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Research on External Fuel Exergy Contribution to the Multi-Energy Integrated System

Junli Zhang*, Jiong Shen, Yiguo Li, Bin Ge

Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, Southeast University, Nanjing, 2l0096，China

zjl_seu@seu.edu.cn

A matrix modelling method based on the production structure is proposed and a general exergy matrix model for the multi-energy integrated system is established, which provides a simple and effective tool for the contribution rate calculation of the external fuel exergy to the multi-energy integrated system. The proposed method is verified by a case study of a solar-aided 600 MW coal-fired power generation system. The influence of two fuel product definitions and different simplified systems on the calculation results is analyzed. The results show that the contribution rate of solar exergy is 4.24 % when the product is defined as the output exergy. But the solar exergy contribution rate is only 1.77 % when the product is defined as the exergy increment and output power. Inappropriate system simplification can also cause the contribution rate of external fuel to deviate from the original value.

1. Introduction

Multi-energy integrated system is currently attracting a lot of attention to achieve efficient and clean use of energy (Kostevšek et al. 2013), such as fossil fuel power plant complement with solar energy (Popov, 2011), hybrid wind-diesel system (Ibrahim et al., 2011) and photovoltaics/fuel cell/wind turbine (PVFCWT) hybrid power system (Lin et al., 2015) and so on.

The energy conversion process of the multi-energy integrated system is more complicated than that of the single-energy system (Jin et al. 2016). Many studies have been carried out based on the second law of thermodynamics for gaining in-depth knowledge of the multi-energy integrated system. Baghernejad et al. (2010) and later (2011) proposed the exergy analysis method for the Integrated Solar Combined Cycle System (ISCCS) to assess the plant performance and pinpoint sites of primary exergy destruction. Then the thermoeconomics concept is applied using genetic algorithm for optimization of an ISCCS that produces 400 MW of electricity, and the cost of electricity produced by steam turbine and gas turbine in the optimum design of the ISCCS are about 7.1 % and 1.17 % lower with respect to the base case. Calderón et al. (2011) applied exergy method to analyse the hybrid wind/solar/hydrogen system, which provides a useful reference for the understanding of these new systems. Integrating renewable energy with conventional coal-fired systems has received great attention in recent years. Cui et al., (2008) applied the coefficient of external bonds method to analyse the effect of solar heat on different parts of different capacity coal-fired units. The results show that better effects could be achieved only when high CEB exergy flow of coal-fired units is replaced by solar heat. The thermoeconomics structural theory was applied to perform a comparative study between the fuel-saving mode and power-boosting mode of solar aided power generation system and the results show that compared to coal-fired power generation system, coal consumption rate is decreased by 15.04 g/kWh in fuel-saving mode, but the unit thermo-economic cost of electricity is increased by 16.9 - 21.6 % due to the large investment of solar collector field (Zhai et al., 2016). Suresh et al. (2010) deals with the 4-E (namely energy, exergy, environment, and economic) analysis of solar thermal aided coal-fired power plants to establish their techno- economic viability.

The above researches mainly focus on the exergy loss distribution or the exergy cost of the integrated system. In this study, a key issue that the contribution rate of each energy resource to the product of the multi-energy integrated system is discussed. A matrix modelling method based on the production structure is proposed, and

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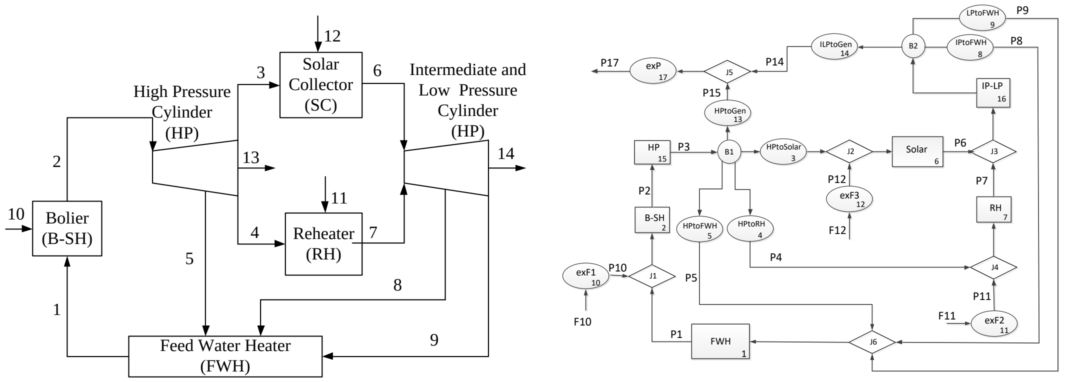
a general exergy matrix model for the multi-energy integrated system is established which provides the simple and effective support for the contribution rate calculation. Two important issues, i.e., structure simplification and fuel-product definition, are discussed based on the general exergy matrix model.

