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Quantification of multi-energy coupling effect in integrated energy systems

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ABSTRACT

As one of the core characteristics of integrated energy system (IES), the coupling effect between energy carriers has been a hot topic in existing studies. However, from the perspective of the whole IES, the quantification of the extent of multi-energy coupling is rarely discussed. To solve this problem, this paper establishes an energy coupling index (ECI) to quantify the multi-energy coupling effect considering energy conversion process. Based on the operation data of an industrial park, a case study is carried out to validate the rationality of the proposed index. The calculation results show that when energy coupling unit connects into the IES, ECIs of different energy carriers show overall upward trend, which means ECI can effectively characterize the coupling status of IES. ECI could quantify and assess the design and operation scheme of IES.

Keywords: coupling effect, quantification, integrated energy system

NONMENCLATURE

Abbreviations	
CCHP	Combined Cooling, Heating and Power
CHP	Combined Heat and Power
ECI	Energy Coupling Index
EH	Energy Hub
IES	Integrated Energy System
ECI	Energy Coupling Index
Symbols	
i, j	Type of energy carrier
t	Hour
r	Response of energy carrier
d	Disturbance of energy carrier
D	Energy demand at the output
C	Energy purchasing price
P	Input energy consumption
Ω	Value of energy coupling index
q	Consumption of energy equipment
L	Production of energy equipment
a, b, c	Cost coefficient of CHP unit
R_{chp}	Heat-electricity ratio of CHP unit
$L^{\min}$	Lower bound of energy equipment
$L^{\max}$	Upper bound of energy equipment
η_{gb}	Conversion efficiency of gas boiler
COP_{wc}	Chiller's coefficient of performance

1. INTRODUCTION

The development of integrated energy system (IES) offers an important opportunity to improve the efficiency of energy utilization and increase the penetration of renewable energy resource, which is mainly brought by the interaction of different energy carriers [1, 2]. Along with the increase in the fluctuating energy production, the benefit of such interaction is increased through providing needed flexibility [3]. In order to clarify the role of coupling effect in IES, researchers have carried out series of studies including coupling optimization and analysis.

In the perspective of coupling optimization, there are extensive discussions based on mixed-integer linear programming (MILP). Lu *et al*. [4] established a correlation model for a combined cooling, heating and power (CCHP) coupled multi-energy system of which the optimization result shows that the total annual operating cost can be reduced by 36.2% compared with the traditional sub-system. Si *et al*. [5] formulated a multi-energy coupling matrix for residential prosumer and a resource-task network for industrial prosumer to optimize the local operations. Liu *et al*. [6] proposed a heat-electricity-coupled model for maximizing profit by dynamically selecting the following-thermal-load mode and the following-electric-load mode.

In terms of studies on coupling analysis, Wei *et al*. [7] investigated the coupling characteristics of IES to reveal the energy interaction between conflicting objectives in the operation of CCHP system. Jiang *et al*. [8] modeled the coupling characteristics of industrial consumers' multi-energy demands and analyzed the impact of the coupling characteristics on the dispatch cost. Pan *et al*. [9] proposed a coupling component model to analyze the coupling mechanisms of IES and revealed the interaction between electricity and heat.

As multi-energy interaction is one of the key drivers for system integration, how tight different energy carriers couple with each other is a question remained to be answered. However, the above studies mainly focus on the modeling and qualitative analysis of coupling relationship. In such context, the concept of coupling is vague and implicit although the modeling and analysis are based on either physical law or data-driven methods. Even though the coupling effect is frequently mentioned by existing literature, such effect has not been given a quantitative definition. Hence, evaluation method of multi-energy coupling effect deserve an investigation to provide a new perspective of IES analysis.

This paper proposes an energy coupling index (ECI) and the corresponding evaluation model to quantify the coupling effect among energy carriers while energy conversion is considered. Furthermore, a case study is carried out to validate the rationality of ECI by changing the IES operating configuration with and without combined heat and power (CHP) unit.

