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Energy saving analysis and management modeling based on index decomposition analysis integrated energy saving potential method: Application to complex chemical processes

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A B S T R A C T

Energy saving and management of complex chemical processes play a crucial role in the sustainable development procedure. In order to analyze the effect of the technology, management level, and production structure having on energy efficiency and energy saving potential, this paper proposed a novel integrated framework that combines index decomposition analysis (IDA) with energy saving potential method. The IDA method can obtain the level of energy activity, energy hierarchy and energy intensity effectively based on data-drive to reflect the impact of energy usage. The energy saving potential method can verify the correctness of the improvement direction proposed by the IDA method. Meanwhile, energy efficiency improvement, energy consumption reduction and energy savings can be visually discovered by the proposed framework. The demonstration analysis of ethylene production has verified the practicality of the proposed method. Moreover, we can obtain the corresponding improvement for the ethylene production based on the demonstration analysis. The energy efficiency index and the energy saving potential of these worst months can be increased by 6.7% and 7.4%, respectively. And the carbon emissions can be reduced by 7.4–8.2%.

1. Introduction

Nowadays, environmental protection and energy-saving emission reduction has become the theme of society. The industrialization of a country is mainly affected by the chemical productivity, especially the ethylene productivity of complex chemical industries. The present demand for the ethylene production is over 155 million tons per year and is still growing [1,2]. In 2014, the ethylene production of China Petrochemical Corporation and China National Petroleum Corporation was 10,420 kt/a and 4976 kt/a, respectively. However, the average fuel and power consumption was 571.39 kg per ton of ethylene [3] and 616.7 kg per ton of ethylene [4], respectively. Thus the energy efficiency level of ethylene production is far lower than the international advanced level in chemical industry [5] or petroleum industry [6]. Moreover, more than 50% of the ethylene plants operating costs come from the cost of energy consumption of ethylene [7]. Therefore, energy saving analysis and management is an effective way to improve the productivity and energy efficiency of ethylene productivity. Meanwhile, reducing the carbon emissions of the ethylene industry has great significance to the energy saving and emission reduction of the whole society [8,9].

Therefore, we put forward an integrated framework which combines the IDA of energy performance with energy-saving potential analysis. The IDA method can obtain the level of energy activity, energy hierarchy and energy intensity effectively based on data-drive to reflect the impact of energy usage. The energy-saving potential method can verify the correctness of the improvement direction proposed by the IDA method. Meanwhile, energy efficiency improvement, energy consumption reduction and energy savings can be visually discovered by the proposed framework. In addition, this method is applied to analyze and manage energy-saving of the ethylene production process. The results of case study show the effectiveness and practicability of this method. In our experiment, the worst energy efficiency index can be increased by 6.7%, and the worst energy-saving potential can be increased by 7.4%.

Our recent work is shown as followed. Section 2 introduces the related work and Section 3 introduces the IDA method and the energy-saving potential method in detail. Then, Section 3 describes

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Symbols

SEC	synthesize energy consumption
IDA	index decomposition analysis
EEI	energy efficiency index
EPI	energy performance index
ES	energy saving
EH	energy hierarchy
P	energy saving potential
EEI_*avg*	energy efficiency index based on the average value of last year
EEI_*min*	energy efficiency index based on the minimum value of last year
EEI_*navg*	energy efficiency index based on the average value of the nearest months
EEI_*nmin*	energy efficiency index based on the minimum value of the nearest months
EEI_*assign*	energy efficiency index based on the assign value of the assign month
EPI_*avg*	energy performance index based on the average value of last year
EPI_*min*	energy performance index based on the minimum value of last year
EPI_*navg*	energy performance index based on the average value of the nearest months
EPI_*nmin*	energy performance index based on the minimum value of the nearest months
EPI_*assign*	energy performance index based on the assign value of the assign month
ES_*avg*	energy saving index based on the average value of last year
ES_*min*	energy saving index based on the minimum value of last year
ES_*navg*	energy saving index based on the average value of the nearest months
ES_*nmin*	energy saving index based on the minimum value of the nearest months
ES_*assign*	energy saving index based on the assign value of the assign month
EH_*avg*	energy hierarchy index based on the average value of last year
EH_*min*	energy hierarchy index based on the minimum value of last year
EH_*navg*	energy hierarchy index based on the average value of the nearest months
EH_*nmin*	energy hierarchy index based on the minimum value of the nearest months
EH_*assign*	energy hierarchy index based on the assign value of the assign month
P_*avg*	energy saving potential index based on the average value of last year
P_*min*	energy saving potential index based on the minimum value of last year
P_*navg*	energy saving potential index based on the average value of the nearest months
P_*nmin*	energy saving potential index based on the minimum value of the nearest months
P_*assign*	energy saving potential index based on the assign value of the assign month

the framework of the integrated method. Section 4 presents case study of energy optimization and analysis of ethylene production industry based on the proposed method that combining the IDA of energy performance with energy-saving potential analysis. Finally, the discussion and the conclusion are obtained in Sections 5 and 6, respectively.

2. Related work

There are many methods to analyze energy efficiency, such as the index method and the mean method [10]. But the energy saving knowledge cannot be applied to guide the energy efficiency analysis of actual situation. The data fusion method is much better to analyze the energy efficiency of ethylene plants. Zhou et al. propose a two stage data envelopment analysis (DEA) model to assess energy efficiency, which takes undesirable outputs into account and is able to recognize energy mix effect on energy congestion [10]. Geng et al. propose an extraction method based on data fusion for ethylene industry [11], and the hierarchical linear optimal fusion algorithm has been used for energy consumption indices acquisition [12]. But they do not consider the impact factors of energy consumption indicators. Kleemann et al. optimize the recovering method to save energy in chemical processes [13]. However, it does not take the economic cost of restructuring industrial plants into consideration. The DEA has been widely used for efficiency analysis of industrial production [14] and optimization process [15]. Geng et al. analyze the performance efficiency of China's ethylene plants using the DEA integrated analytic hierarchy process (AHP) [16] and DEA-cross model [17]. Han et al. proposed a fuzzy DEA cross-model to analyze energy efficiency of complex chemical processes [18]. Bi et al. investigates the relationship between fossil fuel consumption and environmental regulation of China's thermal power generation by the DEA model [19]. However, the efficiency discrimination of DEA will be very poor when more than a third of efficiency values are set to 1 [20,21]. Han et al. propose a method that combines DEA and artificial neural network (ANN) [22]. And Olanrewaju et al. integrated IDA-ANN-DEA to evaluate and optimize energy consumption in industrial sectors [23] and to assess energy potential in South African industry [24]. However, they did not take the local minimization problem, convergence rate and the structure of traditional ANN into account [25]. Also, these methods are used to evaluate the broad industry, but not ensure the specific production process and offer guidance to the process. The existing energy optimization and analysis methods in the complex chemical processes are insufficient. Thus the improving methods need to be pointed out.

The IDA is a popular tool for studying changes in energy consumption over time in a country or region [26–28]. Various studies have contributed to the use of the IDA [29], Unander et al. uses this method to decompose the IEA countries' energy-use [30]. In Brazil, the IDA has been used to decompose energy use [31]. Hatzigeorgiou et al. decomposes the CO_2 emissions in Greece during 1990–2002 into four factors: energy intensity effect, income effect, population effect fuel and share effect using the IDA, and concludes that the main element is income effect [32]. Hammond et al. uses decomposition analysis to separate the contributions of changes into five parts to the reduction in carbon emissions. And reduction in energy intensity is the primary reason [33]. Meanwhile, the IDA can quantify the contribution caused by the percentage change of individual attributes, such as the real energy intensity index and the structural change index [27].

Although the energy efficiency analysis of the IDA can obtain quantified energy-saving space, it is necessary to further distinguish the technological energy-saving potential and the structure energy-saving potential of complex chemical processes and analyze the main factors that influence the technological energy-saving potential and the structure energy-saving potential. Therefore, we should consider two aspects comprehensively and further make analysis of energy-saving potential to more accurately locate the main reasons for affecting energy-saving improvement interval. The energy-saving potential method can reflect the size of the efficient space [34] and energy-saving space [35]. Energy-saving potential can be influenced by the production technology [36] of the production plants [37], energy management structure [38], energy hierarchy [39] and raw materials ratio [40]. Therefore, we put forward an integrated framework of energy performance analysis based on the IDA integrated the energy-saving potential method.

3. The integrated framework combining IDA and energy saving potential method

3.1. The IDA method

Current analysis of energy consumption is mostly through the establishment of various mathematical models to simulate chemical process [36], such as the IDA method [41], and to analyze the effect of some factors in energy consumption, such as operating conditions, raw materials, fuel, and yield [42]. None of them analyze factors in energy consumption together. On the other hand, energy consumption analysis method based on the model has high demands on data, requesting to establish corresponding mathematical model. Moreover, the calculation is complicated and unable to speculate factors that affect energy consumption accurately. So it cannot put forward comprehensive and reasonable energy saving measures. Therefore, we adopt IDA method to make a comprehensive analysis of energy efficiency. Comparing with the chemical process simulation method, the biggest advantage of index analysis method is that the data can be easily accessible. Different factors have different effects on the indices of energy efficiency. The above method can get quantitative results of the effects.