2. Fuel, product and production structure

In the structure theory of thermoeconomics, the complex energy system is often decomposed into multiple physical or logical components, and the various components are connected through various "flows" (such as quality, energy, cost, etc.), and the inputs and outputs of each component are defined by the concept of “fuel-product” (Berit et al., 1999). In this paper, the fuel flow (such as coal exergy, solar exergy and so on) that from the outside of the integrated system is called "external fuel", and the product flow (electricity, heat, cold, etc.) that outputs to the user from the integrated system is called "system product", and the input and output exergy of each component of the integrated system is called fuel and product.

Based on the fuel-product definition, the physical structure of the actual system as shown in Figure 1a can be transformed into the production structure as shown in Figure 1b. With the production structure, the complex coupling relationship between various components and exergy flows in the system can be better clarified. In the conventional production structure diagram, the rectangle represents the component with production function, the diamond (J) represents the collection component, the circle (B) represents the split component, and the input and output arrows represent the fuel flow (F) and the product flow (P). In order to facilitate the matrix construction of exergy flow, an elliptical component is added for the transfer of exergy in this study, and there is no decrease or increase in the component, and its product exergy is equal to its fuel exergy.



(a) Simplified schematic *(b) Production structure*

Figure 1: Simplified schematic and production structure of a solar aided coal-fired power generation system

3. The general matrix model of external fuel exergy contribution ratio

The following assumptions are made to carry out the general matrix model:

(1) The production structure is described by the following three types of components. One is the component with single fuel and single product, i.e., Class I component. The second one is the component with single fuel and multiple products, i.e., Class II component. The last one is the component with multiple fuels and single product, i.e., Class III component.

(2) Any external fuel and system product should be implemented with the Class I component.

(3) The product composition (meaning the contribution rate of each external fuel) of a single fuel component (Class I and Class II) is strictly equal to the composition of the component fuel.

(4) The composition of the external fuel is not affected by other external fuels.

(5) The product composition of the Class III component is determined by the proportion of each fuel of the component and its composition.

Based on above assumptions, the contribution rate of any k-th external fuel to the fuels and products of any component may be described as follows:

$$\alpha'_{lk} = 1, \alpha'_{ls} = 0 \qquad (s = 1, ..., K, s \neq k) \tag{1}$$

$$\alpha_{nk} = \alpha'_{nk} \qquad (n = 1, ..., N) \tag{2}$$

$$\alpha_{mqk} = \alpha'_{mk} \qquad (q = 1, 2, ..., Q_m) \tag{3}$$

$$\alpha_{ik} = \sum_{j=1}^{H_i} \varphi_{ij} \alpha'_{ijk} \tag{4}$$

where α is the production composition, α' is fuel composition, s is the number of the external fuel., K is the total number of external fuels, l is the number of the Class II component which fuel is the k-th external fuel, n is the Class I component number, N is the total number of Class I component, m is the Class II component number, q is the product number of the Class II component, Q_m is total product number of the m-th component, i is the Class III component number, j is the fuel number of the Class III component. H_i is the total fuel flow number of the Class III component. $\varphi_{ij} = F_{ji} / \sum_{h=1}^{H_i} F_{hi}$ represents the proportion of the j-th fuel exergy in the total fuel exergy of the i-th component.

Since Class II and Class III components only have the function of diversion and convergence of products, their fuels and products can be represented by products of Class I components, i.e., Eq(2) may be describe as follow:

$$\alpha'_{nk} = \sum_{j=1}^{N} \beta_{nj} \alpha_{jk} \qquad (n \neq l) \tag{5}$$

where $\beta_{nj} = P_{jn} / \sum_{h=1}^{N} P_{hn}$, P_{jn} is the quantity that the product exergy of the j-th component is used as the fuel of the n-class I component, $\sum_{h=1}^{N} P_{hn}$ is the total fuel exergy amount of the n-th class I component.