2. METHODOLOGY

2.1 energy coupling index

According to energy hub (EH) concept [10], integrated energy system can be formulated as an input-output model. EH communicates energy carriers at the input and output via the connection and transform characteristics of components in IES, as shown in Fig. 1.

Based on the input-output model of IES, the coupling effect can be described as the influence of disturbance in one energy carrier on the other. It should be pointed out that without demand response, the energy consumption at the output could not be adjusted. Energy demand should be satisfied by real-time dispatch under normal operation, which means disturbance at the output has no influence on other output-side energy carriers. Therefore, this paper only discusses the influence on input side when disturbance appears in one of energy carriers at the input or output, as illustrated in Fig. 2.

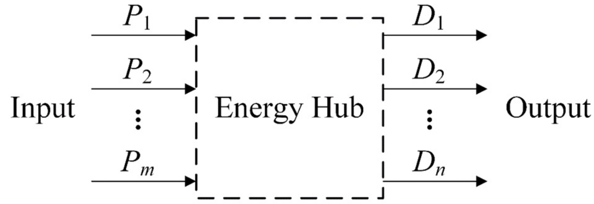


Fig 1 Input-output model of IES.

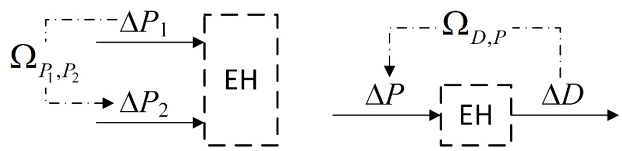


Fig 2 Coupling effect in IES.

Under the above mechanism, energy coupling index is given as follow:

$$\Omega_{i,j} = \frac{r_j}{d_i} \tag{1}$$

Where $\Omega_{i,j}$ is the ECI describing the coupling extent between energy carrier *i* and *j*. d_i is the disturbance occurred in energy carrier *i*. r_j is the corresponding response of energy carrier *j*.

2.2 evaluation model

Response defined in this paper is the variation of one energy carrier following the other one by regulation, which depends on the operating strategy. Since most of IES operators aim at minimizing the operating cost, this paper adopts economic operating strategy to establish an operation objective function:

$$\min \quad f(\mathbf{D}) = \sum_{k=1}^{m} C_i P_i \tag{2}$$

Where $f(\mathbf{D})$ is the operation objective function under a certain demand set $\mathbf{D} = [D_1, D_2, ..., D_n]$. C_i and P_i are respectively the purchase price and the consumption of input energy carrier *i*.

Therefore, ECI between input and output at time *t* can be expressed as:

$$\Omega_{i,j,t} = \left| \frac{P_{j,t} - P_{j,t}|_{\min f(D_i + \Delta D_i)}}{\Delta D_i} \right| \tag{3}$$

And ECI between both input is given by:

$$\Omega_{i,j,t}=\left|\frac{P_{j,t}-P_{j,t}|_{\min f(D_{i,t}),P_{i,t}+\Delta P_i}}{\Delta P_i}\right| \tag{4}$$

Where ΔD_i and ΔP_i are the disturbance imposed on energy carrier *i* at the output and input, respectively. $P_{j,t}$ is the actual quantity of input-side energy carrier *j* at time *t*, while $P_{j,t}|_{\min f(D_i+\Delta D_i)}$ and $P_{j,t}|_{\min f(D_{i,t}),P_{i,t}+\Delta P_i}$ are the optimal quantity under a specific condition. In particular, amplitudes of disturbance and response are measured in kilowatt.

The following assumptions are made for evaluating:

(1) The evaluation model only depends on the current status and structure of the IES to evaluate the ECI under normal operation condition.

(2) Disturbances of all energy carriers are set to one kW to avoid the excessive disturbance resulting in system reconfiguration, which is beyond the scope of this paper.

(3) The change of switch status is neglected during the evaluating process.

2.3 model constraints

The IES studied in this paper consist of gas-fired CHP, gas boilers and water chiller. With electricity imported from grid and natural gas as inputs, the system mainly provides electricity, cooling and heating to the demand side. The IES structure is depicted in Fig. 3. To make the evaluation model work, there are several constraints must be satisfied based on the given system structure.