IDA uses four indices to analyze energy efficiency: (1) EEI, energy efficiency index; (2) EPI, energy performance index; (3) ES, energy saving; and (4) EH, energy hierarchy. The energy efficiency index calculated by IDA can comprehensively reflect the change of energy intensity, the structure and the energy saving. It also can be a general index of energy efficiency and energy saving improvement rate that can synthesize energy consumption (SEC) in all stages of statistics, and statistically analyze the level of energy efficiency in a whole cycle (usually can be chosen as 1 year). It can intuitively give the correlation between the energy usage and the physical production index, so it has extensive practicability to measure the energy demand.

We use E_i^t to represent the total energy consumption of the single production plant i in unit time t. It can be shown by the following calculation process:

$$E_i^t = \sum_{j=1}^{n} E_{ij}^t = \sum_{j=1}^{n} Q^t \frac{Q_i^t}{Q^t} \frac{E_{ij}^t}{Q_i^t} = \sum_{j=1}^{n} Q^t S_i^t I_{ij}^t \tag{1}$$

where i represents the production plant, j represents the working medium, t represents the unit time. E_{ij}^t is the energy consumption of the working medium j of the production plant i in the unit time t. Q^t represents the output of all production plants in the unit time t. It represents the level of activity in the IDA analysis. Q_i^t represents the output of the production plant i in the unit time t. S_i^t is the proportion of the production activity of the production plant i accounts for all production plants activities throughout the unit time t. I^t is the energy intensity of the production plant i in the unit time t. I_{ij}^t is the energy consumption of the working medium j of the production plant i in the unit time t.

In the following formula, E_i^0 is the standard energy consumption amount of the production plant i, and it can be shown by the following calculation process:

$$E_i^0 = \sum_{t=1}^{n} E_i^t / n \tag{2}$$

In the Eq. (3), $\Delta E_i^{0,t}$ is energy consumption change of the unit time t on the basis of standard. Similarly, $\Delta E_{i-act}^{0,t}$ is the activity level energy consumption change, $\Delta E_{i-str}^{0,t}$ is structure of energy consumption change and $\Delta E_{i-int}^{0,t}$ is energy consumption intensity change.Q_i^0 is the standard output of the production plant i. S_i^0 is the standard proportion of the activity of the production plant i accounting for all production plants activities throughout unit time t.

$$\Delta E_i^{0,t} = E_i^t - E_i^0 = \Delta E_{i-act}^{0,t} + \Delta E_{i-str}^{0,t} + \Delta E_{i-int}^{0,t}$$

$$\Delta E_{i-act}^{0,t} = \sum_{j=1}^{n} L(E_{ij}^t, E_{ij}^0) \ln\left(\frac{Q_i^t}{Q_i^0}\right)$$

$$\Delta E_{i-str}^{0,t} = \sum_{j=1}^{n} L(E_{ij}^t, E_{ij}^0) \ln\left(\frac{S_i^t}{S_i^0}\right)$$

$$\Delta E_{i-int}^{0,t} = \sum_{j=1}^{n} L(E_{ij}^t, E_{ij}^0) \ln\left(\frac{\frac{E_{ij}^t}{Q_i^t}}{\frac{E_{ij}^0}{Q_i^0}}\right) \tag{3}$$

where $L(a,b)$ is a piecewise function, if a and b are not equal, the value is the logarithmic average value of integer a and b, otherwise its value is 0. It is defined as follows:

$$L(a,b) = \begin{cases} (a-b)/\ln(\frac{a}{b}), & a \neq b \\ 0, & a = b \end{cases} \tag{4}$$

ES_i^t is energy saving index of the production plant i in the unit time t. Its calculation can be shown as Eq. (5):

$$ES_i^t = -\Delta E_{i-int}^{0,t} \tag{5}$$

EH_i^t is energy hierarchy index of the production plant i in the unit time t. Its calculation can be shown as Eq. (6):

$$EH_i^t = E_i^t - \Delta E_{i-act}^{0,t} \tag{6}$$

$EPI_i^{0,t}$ is energy performance index of the production plant i in the unit time t based on the standard month 0. Its calculation can be shown as Eq. (7):

$$EPI_i^{0,t} = \exp\left(\Delta E_{i-int}^{0,t} \frac{\ln(\frac{E_i^t}{E_i^0})}{E_i^t - E_i^0}\right) = \left(\frac{E_i^t}{E_i^0}\right)^{\frac{\Delta E_{i-int}^{0,t}}{E_i^t - E_i^0}} \tag{7}$$

ES_{ij}^t is the energy saving index of the working medium j of the production plant i in the unit time t. Its calculation can be shown as Eq. (8):

$$ES_{ij}^t = -\Delta E_{ij-int}^{0,t} \tag{8}$$

EH_{ij}^t is the energy hierarchy index of working medium j of the production plant i in the unit time t. Its calculation can be shown as Eq. (8):

$$EH_{ij}^{t} = E_{ij}^{t} - \Delta E_{ij-act}^{0,t} \tag{9}$$

$EPI_{ij}^{0,t}$ is the energy performance index of the working medium j the production plant i in the unit time t based on the standard month 0. Its calculation can be shown as Eq. (10):

$$EPI_{ij}^{0,t} = \exp\left(\Delta E_{ij-int}^{0,t} \frac{\ln\left(\frac{E_{ij}^{t}}{E_{ij}^{0}}\right)}{E_{ij}^{t} - E_{ij}^{0}}\right) = \left(\frac{E_{ij}^{t}}{E_{ij}^{0}}\right)^{\frac{\Delta E_{ij-int}^{0,t}}{E_i^t - E_i^0}} \tag{10}$$

EEI_i^t is the energy efficiency index of the production plant i in the unit time t. Its calculation can be shown as Eq. (11):

$$EEI_i^t = \frac{\sum_{j=1}^{n} E_{ji}^{t}}{\sum_{j=1}^{n} E_{ji}^{0}} \tag{11}$$

For the energy consumption working medium j, the energy efficiency index of the production plant i in the unit time t can be calculated by Eq. (12):

$$EEI_i^t = \frac{E_{ji}^{t}}{E_{ji}^{0}} \tag{12}$$

3.2. Energy saving potential method

The generalized technological (or efficiency) influence usually refers to the effect of changes of the production plant energy intensity having on energy saving potential [43,44]. And it mainly roots in the management of production plants and the improvement of operant level. Therefore, it is also known as the technological energy saving potential. The amount of energy saving that the technological energy saving brings about is called the amount of the technological energy saving.

Because of changes in production capacity of the production plant or changes in the burden, the constituent ratio of capacity of production plants, and raw material structure and production plants are changed. Those changes mainly root in the improvement of activity level, so it is called structural energy saving potential. The amount of energy saving which structural energy saving potential brings about is called the amount of structural energy saving.

ΔE_{tech-i}^{t} is the amount of technology energy saving of the production plant i in the unit time t, and it can be expressed as the Eq. (13):

$$\Delta E_{tech-i}^{t} = Q_i^t * (SEC_i^t - SEC_i^0) \tag{13}$$

where SEC^t represents the comprehensive energy consumption of the production plant i in the unit time t, and SEC^0represents the reference value of the month comprehensive energy consumption. For SEC^0, there are five kinds of values (the whole cycle is 1 year):

(1) SEC^0 is the average value of the month comprehensive energy consumption in last year (*SEC_avg*);
(2) SEC^0 is the minimum value of the month comprehensive energy consumption in last year (*SEC_min*);
(3) SEC^0 is the average value of the month comprehensive energy consumption in the nearest 12 months (*SEC_navg*), for example, the nearest 12 months of 2012-09 is 2011-09 to 2012-09;
(4) SEC^0 is the minimum value of the month comprehensive energy consumption in the nearest 12 months (*SEC_nmin*);
(5) SEC^0 is the appointed value in the appointed month (SEC_assign).

According to SEC^0, E_{ij}^0, E_i^0 and S_i^0 also have five kinds of values similarly.