Then with the Eq(1), Eq(2) and Eq(5), a matrix may be expressed as follow:

$$\boldsymbol{\alpha}_k = \boldsymbol{\beta}\boldsymbol{\alpha}_k + \boldsymbol{\alpha}_{0k} \tag{6}$$

where $\boldsymbol{\alpha}_k = \begin{bmatrix} a_{1k} & a_{2k} & \cdots & a_{Nk} \end{bmatrix}^T$, $\boldsymbol{\alpha}_{0k} = \begin{bmatrix} 0 & \cdots & \overset{l-th}{1} & \cdots & 0 \end{bmatrix}^T$, $\boldsymbol{\beta} = \begin{bmatrix} \beta_{11} & \beta_{12} & \cdots & \beta_{1N} \\ \beta_{21} & \beta_{22} & \cdots & \beta_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ \beta_{N1} & \beta_{N2} & \cdots & \beta_{NN} \end{bmatrix}$.

According to the Eq(6), Eq(7) can be obtained with which the k-th fuel exergy contribution to the products of each Class I component may be calculated

$$\boldsymbol{\alpha}_k = (\boldsymbol{I} - \boldsymbol{\beta})^{-1} \boldsymbol{\alpha}_{0k} \tag{7}$$

where $\boldsymbol{I}$ is identity matrix. $\boldsymbol{I}$, $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}_{0k}$ are determined by the production structure and the amount of fuel exergy and product exergy of each component.

Similarly, the contribution rate of all external fuels to the integrated system is calculated as follow:

$$\boldsymbol{\alpha} = (\boldsymbol{I} - \boldsymbol{\beta})^{-1} \boldsymbol{\alpha}_0 \tag{8}$$

where $\boldsymbol{\alpha} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1K} \\ a_{21} & a_{22} & \cdots & a_{2K} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1} & a_{N2} & \cdots & a_{NK} \end{bmatrix}$, $\boldsymbol{\alpha}_0 = \begin{bmatrix} \boldsymbol{\alpha}_{01} & \boldsymbol{\alpha}_{02} & \cdots & \boldsymbol{\alpha}_{0K} \end{bmatrix}$.

4. Case study

The model is verified by a tower-type solar-assisted 600 MW coal-fired power generation system, as shown in Figure 1. The values of exergy flows are shown in Table 1.

Table 1: Values of exergy flows

Num.	Exergy/kW	Num.	Exergy/kW	Num.	Exergy/kW	Num.	Exergy/kW	Num.	Exergy/kW
1	183,345.23	2	786,172.12	3	43,972.01	4	443,810.25	5	87,508.14
6	57,219.08	7	577,408.81	8	119,553.75	9	72,793.66	10	114,9070.56
11	255,044.16	12	72,901.31	13	194,084.22	14	40,6476.32		

First, the production structure is drawn based on the physical structure, as shown in Figure 1b. Then $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}_0$ is calculated according to exergy values in Table 1, as shown in Table 2, where (R,C) represents the number of row and column of the matrix and the other elements in the matrix are 0 except the value mentioned in Table 2.

Table 2: Values of $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}_0$

Para.	(R,C)	value	(R,C)	value	(R,C)	value	(R,C)	value	(R,C)	value	(R,C)	value
$\boldsymbol{\beta}$	(1,4)	0.313	(1,8)	0.427	(1,9)	0.26	(2,1)	0.138	(2,10)	0.862	(3,15)	1
	(4,15)	1	(5,15)	1	(6,3)	0.376	(6,12)	0.624	(7,5)	0.635	(7,11)	0.365
	(8,16)	1	(9,16)	1	(13,15)	1	(14,16)	1	(15,2)	1	(16,6)	0.09
	(16,7)	0.91	(17,13)	0.323	(17,14)	0.677						
$\boldsymbol{\alpha}_0$	(15,1)	1	(16, 2)	1	(17, 3)	1						

Finally, $\boldsymbol{\alpha}$ is calculated according to Eq(8), as shown in Table 3, where $\boldsymbol{\alpha}_B$, $\boldsymbol{\alpha}_R$ and $\boldsymbol{\alpha}_S$ represent boiler fuel exergy (coal exergy), reheater fuel exergy (coal exergy) and solar exergy.

