Study of exergy costs model based on main and auxiliary energy outputs in produce nodes of UEI

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Abstract. In this paper, the exergy costs apportion problem of SIMO (single input and multiple outputs) energy produce node in UEI (Ubiquitous Energy Internet) is studied. The traditional exergy costs model is not suitable for solving the exergy costs problem in the UEI scenario. Considering the main and auxiliary output exergy, the energy expenses and non-energy expenses divide additionally. Then two apportion rules that used for solving exergy costs problem in the process of energy produce are provided. At last, a new exergy cost share model is built. Comparing this new exergy cost model with traditional exergy cost model, the main output exergy costs are higher and the auxiliary output exergy costs are lower. The exergy cost calculated by the new exergy cost model is closer to the actual exergy costs of the UEI produce node. This exergy costs could be a more reliable cost data in the process of production decision in a Ubiquitous Energy Internet produce nodes.

1. Introduction

The overall operation process of UEI includes four parts, which are energy production, energy storage, energy supply and energy recovery orderly. As for energy production, the common electric generation modes comprise solar power, wind power, ubiquitous machine using natural gas as energy source, coal burning, biomass power, thermal energy and cold energy. Among all these modes, there are two special approaches: using coal burning to generate gas energy and thermal energy, and using ubiquitous machine to produce electric energy, thermal energy and cold energy. One thing in common between these two modes is that they are both SIMO system, and the outputs can be divided into main and auxiliary energy. These two modes focus on UEI with SIMO to study the exergy costs apportionment problem among these produce nodes under the condition of main and auxiliary energy outputs.

2. Related research on exergy costs of SIMO system

Exergy cost of a flow within a system is the amount of exergy resources consumed by that system needed for producing the flow [1]. Exergy cost is used to many areas. Tsatsaronis *et al* use exergy and advanced exergy analysis methods for evaluating design and performance of the hybrid energy systems from thermodynamics point of view [2]. Ansarinasab *et al* analyzes an integrated combined cooling, thermaling and power process by advanced exergy cost analysis method [3]. Mehrpooya *et al*

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proposed conventional and advanced exergoeconomic methods analyzing the process complete the thermoeconomic analysis of multi-product systems [4]. Wang *et al* proposed exergy cost allocation method based on energy level for defining additional allocation equations and calculating the exergy cost of flows on a combined cooling, thermaling and power system [5]. Flórez-Orrego *et al* presents an exergy and environmental assessment of a 1000 metric t/day ammonia production plant based on the steam methane reforming (SMR) process [6-8]. In the study of Carrasquer *et al*, the unit exergy costs of desalination and purification, which are two alternatives commonly used for water supply and treatment, have been characterized as a function of the energy efficiency of the process by combining the Exergy Cost Analysis with Transfer Function Analysis [9] Carrasquer *et al* proposes a methodology for assessing the costs of groundwaters and water transfers from surplus basins within the exergy perspective and an equation to assess the exergy costs of these alternatives is proposed [10]. Sugimoto *et al* introduces an exergy cost-minimisation appraisal method for a simple gas turbine co-generation system [11]. Hua *et al* uses structure theory in thermal economy to analyze exergy cost [12]. Research [13-15] also studies exergy cost based on thermal economic analysis. Among all the research,

All of the research mentioned above of exergy cost for the SIMO system, mainly focus on the allocation of exergy cost for only one system or the modules in relevant equipment. There is no related research of exergy cost apportionment problem for UEI.

3. Traditional exergy cost apportionment model of production nodes in UEI and its problems

3.1. Traditional exergy cost apportionment model of production nodes in UEI

The traditional exergy cost apportionment model of the SIMO system does not consider the difference between main energy output and auxiliary energy output. Furthermore, the traditional apportionment model only considers the gross of exergy output to allocate exergy cost. The detail model is show in figure 1 below.