2.3.1 gas-fired CHP

The relationship between gas consumption and electricity production of CHP are usually quadratic. For unit efficiency, the heat-electricity ratio remains constant and the output power is limited in a certain range.

$$q_{g,chp}=aL_{e,chp}^2+bL_{e,chp}+c \tag{5}$$

$$R_{chp}=\frac{L_{h,chp}}{L_{e,chp}} \tag{6}$$

$$L_{e,chp}^{\min}\le L_{e,chp}\le L_{e,chp}^{\max} \tag{7}$$

Where $q_{g,chp}$ is the gas consumption of CHP under electricity production $L_{e,chp}$ and heat production $L_{h,chp}$. a, b, and c are cost coefficient of the CHP unit. R_{chp} is the design heat-electricity ratio. $L_{e,chp}^{\min}$ and $L_{e,chp}^{\max}$ are respectively the lower and upper bound of electricity production.

2.3.2 gas boiler

Boiler's gas consumption $q_{g,gb}$ is directly relative to heat production $L_{h,gb}$ and conversion efficiency η_{gb}.

$$q_{g,gb}=\frac{L_{h,gb}}{\eta_{gb}} \tag{8}$$

$$L_{h,gb}^{\min}\le L_{h,gb}\le L_{h,gb}^{\max} \tag{9}$$

Where $L_{h,gb}^{\min}$ and $L_{h,gb}^{\max}$ are respectively the lower and upper bound of heat production.

2.3.3 water chiller

The model of water chiller is similar to gas boiler's, which can be formulated as:

$$q_{e,wc}=\frac{L_{c,wc}}{COP_{wc}} \tag{10}$$

$$L_{c,wc}^{\min}\le L_{c,wc}\le L_{c,wc}^{\max} \tag{11}$$

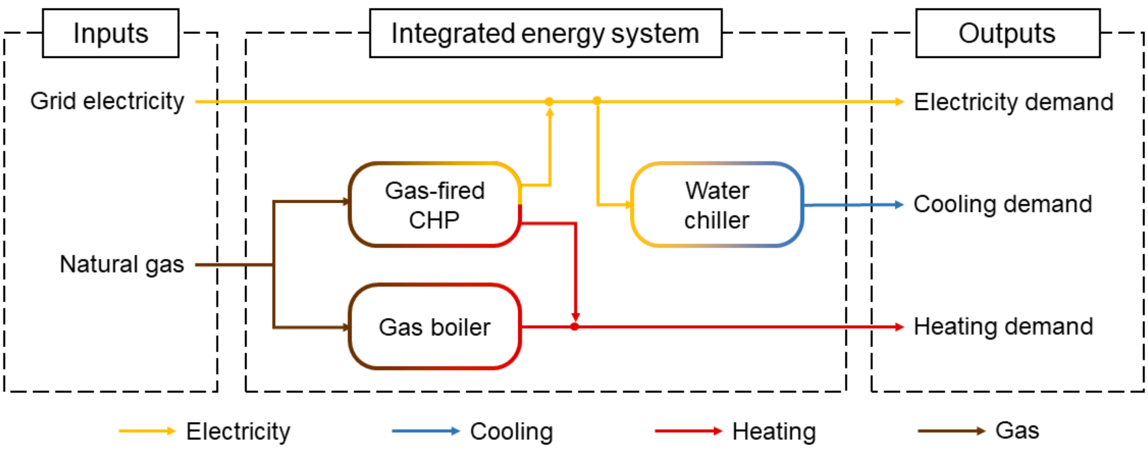


Fig 3 IES structure connecting generation units with energy carriers at input and output.

Where $q_{e,wc}$ is the electricity consumption of water chiller. COP_{wc} is the coefficient of performance. $L_{c,wc}^{\min}$ and $L_{c,wc}^{\max}$ are respectively the lower and upper bound of cooling production $L_{c,wc}$.