ΔE_{str-i}^{t} is the amount of structure energy saving of the production i in the unit time t, and it can be expressed as the Eq. (14):

$$\Delta E_{str-i}^{t} = Q_i^t * \left(\frac{Q_i^t}{Q_i} - \frac{Q_i^0}{Q_i}\right) * (SEC_i^t - SEC_i^0) \tag{14}$$

In the above equations, if the whole cycle is 1 year (this cycle is determined by the data acquisition time, 1 year, 1 month or 1 day all allowed), Q_i^0 and Q_i has five kinds of values (as the five standards):

(1) If SEC^0 is *SEC_avg*, Q_i^0 is the average output of the last year (*Q_avg*), and Q_i is the total output of the last year (*Qt_last*);
(2) If SEC^0 is *SEC_min*, Q_i^0 is the output of the month which the *SEC_min* in (*Q_min*), Q_i is the *Qt_last*;
(3) If SEC^0 is *SEC_navg*, Q_i^0 is the average output of nearest 12 months (*Q_navg*), Q_i is the total output of the nearest 12 months (*Qt_near*);
(4) If SEC^0 is *SEC_nmin*, Q_i^0 is the output of the month which the *SEC_nmin* in (*Q_nmin*), Q_i is the *Qt_near*;
(5) If SEC^0 is *SEC_assign*, Q_i^0 is the output of the appointed month (*Q_assign*), Q_i is the total output of the year which the appointed month in (*Qt_assign*).

ΔE_i is the amount of total energy saving of production plant i in the unit time t. It can be expressed as the Eq. (15):

$$\Delta E_i = \Delta E_{str-i}^{t} + \Delta E_{tech-i}^{t} \tag{15}$$

P_i^t means the energy saving potential of production plant i in the unit time t. And it can be expressed as the Eq. (16):

$$P_i^t = \left(1 - \frac{\frac{\Delta E}{Q_i^t}}{SEC_i^0}\right) * 100\% \tag{16}$$

P_{ij}^t is the energy saving potential of working medium j of the production plant i in the unit time t. it can be expressed as the Eq. (17):

$$P_{ij}^t = \left(1 - \frac{\frac{\Delta E}{Q_{ij}^t}}{E_{ij}^0}\right) * 100\% \tag{17}$$

3.3. The procedure of the integrated framework

The complex chemical production is regarded as a multi-input and multi-output process. The multi-dimensional data can be processed more objectively and accurately after the data reprocessing work. Then, we can obtain the EEI, EPI, ES, EH indicators with the application of the IDA method. At the same time, we can employ energy saving method to get the energy saving potential index P. Finally, according to these two kinds of methods, we can put forward improvement measures for complex chemical production process. The flowchart of integrated framework combining the IDA with energy saving potential method can be shown as Fig. 1.

4. Empirical analyses

Ethylene industry is a representative of the complex chemical industry. In the ethylene industry, different companies will take a different approach to divide energy utilization boundary and calculation method. We divide the ethylene production plants with

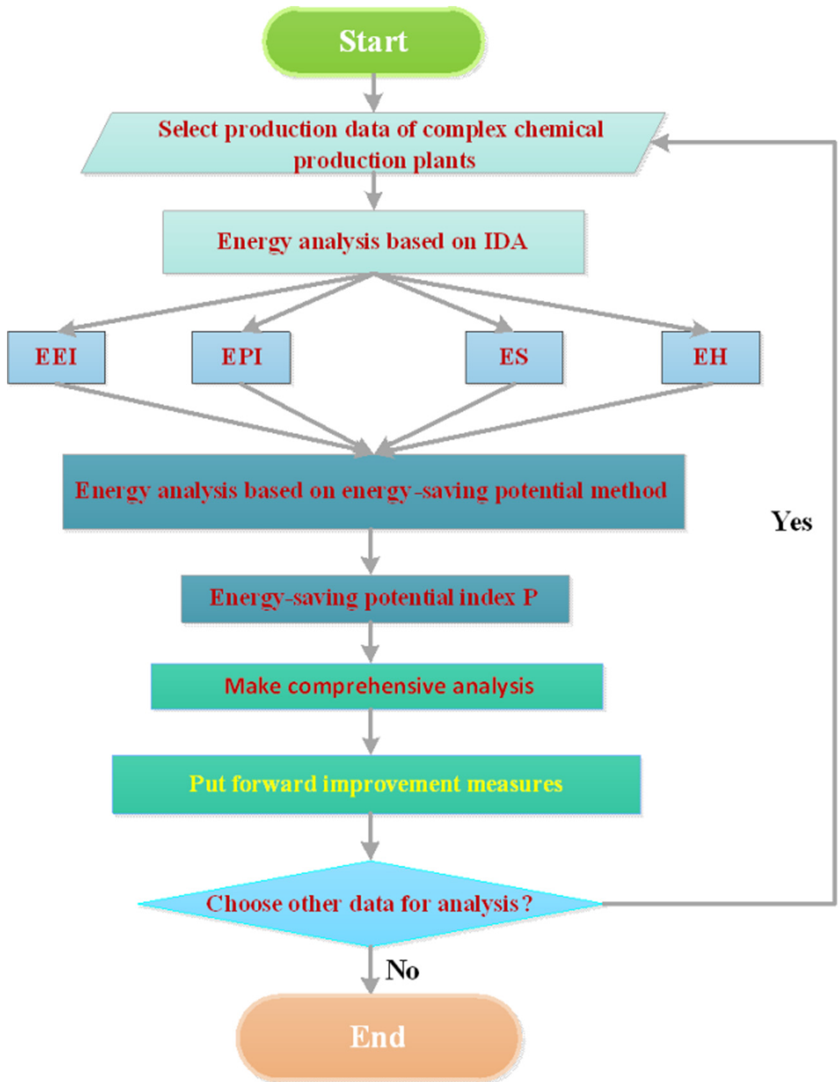

Fig. 1. The flowchart of integrated framework combined IDA and energy saving potential method.

DB 37/751-2007 and GB/T 2589-2008L [45]. The ethylene production system mainly contains processes of cracking and separation. When the cracking furnace is working, a lot of fuels are used to provide heat for cracking reactions in the tube. And the Transfer Line Exchanger (TLE) produces a large number of steams by recovering the waste heat. In order to make raw material hydrocarbon finish the optimal cleavage reactions in a short while, and reduce the coke, the steam should be infused when the hydrocarbon is put into the cracking furnace.

The separation section is divided into three parts: the rapid cooling part, the compression part and the separation part. The main consumed energy contains the power consumption in the compressor, the cooling energy consumption in the compressor and the cold box, the reboiler consumption in the distillation column and the steam consumption in the heat separation part. The main energy consumption in cracking section includes the preheat of the mixture of the raw materials and the stream, the reaction heat consumption in the cracking reactions, and the waste heat released to the environment like afterheat in the flue gas. A typical framework of the ethylene plant flowchart is shown in Fig. 2.

4.1. Production data

Nowadays, there are about seven ethylene production technologies in the ethylene production industries in China [46]. In this paper, we used the monthly statistical data in 2011 and 2012 collected from ethylene units which using the domestic ethylene production technology that annually output 600,000 tons ethylene to make analysis of energy efficiency and the potential of energy conservation. Firstly, initial data are reprocessed and then fuel, steam, water, and electricity are found as the main energy consumption [14]. Therefore, six production indices are selected to make the continue analysis: the output of ethylene (ethylene), the total consumption of fuel (fueltotal), the total consumption of steam (steamtotal), the total consumption of water (watertotal), the total consumption of electricity (electricity), the synthesize energy consumption (SEC). Finally, the energy indicators, EEI, EPI, ES, EH and P, are obtained with the employment of IDA method and the energy saving potential method.

The monthly statistical data of the ethylene plant in 2011 and 2012 are shown as Fig. 3.