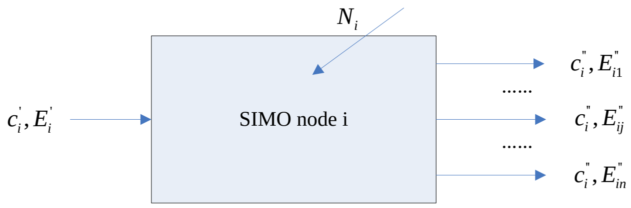

Figure 1. The Exergy transformation model of SIMO based on traditional cost apportionment model

In this exergy transformation model, the corresponding exergy cost apportionment model can depict. According to traditional exergy cost apportionment principles, show as below:

$$c_i^{"} = \frac{c_i^{'} E_i^{'} + N_i}{\sum_{j=1}^{n} E_{ij}^{"}} \tag{1}$$

In this formula, $E_i^{'}$ denotes the input exergy flow entering transformation node i of single input and multi output in computation period. $c_i^{'}$ represents the unit price of input exergy flow entering transformation node i of single input and multi output in computation period. $E_{ij}^{"}$ denotes output exergy flow j of transformation node i of single input and multi output in computation period. N_i denotes the allocating non-energy cost in computation period.

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3.2. Problems of traditional exergy cost apportionment model of production nodes in UEI

In the exergy cost model that uses traditional exergy cost apportionment methods, as shown in formula (1), the cost of output exergy calculates by the gross of various kinds of exergy exported in the whole system. According to traditional exergy cost apportionment methods, the cost of SIMO production nodes is the same regardless of the form of output exergy. The principle is:

$$c_{i1}^{"} = c_{i2}^{"} = \ldots = c_{ij}^{"} = \ldots = c_{in}^{"} = c_{i}^{"}$$

No matter how complicated the form of output exergy is, including electric energy, thermal energy, gas energy and cold energy, the cost is the same.

The two special production methods in UEI, which means using coal burning to generate gas energy and thermal energy, and using ubiquitous machine to produce electric energy, thermal energy and cold energy, are both belonging to SIMO production method. In this kind of method, the output exergy usually divides into main exergy and auxiliary exergy, and the auxiliary exergy can regarded as byproducts. So using formula (1) to calculate exergy cost in UEI has two main problems.

- Firstly, for SIMO production modes, if only main output exergy is used and auxiliary exergy is neglect, exergy cost of main output exergy will be underestimated factitiously.
- Secondly, for SIMO production modes, if the main output exergy and auxiliary exergy are adopt adequately, the cost of these two kinds of exergy will be the same according to traditional exergy cost models. Thus, the cost of main output exergy will be strongly underestimated and the cost of auxiliary exergy will be overrated. The reason for this problem is that the auxiliary output energy is passive produced usually, and the usage necessity of auxiliary energy is not so important compared to main energy production.

Under this circumstance, if the traditional exergy cost model is apply to calculate exergy production cost of SIMO systems in UEI, the apportionment results attach little significance to exergy cost computation in practical UEI. Therefore, there need a more reasonable apportionment model to solve exergy cost allocation problem of SIMO systems in UEI.

4. Exergy cost apportionment model considering main and auxiliary energy production in UEI

4.1. Glossary

Some glossaries are explained in the following table 1:

Table 1. Glossary.

Glossary	Discription
Energy	The energy in this paper composed as four types, they are: electric, gas, thermal and cold energy.
Traditional Exergy cost model	The traditional exergy cost model treats each exergy (such as electric, thermal and cold) cost as the same, this exergy cost model is common in literature.
Proposed Exergy cost model	The proposed exergy cost model treats each exergy (such as electric, thermal and cold) cost as difference, this exergy cost model is proposed in this paper.
Main Exergy cost	A conception in the proposed exergy cost model, this exergy cost contains all the energy cost and some non-energy cost.
Auxiliary exergy cost	A conception in the proposed exergy cost model, this exergy cost contains only some non-energy cost.
Real exergy cost	Real exergy cost denotes real energy cost in different cost model (such as traditional and proposed exergy cost model).

4.2. Two principles for solving exergy cost apportionment problem of production nodes in UEI

To solve exergy cost apportionment problem of SIMO energy production mode under the circumstance of main and auxiliary energy outputs, two principles put out based on the characteristic of this production mode to apportion main exergy cost and auxiliary energy cost.