2.3.4 energy balance

The IES under normal operating condition should always meet the following energy balance equations:

$$P_e = D_e + q_{e,wc} - L_{e,chp} \tag{12}$$

$$L_{h,chp} + L_{h,gb} = D_h \tag{13}$$

$$L_{c,wc} = D_c \tag{14}$$

$$P_g = q_{g,chp} + q_{g,gb} \tag{15}$$

Where P_e and P_g are respectively the quantity of input-side electricity and natural gas. D_e, D_h and D_c are consumption of output-side electricity, heating and cooling.

3. CASE STUDY

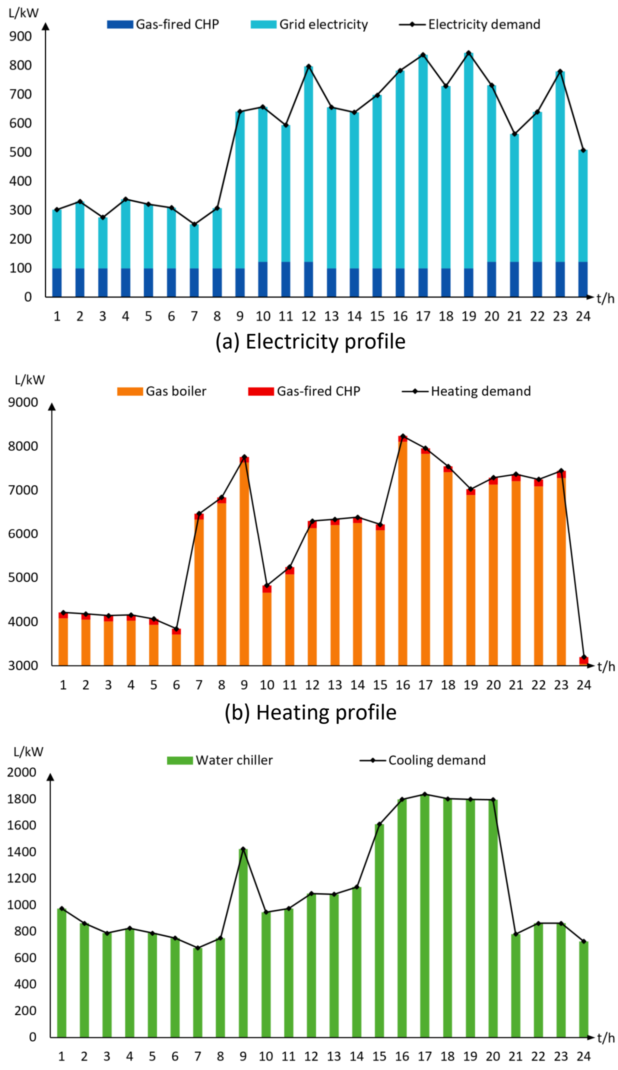
The case study carried out in this paper locates in Shaanxi province, China. It is an IES serving industrial park. Heating and cooling are two main forms of energy supply to meet the needs of industrial production. The equipment parameters of the IES in the park are listed in Tab. 1. The purchasing price of natural gas is constantly ¥2.23/Nm^3, while electricity's varies with time of use, as shown in Tab. 2. Using hourly dispatch interval, the demand profile and energy equipment load of a typical day in this park is illustrated in Fig 4.

Table 1 Equipment parameters of the IES

Parameter	Unit	Value
a	(m^3/kWh)^2	0.0016
b	Nm^3/kWh	0.16
c	kW	25
R_{chp}	1	1.315
$L_{e,chp}^{\min}$	kW	100
$L_{e,chp}^{\max}$	kW	200
η_{gb}	kWh/Nm^3	9.626
$L_{h,gb}^{\min}$	kW	2120
$L_{h,gb}^{\max}$	kW	8400
COP_{wc}	1	5.335
$L_{c,wc}^{\min}$	kW	500
$L_{c,wc}^{\max}$	kW	1974

Table 2 Electricity purchasing price of the IES

Time of use	Purchasing price (¥/kWh)
23:00-7:00	0.31
7:00-8:00	0.56
8:00-11:00	0.926
11:00-18:00	0.56
18:00-23:00	0.926