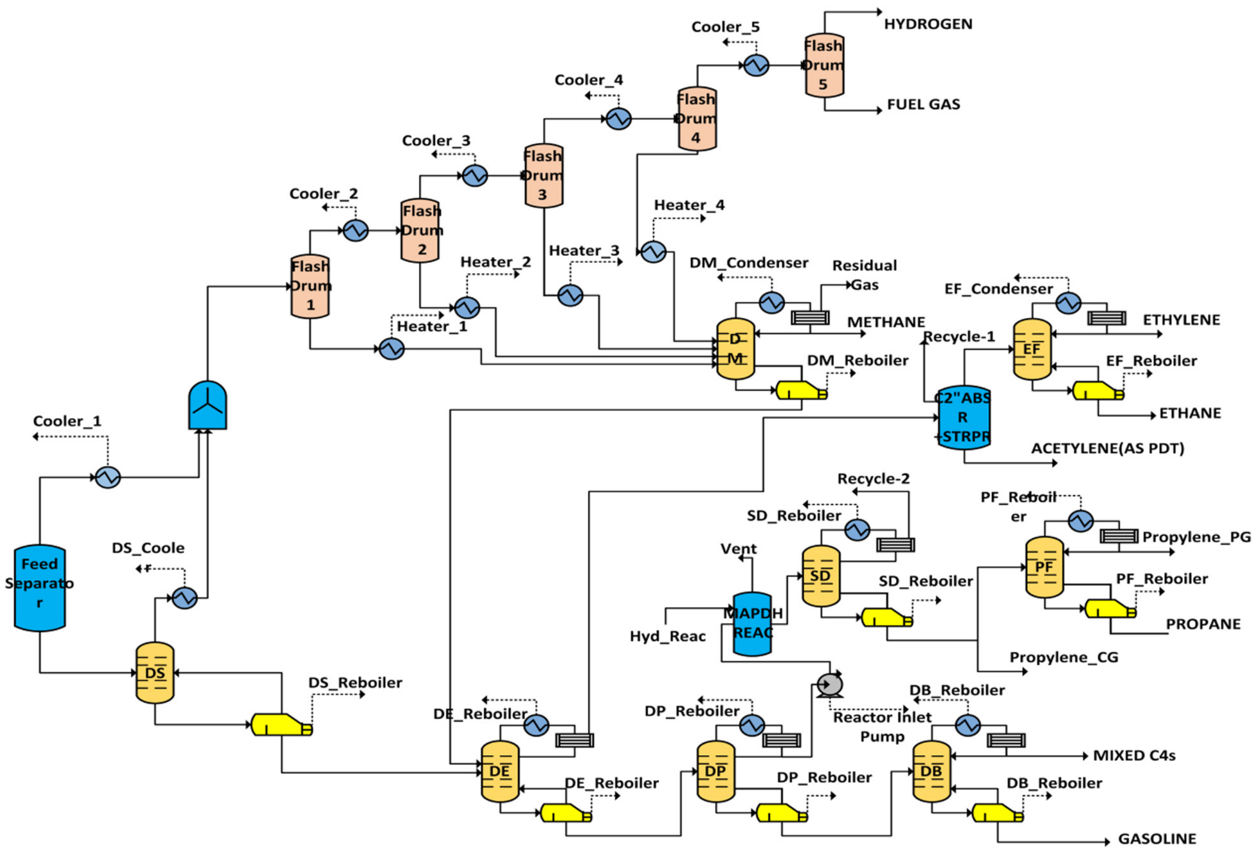

Fig. 2. A typical flowchart of the ethylene plant.

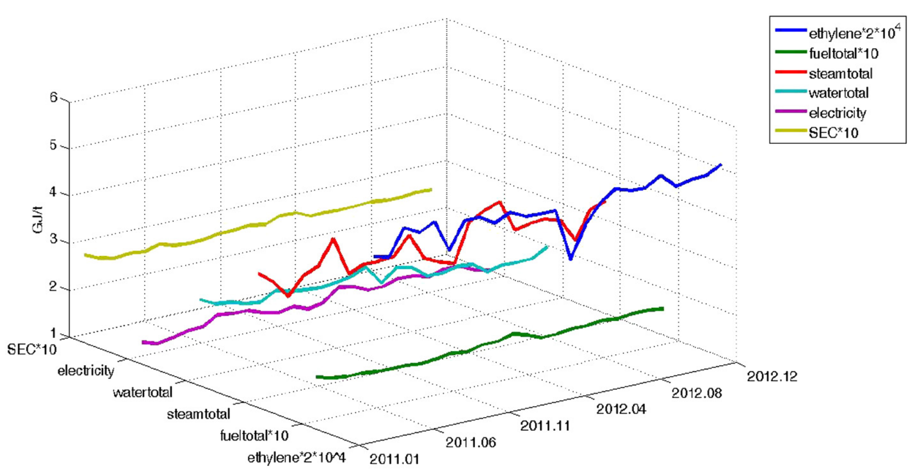

Fig. 3. Energy efficiency index analysis result of ethylene plant from January to December in 2011 and 2012.

4.2. Energy efficiency index

In order to compare the efficiency of the IDA index analysis comprehensively, we make the contrastive analysis of the EEI and the SEC. Using the data in Fig. 3, the Eqs. (1)–(13) and five different standards, we can calculate the energy efficiency indices in 2012. In order to observe the results of the analysis more intuitively, we use Figs. 4–7 to show the energy indices.

We can get lines *EEI_avg* (energy efficiency index based on the average value of last year), *EEI_min* (energy efficiency index based on the minimum value of last year), *EEI_navg* (energy efficiency index based on the average value of the nearest months), *EEI_nmin* (energy efficiency index based on the minimum value of the nearest months) and *EEI_assign* (energy efficiency index based on the assign value of the assign month) using Eq. (11) and different SEC^0, and get lines *EPI_avg* (energy performance index based on the average value of last year), *EPI_min* (energy performance index based on the minimum value of last year), *EPI_navg* (energy performance index based on the average value of the nearest months), *EPI_nmin* (energy performance index based on the minimum value of the nearest months) and *EPI_assign* (energy performance index based on the assign value of the assign month) using Eq. (10) and different E_i^0, and get lines *ES_avg* (energy saving index based

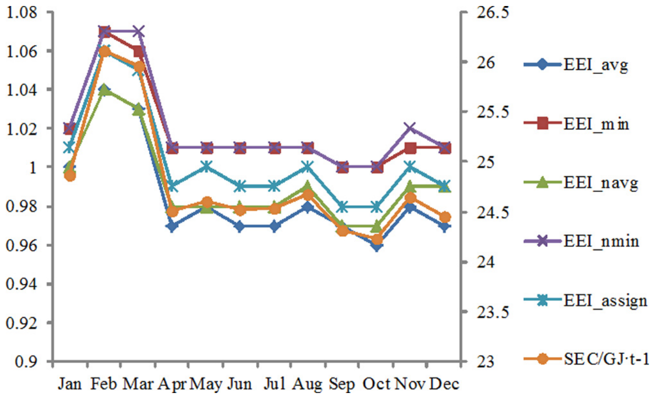

Fig. 4. Different EEI based on different standards.

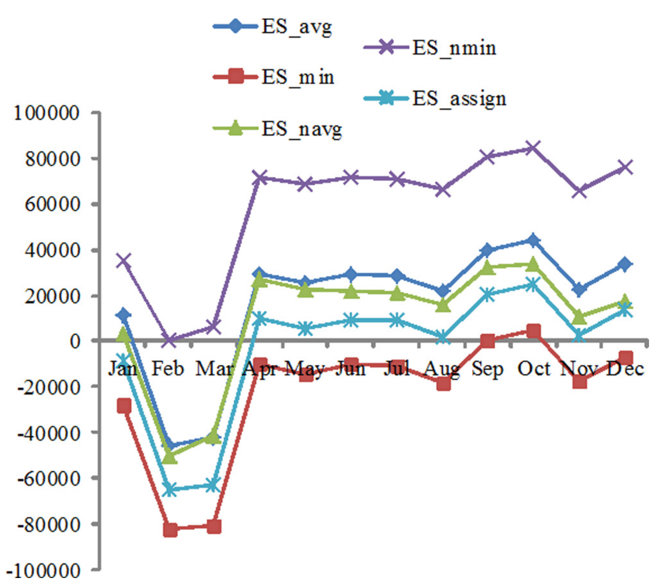

Fig. 5. Different EPI calculated based on different standards.

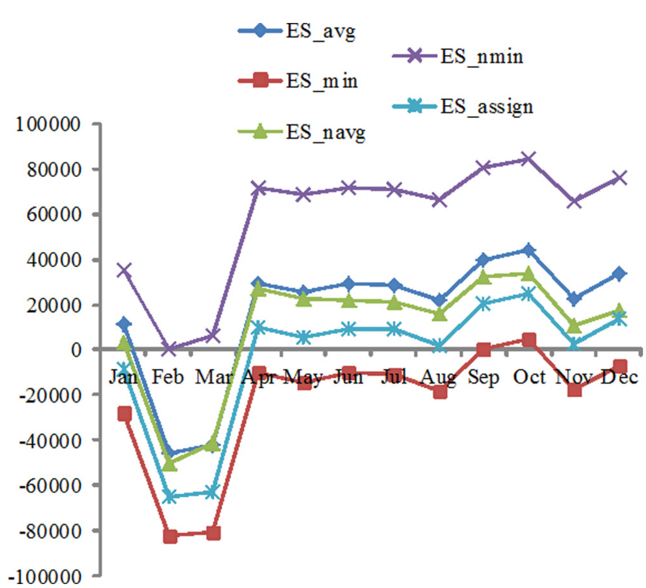

Fig. 6. Different ES calculated based on different standards.