Principle 1: *for SIMO production mode, the energy cost of input exergy will apportion fully to the cost of main output exergy, and the cost of auxiliary output exergy that is deemed to byproduct will be fully apportioned to the energy cost of no energy input.*

The reason for proposing this principle is that the aim of this production mode is to produce main output exergy, and auxiliary output exergy is regard as byproduct.

Principle 2: *for SIMO production mode, non-energy cost must apportion properly based on the gross of energy output.*

The reason for proposing this principle is that multiple energy output in our research produced jointly after input energy influencing energy equipment. It is impossible to distinguish the non-energy cost of different energy output such as equipment cost and labor cost. In conclusion, non-energy cost must apportion properly based on the gross of energy output.

4.3. Ubiquitous exergy cost apportionment model considering main and auxiliary energy production

After proposing these two principles, exergy transformation model of main and auxiliary energy production of SIMO node i in UEI can describe as figure 2:

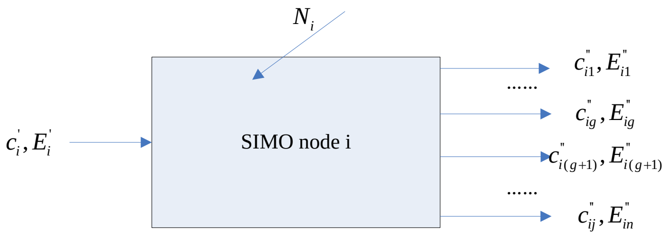

Figure 2. The Exergy transformation model of SIMO based on main and auxiliary energy produce.

In this exergy transformation model in figure 2, No. 1 to No. g outputs exergy defined as main output exergy, and No. g+1 to No. n output exergy as auxiliary output exergy. According to the two principles depicted above, the exergy cost of main output exergy can calculate as formula 2:

$$c_{ij}'' = \frac{c_i' E_i'}{\sum_{k=1}^{g} E_{ik}''} + \frac{N_i}{\sum_{l=1}^{n} E_{il}''} \qquad j = 1, 2, \ldots, g \tag{2}$$

In this formula, E_i' denotes the exergy flow entering into transformation SIMO node i in computation period. $\sum_{l=1}^{n} E_{il}''$ represents the total exergy flow of main and auxiliary exergy output for transformation SIMO node i in computation period. $\sum_{k=1}^{g} E_{ik}''$ represents the total exergy flow of main exergy output for transformation SIMO node i in computation period. N_i denotes the non-energy cost of output exergy flow for transformation SIMO node i in computation period.

According to formula (2), the result can show as below:

$$c_{i1}'' = c_{i2}'' = \ldots = c_{ij}'' = \ldots = c_{ig}'' = c_{im}''$$

This result means that for transformation SIMO nodes, the exergy cost of main exergy is the same.

Meanwhile, the exergy cost of auxiliary exergy can propose in formula (3):

$$c_{ij}^{"} = \frac{N_i}{\sum_{l=1}^{n} E_{il}^{"}} \quad j = (g+1),\dots,n \tag{3}$$

According to formula (3), the result can show as:

$$c_{i(g+1)}^{"} = c_{i(g+2)}^{"} = \dots = c_{ij}^{"} = \dots = c_{in}^{"} = c_{ia}^{"}$$

This result means that for transformation SIMO nodes, the exergy cost of auxiliary exergy is the same.

After this analysis, a conclusion can draw that the exergy cost of main output exergy and auxiliary output exergy is respectively the same in this apportionment mode, but the exergy cost between main output exergy and auxiliary output exergy is different totally.

5. An example of exergy cost of CHPS nodes in UEI

5.1. Traditional exergy cost model of CHPS nodes in UEI

According to formula (1), the calculation formula of exergy cost apportionment in combined thermal and power generation system of natural gas (CHPS: Which system can produce electric, thermal energy by input natural gas energy.) is given in following formula:

$$c_g^{"} = \frac{c_g^{'} E_g^{'} + N_g}{\sum_x E_{g-x}^{"}} \quad x \in \{e,h\} \tag{4}$$

In formula (4), $E_g^{'}$ denotes the input exergy flow entering CHPS in computation period. $c_g^{'}$ represents the unit price of input exergy flow entering CHPS in computation period. $E_{g-x}^{"}$ $x \in \{e,h\}$ denotes the output exergy flow of CHPS in computation period, include electric exergy flow and thermal exergy flow. N_g denotes the non-energy cost of CHPS in computation period.