(a) Electricity profile

(b) Heating profile

(c) Cooling profile

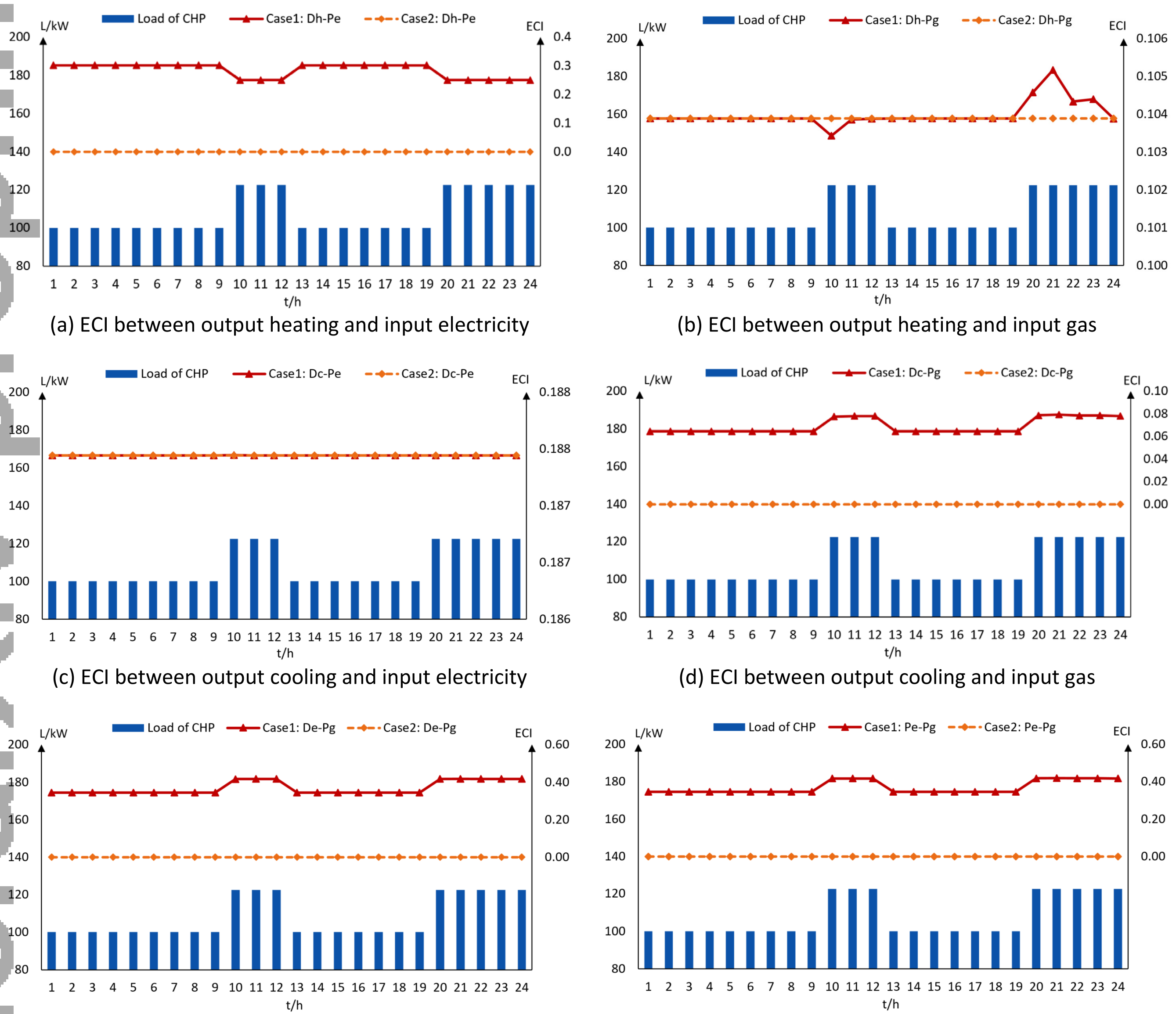
Fig 4 Demand profile and energy equipment load of a typical day in the industrial park

This paper considers two kinds of IES configuration, one with gas-fired CHP on (Case 1) while the other keeps it off (Case 2). Based on the calculation results, analysis and comparison of the relationship between coupling characteristics and ECI is carried out.