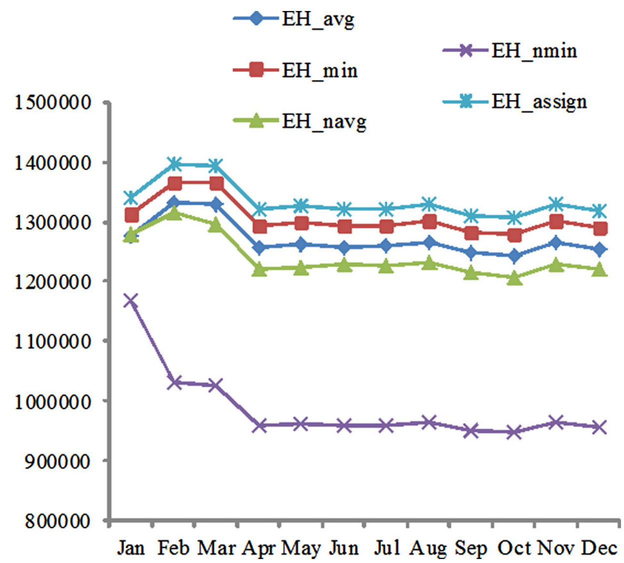

Fig. 7. Different EH calculated based on different standards.

on the average value of last year), *ES_min* (energy saving index based on the minimum value of last year), *ES_navg* (energy saving index based on the average value of the nearest months), *ES_nmin* (energy saving index based on the minimum value of the nearest months) and *ES_assign* (energy saving index based on the assign value of the assign month) using Eq. (5) and different E_{ij}^0 and Q_i^0, and get lines *EH_avg* (energy hierarchy index based on the average value of last year), *EH_min* (energy hierarchy index based on the minimum value of last year), *EH_navg* (energy hierarchy index based on the average value of the nearest months), *EH_nmin* (energy hierarchy index based on the minimum value of the nearest months) and *EH_assign* (energy hierarchy index based on the assign value of the assign month) using Eq. (6) and different E_{ij}^0 and Q_i^0.

According to Figs. 4–7, it is shown that in the standard year 2011, the monthly average ethylene output is 51305.17t, the total output is 615662t, and the average SEC is 25.09 GJ t^{-1}, and the minimum SEC is 24.32 GJ t^{-1}, the output is 52768t in the corresponding month. In Fig. 6, compared with the baseline values, the values which are less than 0 mean that this unit uses less energy consumption, and the energy saving space is larger than the standard value.

From Fig. 6, the sum of energy consumption in 2012 is 13002.75 GJ as line *ES_avg* shows. From Figs. 4 and 5, what is found is that the EEI and the EPI of April to December are less than 1 as lines *EEI_avg* and *EPI_avg* show. This indicates that the energy consumption levels of those months are relatively lower. Meanwhile, as Fig. 4 shows, the monthly energy consumption in 2012 are more than the minimum value in 2011. In Figs. 4 and 5, all EEI and EPI results except September and October are more than 1 as lines *EEI_min* and *EPI_min* show. The EEI and EPI results of September and October are equal to 1, which means that the energy efficiency level is the same as the lowest level of 2011, while the energy efficiency levels of other months are slightly higher than the minimum value. The fact shows that compared with standard year 2011, the level of energy consumption of 2012 is relatively low.

In addition, as lines *EEI_navg* in Fig. 4, *EPI_navg* in Fig. 5, and *ES_navg* in Fig. 6 show, the levels of energy saving of April to December are higher than the average level of those nearest months. And the EEI and EPI of those months are less than 1. It indicates that the energy efficiency levels of those months are higher than the average level of those nearest months. Meanwhile, it is obvious that the EEI and EPI of September and October are the lowest, and the ES of those months are the largest.

Interestingly, as lines *EEI_nmin* in Fig. 4, *EPI_nmin* in Fig. 5 show, the EEI of all months in 2012 are less than 1, while the EPI are more than 1. It means the energy consumption levels of all months in 2012 are higher than the minimum level of those nearest 12 months, and those energy efficiency levels are also higher than the minimum level of those nearest 12 months. It is due to the situation that the minimum output of those nearest 12 months is extremely low. The outputs of all months in 2012 are much higher than the minimum output of those nearest 12 months. Through the analysis of data, it is demonstrated that the energy consumption of September and October are the lowest and the energy efficiency of September and October are the highest compared to those nearest minimum value.

In the same way, compared to the value of the assign month (2011-05), as lines *EEI_assign* in Fig. 4, *EPI_assign* in Fig. 5, and *ES_assign* in Fig. 6 show, the EEI and EPI of November and October are the lowest, the ES of November and October are the highest, which indicates that the energy efficiency level of November and October is the highest and the energy saving of those months are the biggest.

Through these five comprehensive analyses, it is noticeable that the levels of energy efficiency in September and October are the highest, the levels of energy efficiency in February and March are the lowest. We can conclude from Figs. 4 and 5 that the variances of all EEI and EPI are between 0.02 and 0.03, implying that this unit runs smoothly and the overall productive process runs normally.

As is shown in Fig. 1, the variation tendency of SEC, EPI, EEI and EH calculated based on five standards are almost the same. From Fig. 4, it is can be seen that variation tendency of SEC is similar to the variation tendency of EEI, and it has the highest image fit with the line *EEI_navg*. However, the most different line in each image is the line based on the minimum value of the nearest 12 months. Through analyzing the data, the reason is that the output of 2012-02 is quite low which causes that the indices value based on this standard has a great distance with the indices value based on other standard.

In conclusion, when using the minimum value or assigned value as a standard, the results will be not very representative if we met an abnormal data. Otherwise, using the average value of last year or the average value of the nearest 12 months as a standard can balance the big deviation to a certain extent. But in most cases, we can get the excellence of this month based on the minimum value, as well as the excellence of this month compared to the assigned month.

Although we can get the above conclusion, the key success factor (KSF) that influenced energy efficiency and energy saving cannot be found. Therefore, comprehensive analysis of the energy saving and energy hierarchy of each working medium need to be carried out to further analyze the impact of the change of each working medium on energy efficiency. We calculated the energy consumption of each working medium by Eqs. (8) and (9) and different E^0_{ij} and Q^0_i, as shown in Figs. 8–12.

As Figs. 8–12 shows, the left figure is the chart analysis of monthly energy saving of each working medium, and the right figure is the chart analysis of monthly energy hierarchy of each working medium. Figs. 8–12 are the chart analyses based on five different standards. Considering Figs. 8–12 comprehensively, no matter based on which standard, the proportion of fuel savings accounting for the total energy savings is the largest. The fuel savings accounts for about 45% of the total energy savings. The water and steam savings accounts for about 23% of the total energy saving, and the electricity savings accounts for less than 10% of the total energy savings under the five conditions. At the same time, the fuel accounts for more than 70% of the energy hierarchy in Figs. 8–12. Besides, the sum of water and steam accounts for about 20% of the energy hierarchy. It indicates that fuel is the most important factor that affects ethylene plant, and the effect of water and steam on energy savings cannot be ignored. Therefore, increasing the energy efficiency of fuel, steam, and water is crucial to the energy performance and energy saving of ethylene plant.

Based on previous analysis, the summary is that September and October are the most energy efficient month while February and March are the worst. According to Figs. 8–12, the proportion of water and steam energy savings in higher energy saving months is significantly higher than the proportion in lower energy savings months. It illustrates that although the fuel energy savings of the total energy savings ratio is the highest, the energy savings does not grow by the increase of the fuel input. Furthermore, the steam and water savings plays a relatively larger role in total energy savings in the month when the energy saving is relatively high.

According to the IDA analysis results, we can make the following improvements. EEI, EPI, ES and EH reaches the best in September and October, regardless of the standard. We can make improvements according to the inputs of each working medium in September and October. Furthermore, we can carry out the specific analysis according to the ES value of each working medium. According to Figs. 8–12, we can see that the value ES of steam was the highest in October, the value ES of water was better in September, the value ES of fuel was better in September, and the value ES of electricity was comparable in September and October.

In order to further speculate the effect that the level of energy efficiency of each working medium having on the energy efficiency of the total plants, and to determine whether the improvement recommendations made by the IDA are consistent with the improvement direction of the energy saving potential, this paper analyzes the energy saving potential. Meanwhile, we distinguish the technological energy saving potential and the structure energy saving potential. Furthermore, the most important factors influencing the energy efficiency of ethylene plants can be identified.

4.3. Energy saving potential analysis

Based on Eqs. (13)–(16) and the five standards, we can calculated the total energy saving potential of ethylene plants in each month of 2012, and make the chart analysis of calculated results and the SEC as shown in Fig. 13.

P_lastavg (energy saving potential index based on the average value of last year) can be calculated by the Eq. (13) with *SEC_avg*, *Q_avg* and *Qt_last*;
P_lastmin (energy saving potential index based on the minimum value of last year) can be calculated by the Eq. (13) with *SEC_min*, *Q_min* and *Qt_last*;
P_nearavg (energy saving potential index based on the average value of the nearest months) can be calculated by the Eq. (13) with *SEC_navg*, *Q_navg* and *Qt_near*;
P_nearmin (energy saving potential index based on the minimum value of the nearest months) can be calculated by the Eq. (13) with *SEC_nmin*, *Q_nmin* and *Qt_near*;
P_assign (energy saving potential index based on the assign value of the assign month) can be calculated by the Eq. (13) with *SEC_assign*, *Q_ assign* and *Qt_ assign*.

Based on Fig. 13, the change trend of the SEC is opposite to energy saving potential. Combining with Fig. 6, the trend of energy saving potential is the same with that ES, while opposite to energy EEI and EPI. It means that the higher the SEC, the lower energy saving potential, and the more energy efficient space, the higher EEI and EPI.

