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RESEARCH ARTICLE

Methods for assessing the energy-saving efficiency of industrial symbiosis in industrial parks

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Abstract The available energy resources are being depleted worldwide. Industrial symbiosis (IS) provides a promising approach for increasing the efficiency of energy utilization, with numerous studies reporting the superiority of this technology. However, studies quantifying the energy-saving efficiency of IS remain insufficient. This paper proposes an index system for the quantitative evaluation of the energy-saving efficiency of IS. Both energy-saving and financial indexes were selected, the former include the IS energy-saving index, the contribution rate of energy saved through IS, fractional energy savings, and cut rate of energy consumption per total output value; and the latter include the IS investment payback period, IS input–output ratio, net present value (NPV), and internal rate of return (IRR) of IS. The proposed methods were applied to a case study on the XF Industrial Park (XF IP), in the city of Liaocheng in Shandong Province of China. Three energy-saving channels using IS were found in the XF IP: (a) utilizing the energy of high-temperature materials among industrial processes, (b) recovering waste heat and steam between different processes, and (c) saving energy by sharing infrastructures. The results showed that the energy efficiency index of IS was 0.326, accounting for 34.6 % of the comprehensive energy-saving index in 2011, and the fractional energy-savings were 12.42 %. The index of energy consumption per total industrial output value varied from 90.9 tce/MRMB to 51.6 tce/MRMB. Thus, the cut rate of energy consumption per total industrial output value was 43.42 %. The average values of the IS input–output ratio was 406.2 RMB/tce, 57.2 % lower than the price of standard coal. Static investment payback period in the XF IP was 8.5 months, indicating that the XF IP began to earn profit 8.5 months after the construction of all IS modes. The NVP and IRR of each IS mode in the XF IP were greater than zero, with average values equal to 1,789.96 MRMB and 140.96 %, respectively. The computation result for each indicator revealed that IS could lead to the use of energy with high efficiency and lighten the financial burden of enterprises in the XF IP. And the proposed index system may help IPs and EIPs to make strategic decisions when designing IS modes.

Keywords Industrial symbiosis · Energy-saving · Efficiency · Industrial park

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Introduction

The amount of available energy is rapidly being depleted worldwide, thus finding the exploration of effective approaches to increase the efficiency of energy utilization (EEU) is urgent, particularly in China (Jiang and Lin 2012; Lo and Wang 2013; Ng et al. 2013). The EEU of China is only 33 %, much lower than that of developed countries (Andrews-Speed 2009; Liu and Li 2006). Therefore, mitigating the imbalance between EEU and the total amount of energy resources is important for energy-saving efforts in China (NDRC 2004; Li et al. 2010).

Industrial symbiosis (IS) provides a promising approach for increasing the EEU. IS refers to the cooperation among different enterprises with a focus on material and energy exchange (Harper and Graedel 2004; Zhang et al. 2013; Yang and Feng 2008), sharing waste and by-product resources among industries to add value, and reduction of costs (Chertow 2000, 2007; Chertow et al. 2004).

Numerous reports have been made on the contribution of IS to energy saving and cascade utilization of energy. Taking the Jinqiao Eco-Industrial Park (EIP) as an example, Liu et al. (2011) conducted a life-cycle assessment of an IS based on energy recovery from dried sludge and used oil, arguing that the proposed IS resulted in a reduced burden to the environment. Sokka et al. (2011) analyzed the flow of materials and energy in the Kymenlaakso forest industry to determine the contribution of IS to sustainable energy usage. Korhonen and Snäkin (2005) determined the significant energy-saving potential of IS by analyzing the evolution of the Uimaharju forest industrial park in Eastern Finland. Usón et al. (2012) applied the theory of thermo-economics to analyze the process of energy cost formation of flows within an IS system. Dong et al. (2014, 2013) reported the different IS modes in the iron/steel industry of different cities in China and calculated the energy-savings achieved by each IS mode.

Moreover, in recent years, a number of articles have focus on economic gains of industrial symbiosis. Paquin et al. (2013) analyzed firm level environmental and economic outcomes for 313 industrial symbiosis exchanges across the United Kingdom and found that firms with prior industrial symbiosis experience are more likely to create economic value. Dong et al. (2013) evaluated the economic gains of IS activities in iron/steel-centered industrial areas in Liuzhou, Jinan, and Kawasaki and found that economic revenue of IS in iron/steel-centered industrial areas reached at least 36.55 million USD and 158 million USD at the most. Karlsson and Wolf (2008) evaluated the economic benefits of industrial symbiosis in the forest industry through an optimization model and gave decision support when planning industrial symbiosis initiatives in the forest industry.

It is clear from the previous literatures that energy savings and economic gains via IS have been studied theoretically and experimentally. However, studies quantifying the energy-saving efficiency of IS and economic feasibility of IS remain insufficient. The aim of this article is to propose an index system including the energy-saving and financial indexes of IS to study the energy-saving efficiency of IS quantitatively and confirm whether the index system works by a case study.

The remainder of this paper is organized as follows: "Methods" describes each index used for quantifying the energy-saving efficiency of IS. "Case study" applies the method of quantifying the energy-saving efficiency of IS to a case study. "Results and discussion" discusses the results of the case study. "Conclusion" contains a summary of the conclusions from this paper.