4. RESULTS AND DISCUSSION

Under the cases with and without gas-fired CHP, the calculation results of ECI between different energy carriers are shown in Fig. 5. The ECI curves have various shape depending on the selected energy carriers and the structure of IES.

In Fig. 5(a), the ECI between output heating and input electricity range from 0.25 to 0.3, changing with load of gas-fired CHP. The ECI drops due to the decrease of input electricity caused by unchanged electricity demand and increased output of CHP. Without CHP unit, the ECI is always zero since there is no component connecting the heating carrier and electricity carrier. In Fig. 5(b), the ECIs in case 1 and case 2 are approximately the same because the gas boiler takes on the task of basic heating load. Therefore, there are only minor fluctuations on the ECI curve along with the change of CHP load, which is mainly brought by the difference in the energy efficiency of various heating equipment. The ECI curve in Fig. 5(c) is akin to that in Fig. 5(b). Since the input electricity can flexibly response to the disturbance on cooling demand, the state of CHP has little effect on the ECI between output cooling and input electricity. The cooling carrier and gas carrier are communicated by the CHP unit. So the ECI curve shown in Fig. 5(d) is related to the switch state and load of the unit, similar to Fig. 5(a). It's remarkable that the ECI in Fig. 5(d) is very small comparing to Fig. 5(c), which means electricity carrier dominates the coupling effect of cooling demand. As can be seen from Fig. 5(e) and Fig. 5(f), the ECI between



(a) ECI between output heating and input electricity
(b) ECI between output heating and input gas
(c) ECI between output cooling and input electricity
(d) ECI between output cooling and input gas
(e) ECI between output electricity and input gas
(f) ECI between input electricity and input gas

Fig 5 Calculation results of ECI between different energy vecotrs under cases with and without gas-fired CHP electricity and gas increases when the CHP load is upward, and the value drops to zero when CHP unit disconnects. The result is sensitive to the load of the unit since the gas fired CHP is the unique technology to interact electricity and natural gas in this IES. From the perspective of energy carrier, the curves in Fig. 5(e) and Fig. 5(f) keep consistent both on the aspect of values and trends. It is mainly because they share the same two energy carriers in IES. This phenomenon shows that two energy carriers should have the same ECI value whether from the angle of input or output.

Interestingly, the ECI between cooling and gas, and between electricity and gas, similar to the ECI between output heating and input electricity, become zero after losting the connection provided by gas-fired CHP. Futhermore, it can be seen from Fig. 5 that the change of ECI is tightly associated with the load of CHP, which is thought to be a typical energy coupling component. The above analysis shows that the energy coupling index proposed in this paper can explain the coupling characteristics of IES.

5. CONCLUSIONS

This paper establishes an energy coupling index to quantify the coupling effect of IES and proposes an economic-based evaluation model to assess the ECI according to the energy configuration of IES. The calculation results are obtained and analyzed through a case study with and without energy coupling component in a given IES. The following conclusions can be drawn:

(1) The proposed index can effectively quantify the coupling extent of IES.

(2) ECI curve varies with the load of energy coupling component. When the component disconnects, the ECI value of the corresponding energy carriers will have an obvious drop.

(3) ECI of an energy carrier is dominated by the energy carrier which provides basic load.

(4) Each two energy carriers should have the same ECI value whether from the angle of input or output.

Overall, this paper provides a new perspective to understand the coupling effect between different energy carriers of IES. However, this paper only use a simple case for convenience of validation. The performance of ECI on complex IES is not clear. Besides, the ECI in this paper is only for operation stage. Evaluation method at planning stage needs further investigation. Moreover, coupling analysis with demand response also deserves attention. These are the points worth exploring in the future research.

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