Table 3: External fuel exergy contribution rates of I component products

Comp.	$\boldsymbol{\alpha}_B$ (%)	$\boldsymbol{\alpha}_R$ (%)	$\boldsymbol{\alpha}_S$ (%)	Comp.	$\boldsymbol{\alpha}_B$ (%)	$\boldsymbol{\alpha}_R$ (%)	$\boldsymbol{\alpha}_S$ (%)
1	70.32	25.38	4.30	10	100	0	0
2	95.92	3.49	0.59	11	0	100	0
3	95.92	3.49	0.59	12	0	0	100
4	95.92	3.49	0.59	13	95.92	3.49	0.59
5	95.92	3.49	0.59	14	58.67	35.34	5.99
6	36.09	1.31	62.60	15	95.92	3.49	0.59
7	60.91	38.71	0.38	16	58.67	35.34	5.99
8	58.67	35.34	5.99	17	70.71	25.05	4.24
9	58.67	35.34	5.99				

The form of Eq(8) is versatile and very suitable for computer implementation, which can greatly improve the efficiency of quantitative analysis of complex multi-energy integrated systems. There are two issues to be aware of when applying: one is the simplification of the system, and the other is the fuel-product definition.

4.1 Production structure simplification

Simplifying the production structure of Figure 1b with combining the high, intermediate and low pressure cylinders, as shown in Figure 2, and the contribution ratio calculation results are shown in Table 4.

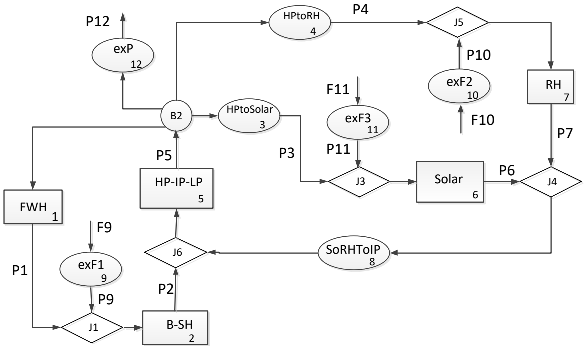


Figure 2: Simplified production structure

Compared with Table 3, it can be found that the contribution rate of solar energy to system products is reduced to 3.86 %. The reason is that in the original structure, most of the solar exergy generate power through the intermediate and low pressure cylinders except a small part passes through the regenerative system and the boiler into the high pressure cylinder to generate power externally, however, the role of the intermediate and low pressure cylinders is weakened in the simplified structure which resulting in the declined of solar exergy contribution.

Table 5 shows various simplified scheme and their results. The advantage of simplified production structure is that the complexity of the calculation drops dramatically, which can be known from the dimension of matrix in Table 5. However, the disadvantage of simplified production structure is significant, i.e., the external fuel exergy contribution value of the simplified production structure is seriously deviated from the original value.

Table 4: External fuel exergy contributions of simplified production structure

Comp.	α_B (%)	α_R (%)	α_S (%)	Comp.	α_B (%)	α_R (%)	α_S (%)
1	73.34	22.80	3.86	7	46.58	50.97	2.45
2	96.33	3.14	0.53	8	44.87	47.15	7.99
3	73.34	22.80	3.86	9	100	0	0
4	73.34	22.80	3.86	10	0	100	0
5	73.34	22.80	3.86	11	0	0	100
6	27.59	8.58	63.83	12	73.34	22.80	3.86

Table 5: Production components of each simplified scheme

Comp.	Simplified scheme				
	1	2	3	4	5
B-SH	①	①	①	①	①
RH	②	②			
FWH	③	③	②		
HP	④	④			
IP-LP	⑤				
Solar	⑥	⑤	③	②	
β dimension	17	12	9	7	5
α_S (%)	4.24	3.86	3.65	2.48	4.94

4.2 Fuel-product definition

There are mainly two fuel-product definitions: one is that the fuel is defined as the input exergy of components and the product is defined as the output exergy of components. The second is that the exergy increment and output power of the working medium is taken as the product, and other exergy flows are as fuels. The production structure shown in Figure 2 is based on the former definition. The production structure corresponding to the latter definition is shown in Figure 3. External fuel exergy contributions ration based on the latter definition is shown in Table 6.

