{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{O},1}^{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{N},1}^{\mathrm{s}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1.7784 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1.3337 & 0 & 0 \\ 0 & 1 & -4.4524 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & -2 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & -2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 \end{bmatrix} \tag{18}$$

The input end of ES2 is connected to electric network and natural gas network, while the output end is connected to heat network to provide thermal energy. The EQC of electric, gas and heat energy are 1, 0.7013 and 0.1853, respectively. In response to the informatic equivalent thermodynamic entropy increase caused by source load uncertainty, this paper constructs a source load entropy state model based on hourly data of source load throughout the year, taking the weak prediction scenario in Ref[4] as an example.

$$\begin{bmatrix} \boldsymbol{X}_{\mathrm{U},2}^{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{I},2}^{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{O},2}^{\mathrm{s}} \\ \boldsymbol{X}_{\mathrm{N},2}^{\mathrm{s}} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -5.6818 & 0 & 0 \\ 0 & 1 & 0 & -4.4524 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & -1 \end{bmatrix} \tag{19}$$

The FH model for ES1 and ES2 are established based on the modelling method mentioned in 2.3 and the labelling of branches, ports and nodes are as shown in Fig.8-9.

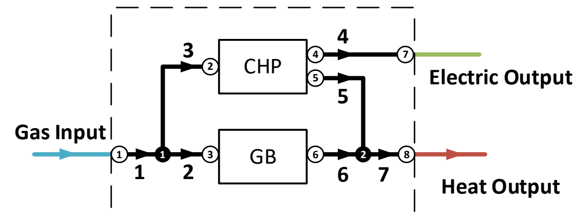

Fig. 8. Schematic diagram of flow hub model for energy station 1

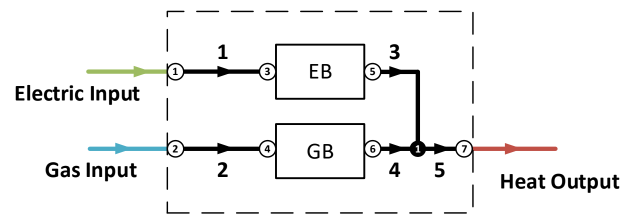

Fig. 9. Schematic diagram of flow hub model for energy station 2

The dispatch ratio of natural gas at Node 1 in ES1 is set to 1:1, and all the other node are considered flexible nodes, meaning there is not restriction on ratio of the input or output. For demonstration purpose, the generalized source/resistor – coupling matrix of entropy increase FH model for ES1 and ES2 is as Eq.(18)-(19) shows:

Combining entropy state mechanism model and FH model, the entropy state model of the whole IES can be established, the calculation process of this IES is shown in Fig.10.

In the schematic diagram of entropy state solution for this IES, as shown in Fig.11, the "number" form represents the value of the branch entropy increase flow, the "+number" form represents the value of entropy increase source, and the "number" with a dotted line pointing to the node represents the node entropy increase of the network node or supplementary node.

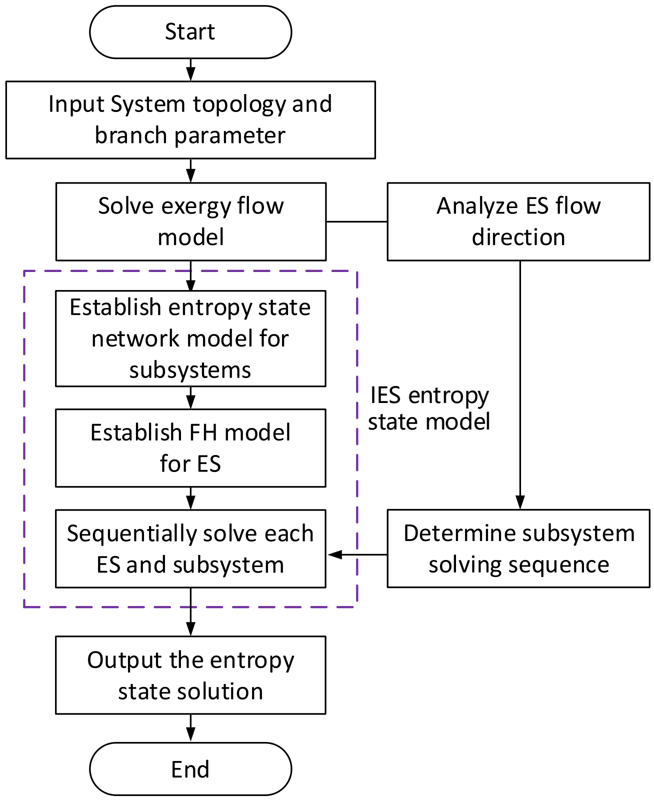

Fig. 10. Flowchart of entropy state calculation procedure

The entropy increase generated by various entropy increase sources propagates towards the load in the entropy state model, so the total entropy increase of the entropy increase sources and the total entropy increase received by loads should be consistent. The total entropy increase of the entropy increase sources in the example system is 4.30kW/K, and the total entropy increase of the supplementary load nodes is 4.30kW/K. The overall entropy balance relationship of the system entropy increase mentioned above is met.

It is worthwhile to note that over the 4.30kW/K total entropy increase, two of the ES take up 1.8kW/K at 42%. So researchers should pay more attention to the management of energy conversion according to the entropy increase caused by energy conversion equipment, and meanwhile consider the redistribution effect of entropy increase flow.

The renewable energy generation injects informatic equivalent thermodynamic entropy increase to the electric system and further to the heat system. To mitigate the uncertainty impact of renewable energy to a wider range, researchers could analyze the distribution of overall or local entropy increase, identify high entropy increase sections, and then reduce system entropy increase through optimization methods such as planning and operational control.

Furthermore, understanding the characteristics of entropy distribution is beneficial for analyzing the mechanism of entropy increase in energy generation, transmission, and consumption in the system, slowing down the entropy increase in the system, and improving energy availability.

In subsequent research work, a matrix-based calculation model for the entropy state parameters of a comprehensive energy system oriented towards renewable energy integration will be considered. From the perspectives of planning, operational optimization, and market-oriented trading mechanisms, methods to slow down the overall or local entropy increase of the system will be studied.

4. CONCLUSTION

Both "energy degradation" and "uncertainty" will increase the energy unavailability of IES and increase the entropy increase of the system. This article proposes the entropy state theory and the FH model for energy quality analysis on the perspective of entropy increase property.

Case study shows that the developed methods can effectively solve the distribution of entropy increase flow in subsystem and ES with sequential calculation procedure, and verifies the entropy increase balance between sources and loads. This article provides a new tool to model, evaluate and analyze the impact of energy unavailability caused by exergy loss and uncertainty factor in IES.

ACKNOWLEDGEMENT

This work was supported by National Key R&D Program of China (No. 2018YFB0905000); Science and Technology Project of SGCC (SGTJDK00DWJS1800232); National Natural Science Foundation of China (NSFC) (51977141).

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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