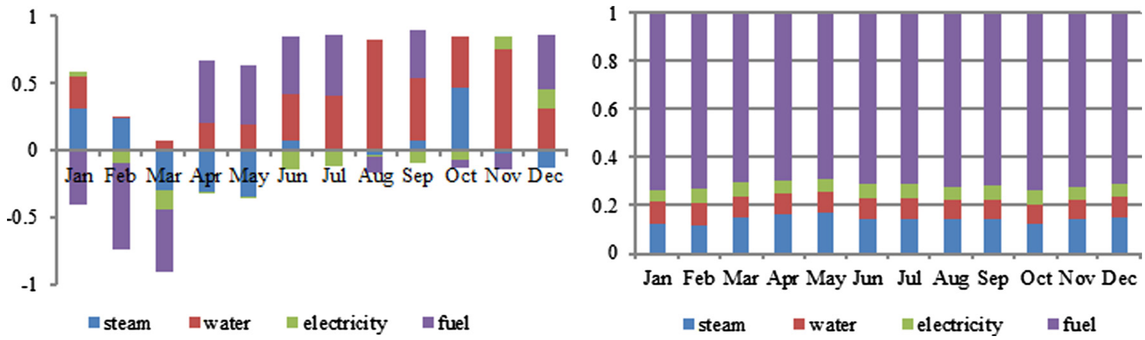

Fig. 8. *ES_avg* & *EH_avg* for all energy consumption working medium of ethylene plants in 2012.

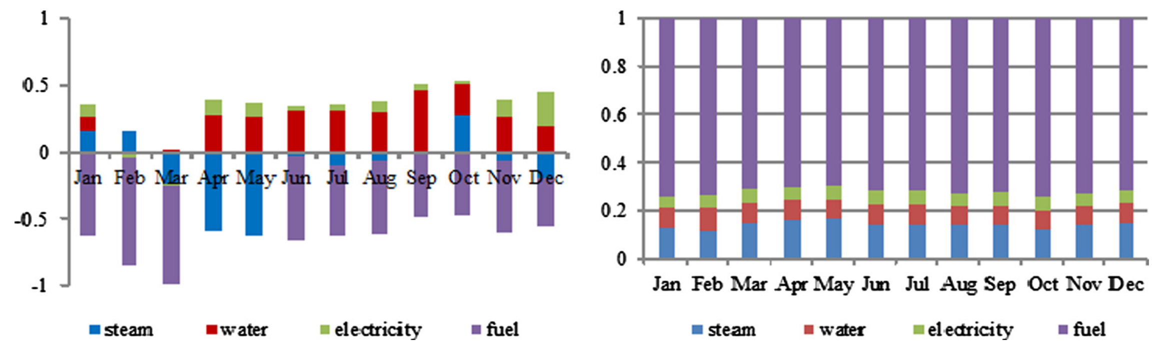

Fig. 9. *ES_min* & *EH_min* for all energy consumption working medium of ethylene plants in 2012.

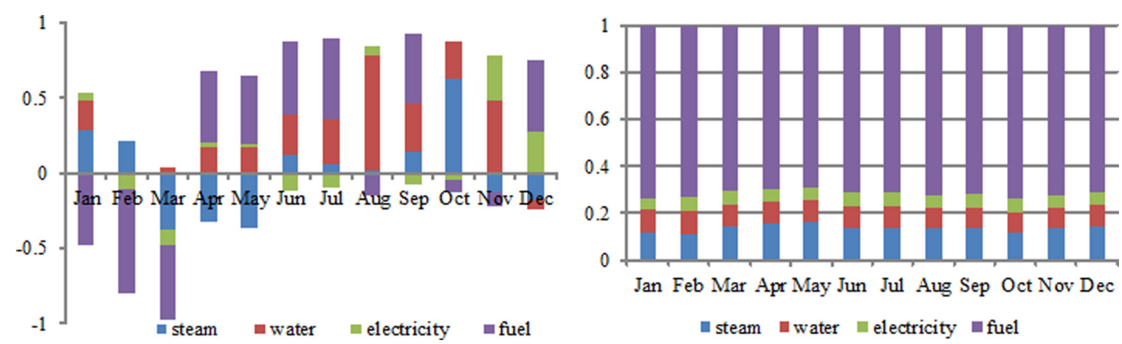

Fig. 10. *ES_navg* & *EH_navg* for all energy consumption working medium of ethylene plants in 2012.

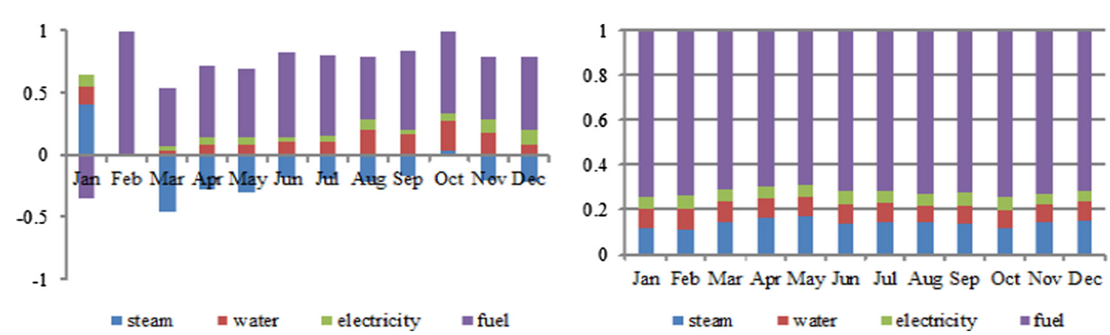

Fig. 11. *ES_nmin* & *EH_nmin* for all energy consumption working medium of ethylene plants in 2012.

In order to further analyze the relationship between the energy saving potential of each working medium and total energy saving potential, we make the chart analysis of the energy saving potential of each working medium as Figs. 14–18.

It can be seen from Figs. 14–18 that the results of the energy saving potential of each working medium based on different standards. Analyzing Figs. 14–18 and 13, the fuel energy saving potential is the closest to the total energy saving potential in the energy

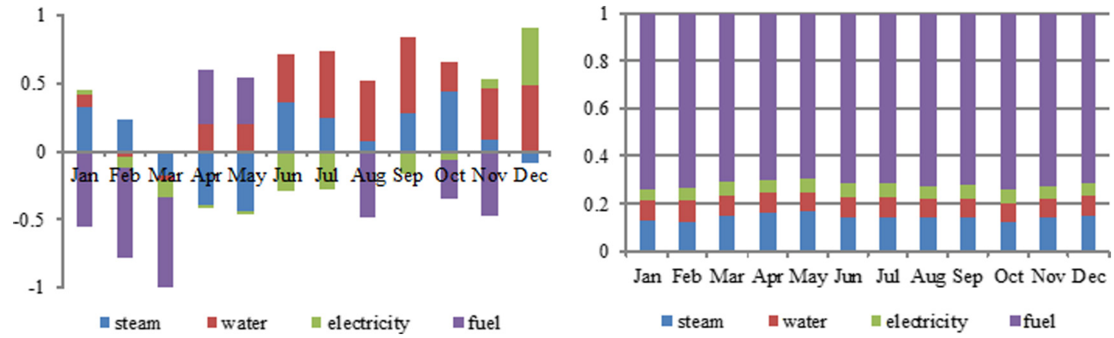

Fig. 12. *ES_assign* & *EH_assign* for all energy consumption working medium of ethylene plants in 2012.

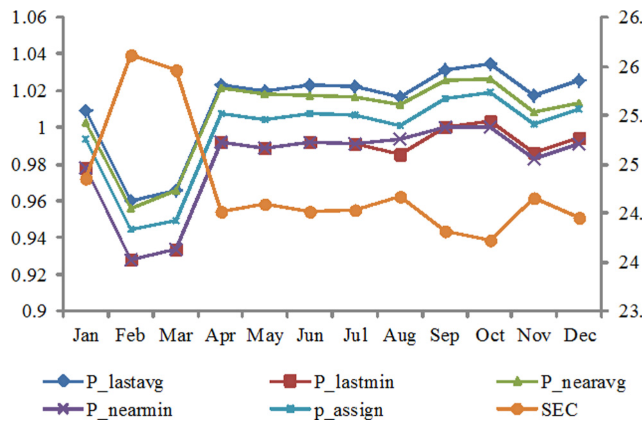

Fig. 13. Monthly energy saving potential in 2012 based on five standards of ethylene plants.

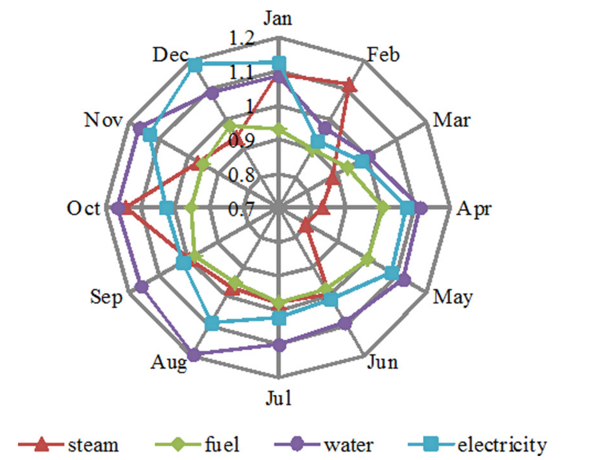

Fig. 15. Monthly energy saving potential of each working medium in 2012 based on the minimum value of 2011.