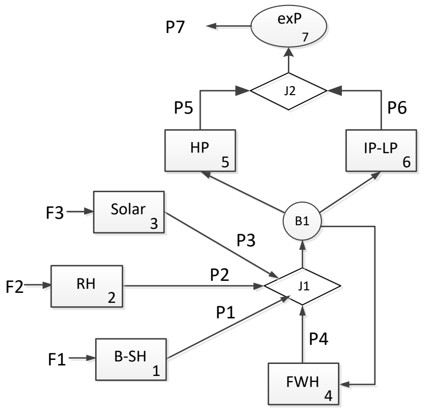


Figure 3: Production structure with the latter definition

Table 6: External fuel exergy contributions rate based on the latter definition

Comp.	α_B (%)	α_R (%)	α_S (%)
1	100	0	0
2	0	100	0
3	0	0	100
4	80.41	17.82	1.77
5	80.41	17.82	1.77
6	80.41	17.82	1.77
7	80.41	17.82	1.77

As shown in Table 6, the contribution of solar energy to system products is only 1.77 %, which is much lower than the 4.24 % of the former definition. The reason is that the transfer function of the component is amplified under the former definition. For example, solar exergy was completely lost for some reason at the moment of entering the component, resulting in no increase or decrease in the product exergy of the component. According to the previous definition, the product of the component is the output exergy of the component, so the solar exergy contribution of the component product is equal to $E_{12} / (E_{12} + E_3)$ = 62.38 %, however, the result is 0 % according to the later definition. From this point of view, the latter definition is more reasonable than the former definition.

5. Conclusions

The products in the multi-energy integrated system are the result of the interaction of multiple external fuels. The calculation of the contribution of each external fuel is of challenge. This paper proposes a matrix modelling method based on production structure, and establishes a general matrix model which easy to get the contribution rate of the external fuel exergy. The proposed method is verified with a solar-assisted 600 MW coal-fired power generation system. The effects of the production structure simplification and fuel-product definition on the external fuel exergy contribution are analyzed. The results show that the production structure should be decomposed in detail to increase the accuracy of the results. The definition that uses the exergy increment and output power as product is more reasonable than the definition that uses the output exergy as product.

Acknowledgments

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References

Baghernejad A., Yaghoubi M., 2010, Exergy analysis of an integrated solar combined cycle system. Renewable Energy, 35, 2157-2164.

Baghernejad A., Yaghoubi M., 2011, Exergoeconomic analysis and optimization of an Integrated Solar Combined Cycle System (ISCCS) using genetic algorithm, Energy Conversion and Management, 52, 2193-2203.

Berit E., Serra L., Valero A., 1999, Structural theory as standard for thermoeconomics, Energy Conversion & Management, 40, 1627-1649.

Calderón M., Calderón A.J., Ramiro A., González J.F., González I., 2011, Evaluation of a hybrid photovoltaic-wind system with hydrogen storage performance using exergy analysis, International Journal of Hydrogen Energy, 36, 5751-5762.

Cui Y., Yang Y., Yang Z., Hou H., Guo X., 2008, Coupling Mechanism of Solar Supported Coal-fired Electric Generation System, Proceedings of the CSEE, 28, 99-104.

Ibrahim H., Younès R., Basbous T., Ilinca A., Dimitrova M., 2011, Optimization of diesel engine performances for a hybrid wind-diesel system with compressed air storage, Energy, 36, 3079-3091.

Jin H., Sun J., Xu C., Zhang D., Shi L., 2016, Research on theory and method of multi-energy complementary Distributed CCHP system, Proceedings of the CSEE, 32, 3150-3160.

Kostevšek A., Cizelj L., Petek J., Čuček L., Varbanov P. S., Klemeš J. J., Pivec A., 2013, Use of renewables in rural municipalities' integrated energy systems, Chemical Engineering Transactions, 35, 895–900.

Lin M., Adi V. S. K., Chang C., 2015, Flexible photovoltaics/fuel cell/wind turbine (PVFCWT) hybrid power system designs, Chemical Engineering Transactions, 45, 559-564.

Popov D., 2011, An option for solar thermal repowering of fossil fuel fired power plants, Solar Energy, 85, 344-349.

Suresh M.V.J.J., Reddy K.S., Kolar A.K., 2010, 4-E (Energy, Exergy, Environment, and Economic) analysis of solar thermal aided coal-fired power plants, Energy for Sustainable Development, 14, 267-279.

Zhai R., Liu H., Li C., Zhao M., Yang Y., 2016, Analysis of a solar-aided coal-fired power generation system based on thermo-economic structure theory, Energy, 102, 375-387.