5.2. Exergy cost model considering main and auxiliary energy production of CHPS node in UEI

According to formula (2), the calculation of main output exergy cost in CHPS is given in formula (5):

$$c_{g\text{-}m}^{"} = \frac{c_g^{'} E_g^{'}}{\sum E_{g-m}^{"}} + \frac{N_g}{\sum E_{g-x}^{"}} \quad m \in \{e,h\} \quad x \in \{e,h\} \quad m \subseteq x \tag{5}$$

In formula (5), $\sum E_{g-x}^{"}$ denotes the total of main and auxiliary output exergy flow of CHPS in computation period. $\sum E_{g-m}^{"}$ represents the total of main output exergy flow of CHPS in computation period. N_g denotes the non-energy cost of CHPS in computation period.

According to formula (3), the calculation of auxiliary output exergy cost in CHPS is given in formula (6):

$$c_{g\text{-}a}^{"} = \frac{N_g}{\sum E_{g-x}^{"}} \quad x \in \{e,h\} \tag{6}$$

5.3. The comparison of exergy cost calculation between these two models

Some particular hour data of CHPS were collected in ENN Science & Technology Ltd. in Langfang at 2017. These data are given in table 2:

Table 2. Some particular hour data of CHPS node in Langfang ENN at 2017.

$c_g^{'}$ (¥/m^3)	$E_g^{'}$ (KW.h)	$E_{g-e}^{''}$ (KW.h)	$E_{g-h}^{''}$ (KW.h)	N_g (¥)
2.50	2985	1160	798	83.90

Tips: (1). The calorific value of natural gas for this node is 8500 kilocalorie (1 kilocalorie=0.0011627KW.h);
(2). The market price of natural gas is 3.12 ¥/ m^3, the estimated cost is 2.50 Yuan/ m^3 according to Internet;
(3). Due to company privacy, the non-energy cost is estimated at 10% of total cost of CHPS.

In this example, the results of these two models are show in table 3. For exergy cost model of main and auxiliary energy production, 3 scenarios are taken into consideration, which include defining electric energy as main output energy, thermal energy as main output energy, and both electric energy and thermal energy as main output energy. Using formula (4) to formula (6) calculates exergy cost of these two models.

Table 3. Exergy cost calculation result of two models (Unit: ¥/KW).

Projects	Traditional model	Proposed model		
		Electric energy	Thermal energy	Electric and thermal energy
Electric output exergy cost	0.428	0.694	0.043	0.428
Thermal output exergy cost	0.428	0.043	0.989	0.428

6. Discussion

6.1. Result discussion of the proposed and traditional model

In traditional model, the exergy cost of electric and thermal output is the same, 0.428 ¥/KW. In proposed model, if electric energy is treated as the main output exergy, the exergy cost is 0.694 ¥/KW and thermal output exergy cost is 0.043 ¥/KW. In proposed model, if thermal energy is treated as the main output exergy, the exergy cost is 0.989 ¥/KW and electric output exergy cost is 0.043 ¥/KW. In proposed model, if thermal and electric energy are all treated as main exergy, their output exergy cost is the same, 0.428 ¥/KW, just as the exergy cost of the traditional model. All these result list in table 3.

For the traditional exergy cost model provides the same cost of exergy, and the proposed exergy cost model also provides the same cost of exergy. So the proposed model will have the same results if treats all the exergy as the main. If different exergy takes different real exergy cost, the proposed exergy cost model obtains real exergy cost but the traditional cost model cannot. So if want the cost of the working exergy cost model to near the real exergy cost, the working exergy cost model must adopt proposed exergy cost model, the traditional exergy cost model maybe produce the fault exergy cost.