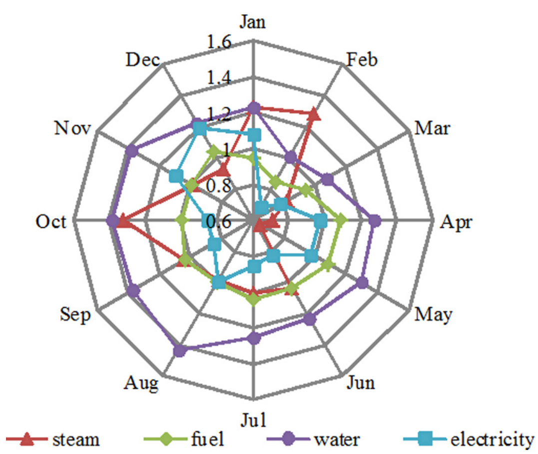

Fig. 14. Monthly energy saving potential of each working medium in 2012 based on the average value of 2011.

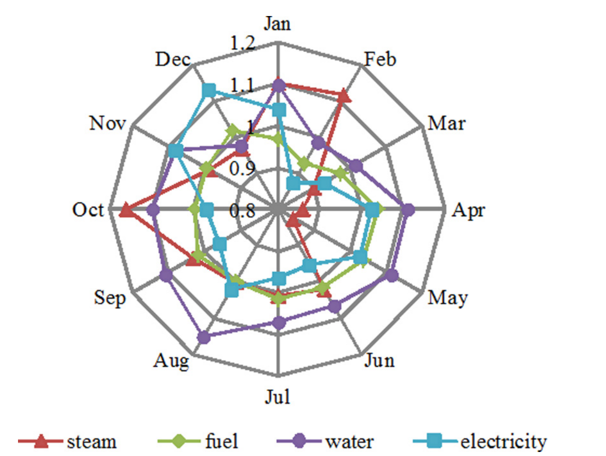

Fig. 16. Monthly energy saving potential of each working medium in 2012 based on the average value of the nearest 12 months.

saving potential results of each working medium based on different standards. However, the energy saving potential of steam has the rapidest change, and lots of values of steam energy saving potential are less than 1. It means that the energy saving potential of steam has big improvement space. Besides, the water energy saving potential is the biggest whichever standard and the trend of the water energy saving potential is the same as the trend of the total energy saving potential. The electricity energy saving potential is not significantly related to the total energy saving potential. This suggests that the fuel energy saving potential has the greatest impact on the total energy saving potential, but the impact of water and steam energy saving potential should not be overlooked.

Combining Figs. 14–18 with 13, we can see that the total energy saving potentials of September and October are very high based on whichever standard, but the fuel energy saving potentials of these months are not the biggest, while the energy saving potential of steam and water of these months are very high. In February and March, the energy saving potential is low. Although the energy saving potential of steam in February is relatively high, the energy saving potential of fuel and water in this month is low, resulting

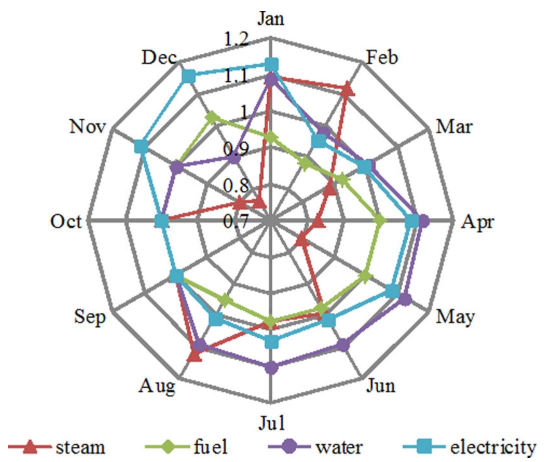

Fig. 17. Monthly energy saving potential of each working medium in 2012 based on the minimum value of the nearest 12 months.

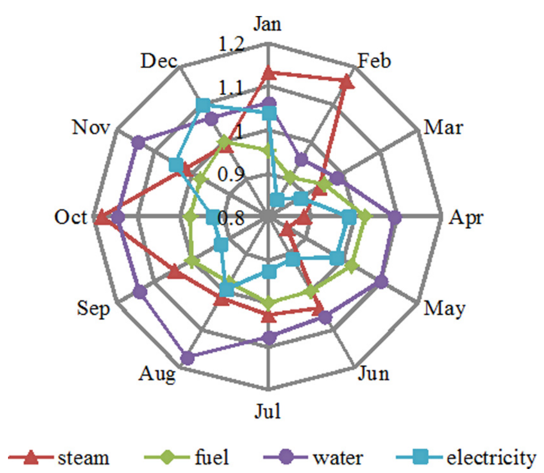

Fig. 18. Monthly energy saving potential of each working medium in 2012 based on the value of assigned month.

in low total energy saving potential. In March, the potential of each working medium is low, leading to the low overall energy saving potential.

In summary, based on the IDA and the energy saving potential analysis, the ES, EEI and P reach the highest in September and October, but touch the bottom in February and March. This reflects the consistency of energy efficiency analysis and energy saving potential analysis, and reflects the improvement direction of the indices obtained by the IDA in line with the improvement direction of the energy saving potential. The best steam energy saving potential and the best ES of steam are in October and the best fuel energy saving potential is in September, so we can take the amount of steam in October and take the amount of fuel input in September. The best water energy saving potential in September and October are almost the same, but the ES of water is better in September, so we take the amount of water input in September. The amount of electricity input in September and October are the same, so we take this input. Besides, we can get the carbon emissions are 73.18 and 72.52 million tons according to the studies of the carbon emissions calculation of Shanghai [47] and Japan [48]. Therefore, reducing the carbons emissions [49] has great significance to the environmental protection [50] in the sustainable development.

If this proposal is used to improve the energy efficiency and energy efficiency potential of the February and March, the energy efficiency index of these months can be increased by 6.7%, the energy saving potential can be increased by 7.4%, and the carbon emissions of the February and March can be reduced by 8.2% and 7.4%, respectively.

5. Discussion

First, the comprehensive framework that combines the IDA with the energy saving potential method is proposed. Based on the analysis of the ethylene production example, the comprehensiveness and effectiveness of this model has been proved.

Second, this proposed method serves as an operating guidance for the ethylene industry, and find the KSF of energy efficiency from the technical management level, the production structure and the working medium consumption. Meanwhile, this framework can propose the improvement measures for raw materials consumption of ethylene production processes. The usage of energy saving potential analysis also can verify the importance of the production structure and the technique.

Third, we can get the excellence of every months comparing with the minimum value or the assigned value, and get the changes of the energy efficiency level of time series more intuitively by using different standards. In our empirical analysis, the energy efficiency index of these months can be increased 6.7%, the energy saving potential can be increased 7.4%, and the carbon emissions of the February and March can be reduced by 8.2% and 7.4% if the improvement proposal is adopted.

Finally, the proposed framework is applied to analyze the ethylene production data and put forward the improving measures for raw materials. However, this method cannot put forward the specific improvement for the production structure. Therefore, our framework need be improved on the drawback.

6. Conclusion

This paper proposes a novel integrated framework combining the IDA with the energy saving potential method to deal with energy saving analysis and management of the complex chemical industry. Meanwhile, the proposed method provides operable support and improvement for the raw material input of the plant and optimize the operation as well. This analysis framework makes comprehensive analysis from two aspects of energy performance indices and energy saving potential. Compared with the previous method, the integrated framework can find the KSF of energy efficiency from the technical management level, the production structure and the working medium consumption. The IDA method can quantify the contribution caused by the percentage change of individual attributes. Besides, we can speculate the effect that the level of energy efficiency of each working medium has on energy efficiency of total plant by energy-saving potential analysis. Moreover, this proposed method can reflect the influence of the activity level of energy utilization, energy hierarchy and energy intensity. Besides, this analysis framework can get the quantitative effect of operation technique and energy hierarchy on energy saving technology. With the integration of different standards, the change of energy performance in time series can be observed. Finally, we can get the excellent extent of every month based on the minimum value and the assign value to reduce carbon emission and improve energy efficiency.

In our future studies, we enhance the generality of our method to put forward the specific improvement for production structure. Furthermore, we will collect the data of per day or per hour to achieve the real time application and focus on the real time production data to improve the real time energy saving and optimization of the complex chemical processes. Finally, we will combine some more optimization methods, such as nonlinear mechanistic models, particle swarm optimization etc., to compare with the current result of the work.

Acknowledgments

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References

[1] Siemens AG. Ethylene production overview; 2007.
[2] Hernández AYR. A model for the prediction of olefin production and coke deposition during thermal cracking of light hydrocarbons. M.Sc. Thesis, University of National Colombia, Colombia; 2012.
[3] Ma GF, Xu YH, Guo X. Ethylene business review of China petrochemical in 2014. Ethyl Ind 2015;27(1):1–5.
[4] Zhang LJ, Hu J. Ethylene business review of china petroleum in 2014. Ethyl Ind 2015;27(1):6–10.
[5] Ma GF, Xu YH, Guo X. Review of Sinopec's ethylene production in 2014. Ethyl Ind 2015;1:1–5.
[6] Zhang LJ, Hu J. Review of petrochina's ethylene production in 2014. Ethyl Ind 2015;1:6–10.
[7] Ren T, Patel M, Blok K. Olefins from conventional and heavy feedstocks. Energy 2006;31(4):425–51.
[8] Li X, Duan L, Wang S, et al. Emission characteristics of particulate matter from rural household biofuel combustion in China. Energy Fuels 2007;21(2):845–51.
[9] Wieslaw G, Wojciech S. Influence of power source type on energy effectiveness and environmental impact of cooling system with adsorption refrigerator. Energy Convers Manage 2014;87:1107–15.
[10] Zhou DQ, Meng FY, Bai Y, et al. Energy efficiency and congestion assessment with energy mix effect: The case of APEC countries. J Clean Prod 2016.
[11] Geng ZQ, Han YM, Zhang YY, Shi XY. Data fusion-based extraction method of energy consumption index for the ethylene industry. Lect Notes Comput Sci 2010;6329:84–92.
[12] Geng ZQ, Shi XY, Gu XB, Zhu QX. Hierarchical linear optimal fusion algorithm and its application in ethylene energy consumption indices acquisition. J Chem Ind Eng (China) 2010;61(8):2056–60.
[13] Kleemann G, Paul W. Energy saving by optimal energy recovery in chemical process technology. Chem Eng Technol 2010;33(4):603–9.
[14] Han Y, Geng Z, Wang Z, et al. Performance analysis and optimal temperature selection of ethylene cracking furnaces: A data envelopment analysis cross-model integrated analytic hierarchy process. J Anal Appl Pyrol 2016;122:35–44.
[15] Han Y, Geng Z, Xiangbai G, et al. Energy efficiency analysis based on DEA integrated ISM: A case study for Chinese ethylene industries. Eng Appl Artif Intell 2015;45:80–9.
[16] Han YM, Geng ZQ, Liu QY. Energy efficiency evaluation based on data envelopment integrated analytic hierarchy process in ethylene production. Chin J Chem Eng 2014;22(12):1279–84.
[17] Han YM, Geng ZQ, Gu XB, Wang Z. Performance analysis of china ethylene plants by measuring malmquist production efficiency based on an improved data envelopment analysis cross-model. Ind Eng Chem Res 2015;54:272–84.
[18] Han YM, Geng ZQ, Zhu QX. Energy efficiency analysis method based on fuzzy DEA cross-model for ethylene production systems in chemical industry. Energy 2015;83:685–95.
[19] Bi GB, Song W, Zhou P, Liang L. Does environmental regulation affect energy efficiency in China's thermal power generation? Empirical evidence from a slacks-based DEA model. Energy Policy 2014;66:537–46.
[20] Ruggiero J. Impact assessment of input omission on DEA. Int J Inform Technol Decision Making 2005;4(3):359–68.
[21] Han Y, Geng Z, Gu X, et al. Performance analysis of china ethylene plants by measuring malmquist production efficiency based on an improved data envelopment analysis cross-model. Ind Eng Chem Res 2014;54(1):272–84.
[22] Han YM, Geng ZQ, Zhu QX. Energy optimization and prediction of complex petrochemical industries using an improved artificial neural network approach integrating data envelopment analysis. Energy Convers Manage 2016;124:73–83.
[23] Olanrewaju OA, Jimoh AA, Kholopane PA. Integrated IDA–ANN–DEA for assessment and optimization of energy consumption in industrial sectors. Energy 2012;46(1):629–35.
[24] Olanrewaju OA, Jimoh AA, Kholopane PA. Assessing the energy potential in the South African industry: A combined IDA-ANN-DEA (index decomposition analysis-artificial neural network-data envelopment analysis) model. Energy 2013;63:225–32.
[25] Ang BW, Xu XY, Su B. Multi-country comparisons of energy performance: The index decomposition analysis approach. Energy Econ 2015;47:68–76.
[26] Ang BW, Wang H. Index decomposition analysis with multidimensional and multilevel energy data. Energy Econ 2015;51:67–76.
[27] Xu XY, Ang BW. Index decomposition analysis applied to CO_2 emission studies. Ecol Econ 2013;93:313–29.
[28] Su Bin, Ang BW. Structural decomposition analysis applied to energy and emissions: some methodological developments. Energy Econ 2012;34:177–88.
[29] Chung W, Kam MS, Ip CY. A study of residential energy use in Hong Kong by decomposition analysis, 1990–2007. Appl Energy 2011;88(12):5180–7.
[30] Unander F. Decomposition of manufacturing energy-use in IEA countries: How do recent developments compare with historical long-term trends? Appl Energy 2007;84(7):771–80.
[31] Wachsmann U, Wood R, Lenzen M, et al. Structural decomposition of energy use in Brazil from 1970 to 1996. Appl Energy 2009;86(4):578–87.
[32] Hatzigeorgiou E, Polatidis H, Haralambopoulos D. CO 2 emissions in Greece for 1990–2002: a decomposition analysis and comparison of results using the Arithmetic Mean Divisia Index and Logarithmic Mean Divisia Index techniques. Energy 2008;33(3):492–9.
[33] Hammond GP, Norman JB. Decomposition analysis of energy-related carbon emissions from UK manufacturing. Energy 2012;41(1):220–7.
[34] Choi KH, Ang BW. Attribution of changes in Divisia real energy intensity index—An extension to index decomposition analysis. Energy Econ 2012;34(1):171–6.
[35] Lin B, Moubarak M. Estimation of energy saving potential in China's paper industry. Energy 2014;65:182–9.
[36] Rao X, Wu J, Zhang Z, et al. Energy efficiency and energy saving potential in China: an analysis based on slacks-based measure model. Comput Ind Eng 2012;63(3):578–84.
[37] Tong ZHU. Analysis of energy efficiency and energy saving potential of petrochemical industry in China. Econ Manage 2010;32(10):27–35.
[38] Fisher-Vandern Karen. Management structure and technology diffusion in Chinese state-owned enterprise. Energy Policy 2003;31:247–57.
[39] Bor Yunchang Jeffref. Consistent multi-level energy efficiency indicators and their policy implications. Energy Econ 2008;30:2401–19.
[40] Ouyang J, Hokao K. Energy saving potential by improving occupants' behavior in urban residential sector in Hangzhou City, China. Energy Build 2009;41(7):711–20.
[41] Ang BW, Zhang FQ. A survey of index decomposition analysis in energy and environmental studies. Energy 2000;25:1149–76.
[42] Hoekstra R, Van Der Bergh JCJM. Comparing structural and index decomposition analysis. Energy Econ 2003;25:39–64.
[43] Lu SM, Lu C, Tseng KT, et al. Energy saving potential of the industrial sector of Taiwan. Renew Sustain Energy Rev 2013;21:674–83.
[44] Bolla R, Davoli F, Bruschi R, et al. The potential impact of green technologies in next-generation wireline networks: Is there room for energy saving optimization? IEEE Commun Mag 2011;49(8):80–6.
[45] Geng ZQ, Zhu QX, Gu XB. Dependent function analytic hierarchy process model for energy efficiency virtual benchmark and its applications in ethylene equipments. CIESC J 2011;62(8):2372–7.
[46] Geng ZQ, Han YM, Gu XB, Zhu QX. Energy efficiency estimation based on data fusion strategy: case study of ethylene product industry. Ind Eng Chem Res 2012;51:8526–34.
[47] Zhao M, Zhang WG, Yu LZ. Carbon emissions from energy consumption in Shanghai City. Res Environ Sci 2009;22(8):984–9.
[48] IPCC. 2006 IPCC guidelines for national greenhouse gas inventories:volume 17. Japan: the Institute for Global Environmental Strategies, 2008 [2008-07-20]. <http://www. ipcc. Ch/ipccreports/Methodology-reports.htm>.
[49] Nicoletti G, Arcuri N, Nicoletti G, Bruno R. A technical and environmental comparison between hydrogen and some fossil fuels. Energy Convers Manage 2015;89:205–13.
[50] Tian W, Liu Y, Heo Y, Yan D, Li Z, An J, et al. Relative importance of factors influencing building energy in urban environment. Energy 2016;111:237–50.