In reality scene if the proposed exergy cost model is adopt the calculation of the exergy cost of energy will be complicated and not the same comparing with different energy. For different exergy will produce different exergy cost in the proposed exergy cost model.

6.2. The characteristics, advantages and some problems of the proposed model

Compared to traditional exergy cost model in UEI, our exergy cost model in UEI considering main and auxiliary energy output has three new characteristics: Firstly, because the cost of input exergy apportioned to the cost of main output exergy completely, the cost of main output exergy in our proposed model is higher than traditional one. Generally, when this energy production mode of SIMO is applied, main output exergy is usually view as a necessary energy supplementary. Therefore, this higher cost is suitable to decide whether to use this energy production mode of SIMO, which can give us a cautious consideration from the aspect of exergy cost. Secondly, because only the non-energy part of auxiliary exergy cost is calculated, compared to traditional model, the cost of byproduct exergy in our model is lower. This lower cost is conforms to the decision of this auxiliary exergy usage, which means that auxiliary exergy should be fully used once it is produced due to its lower cost. Thirdly, if all of output energy regards as main output exergy, the calculation result of the proposed model is the same as traditional model.

There are also advantages of the proposed exergy cost calculation model considering main and auxiliary energy production. On one hand, no matter whether auxiliary output exergy is used, the cost of main and auxiliary output exergy is closer to the real exergy cost. On the other hand, because the main output exergy and auxiliary output exergy is comparatively independent, whether to use auxiliary output exergy does not affect the cost calculation of main output exergy.

In addition, some problems should consider before use proposed exergy cost model: Firstly, the relationship between main and auxiliary energy production has nothing to do with the production sequence of energy equipment. To a same kind of energy production nodes, the production sequence of main and auxiliary energy can vary for different energy urges. For instance, in the system of using ubiquitous machine to generate electric energy, thermal energy and cold energy, if there is a shortage of electric energy, electric exergy can viewed as main output exergy and thermal exergy and cold exergy as auxiliary output exergy. Similarly, if there is a shortage of thermal energy, thermal exergy can view as main output exergy and electric exergy and cold exergy as auxiliary output exergy. Secondly, main output exergy can be the combination of different energy forms. For example, in the system of using ubiquitous machine to generate electric energy, thermal energy and cold energy, electric exergy and thermal exergy can be both regarded as main output exergy and cold exergy as auxiliary output exergy in winter. Meanwhile, in summer, electric exergy and cold exergy are regard as main output exergy and thermal exergy as auxiliary output exergy. Thirdly, it is not necessary to use auxiliary output exergy. For example, in the system of using ubiquitous machine to generate electric energy, thermal energy and cold energy, in winter, cold exergy as auxiliary output exergy is not obligatory used; in summer, thermal exergy as auxiliary output exergy is not integrant used. Because the cost of auxiliary output exergy is quite low, the influence on total exergy cost can neglected.

7. Conclusion

We studied and improved traditional exergy cost model in this paper by proposing a brand new exergy cost apportionment model appropriate for energy transformation nodes of SIMO in UEI. In our improved model, the calculation of main output exergy cost must take both input exergy cost and non-energy cost into consideration. Comparatively, the calculation of auxiliary output exergy cost considers only non-energy cost into consideration. The advantage of this calculation method is that the cost of main and auxiliary exergy is much closer to the real exergy cost no matter whether auxiliary exergy is used. Compared with traditional exergy cost model, the calculation result of main output exergy cost in the proposed model is higher, which can help make the decision prudent whether to use this supplementary energy production mode. In the same time, the cost of auxiliary exergy is lower than the traditional model, which can benefit the whole energy efficiency of auxiliary exergy transformation in UEI. As a whole, the exergy cost apportionment model considering main and auxiliary energy output in UEI is more suitable for the practical needs of calculating exergy cost apportionment in the UEI scenario.

If the proposed exergy cost adopts commonly, the exergy cost will near the real exergy cost of energy, and the working exergy cost model will meaningful to decision organization. Nowadays, the traditional exergy cost model is common used, so the proposed exergy cost model has a broad applicability perspective if the exergy cost calculation will be easy such as calculating by computer.

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