Nomenclature (Johansson and Söderström 2011)

IS	Industrial symbiosis
NIS	Non-industrial symbiosis
EIP	Eco-industrial Park
IP	Industrial Park
EEU	Efficiency of energy utilization
GOV	Gross industrial output value
NPV	Net present value
IRR	Internal rate of return
EPA	Environmental Protection Agency
EP	Electric power
MDF	Medium-density fiberboard
UET	Utilizing energy of thermokalite
UEH	Utilizing energy of hot calcium oxide
RFRG	Remaking calcium carbide furnace and recovering off-gas
MEAL	Manufacturing electrolytic aluminum liquid into ingot blank directly
RWH	Recovering waste heat through remolding boilers in the EP plant
RS	Recovering steam from productive process of PVC
ROG	Recovering off-gas from calcinatory in carbon plant
SI	Sharing infrastructures

Methods

The methods used for the quantitative assessment of the energy-saving efficiency of IS involve the selection of energy-saving indexes, including the energy-saving index of IS, contribution rate of energy saved through IS, fractional energy saving, cut rate of energy consumption per gross industrial output value (GOV), as well as financial indexes (Park and Behera 2014), such as the IS input–output ratio, the static investment payback period of IS, and the net present value (NPV), and internal rate of return (IRR) of IS.

Energy-saving index of IS

The IS energy-saving index is based on the comprehensive energy-saving index (C_e) (Dan et al. 2010), which is defined as the ratio of the total energy saved through IS and non-industrial symbiosis (NIS), as well as the rise in energy attributed to economic development, as calculated by Eq. (1). Thus, the IS energy-saving index (C_{IS}) refers to the ratio of the energy saved through IS and the rise in energy attributed to economic development, which can be calculated from Eq. (2). A larger value of C_e indicates greater energy saving effect and more advanced modes of IS and NIS. A larger value of C_{IS} results in a better effect of the energy saved through IS in an IP or EIP.

$$C_e = \frac{\sum_{i=1}^{n} \Delta E_{ISi} + \Delta E_{NIS}}{\Delta E_e} \quad (1)$$

$$C_{IS} = \frac{\sum_{i=1}^{n} \Delta E_{ISi}}{\Delta E_e} \quad (2)$$

where C_e is the comprehensive energy-saving index; C_{IS} is the energy-saving index of IS; ΔE_{ISi} is the amount of energy saved by IS mode i in the XF Industrial Park (XF IP); n is the number of IS modes; ΔE_{NIS} is the total energy saved through other methods, which are called NIS; and ΔE_e is the rise in energy attributed to economic development.

Contribution rate of energy saved through IS

The contribution rate (URL 2013) of energy saved through industrial symbiosis is defined as the ratio of energy saved by IS to the total energy saved in an industrial park or eco-industrial park through IS and NIS, as calculated by Eq. (3). This index illustrates the contribution and significance of IS to the total energy saved. Larger values of W_{IS} indicate a more role of the IS in saving energy.

$$W_{IS} = \frac{\sum_{i=1}^{n} \Delta E_{ISi}}{\Delta E_{IS} + \Delta E_{NIS}} \quad (3)$$

where W_{IS} is the contribution rate of energy saved through IS and ΔE_{IS} is the total energy saved through all IS modes in the XF IP.

Fractional energy savings

Under the condition that enterprises in IPs expand annually, C_{IS} is an ideal index for the assessment of IS efficiency in IPs. However, C_{IS} cannot be used if the enterprises in an IP do not expand. Thus, this paper selected another index, that is, fractional energy saving (η_{IS}), to assess IS efficiency. Fractional energy savings refers to the ratio of energy saved through IS to the total consumption of energy in an IP, which can be calculated using Eq. (4). Compared with C_{IS}, η_{IS} is unrestricted regardless of whether the IP expands.

$$\eta_{IS} = \frac{\sum_{i=1}^{n} \Delta E_{ISi}}{E_{ty}} \quad (4)$$

where η_{IS} is the fractional energy saving, and E_{ty} is the total energy consumption during the target year.

Cut rate of energy consumption per GOV

Taking a certain year as the base year, we calculated the energy consumption per GOV in this year and compared this value with that of the target year when all IS modes were completely constructed. We can then obtain the index cut rate of energy consumption per GOV, as calculated in Eq. (5), which can be utilized to analyze the intensity of energy saved through IS at the IP level.

$$D = \frac{\frac{E_{ty}}{GOV_{ty}} - \frac{E_{by}}{GOV_{by}}}{\frac{E_{by}}{GOV_{by}}} \quad (5)$$

where D is cut rate of energy consumption per GOV; and E_{by}, E_{ty}, and GOV_{by}, GOV_{ty} are the total energy consumption energy and GOV in the XF IP, respectively, for the base and target years.

IS input–output ratio

The IS input–output (Proops 1984) ratio formulated in Eqs. (6) and (7) is the financial input per energy saved through IS; more specifically, it is the ratio of the static investment and the energy saved through each IS mode. When the value of input–output ratio is smaller, the economic effect is better thus easily revealing the economic value of IS in an IP or EIP.

$$R_{ISi} = \frac{I_i}{\Delta E_{ISi}} \quad (6)$$

$$\overline{R} = \frac{\sum_{i=1}^{n} I_i}{\sum_{i=1}^{n} \Delta E_{ISi}} \quad (7)$$

where R_{ISi} is the input–output ratio of IS mode i, $\overline{R}$ is the average value of the IS input–output ratio, and I_i is the static investment of IS mode i.

Static investment payback period of IS

Static investment is the one-off construction cost of each IS mode, barring maintenance charges and management costs at a later period. The static investment payback period (SBEP 1996) of IS formulated in Eqs. (8) and (9) refers to the period in which the static investment is earned back. This index indicates the economic feasibility of an IS mode and will help IPs identify effective energy saving measures.

$$N_i = \frac{I_i}{\left(\Delta E_{ISi} \cdot p - \frac{I_i}{m}\right) \times (1 - \Gamma) + \frac{I_i}{m}} \quad (8)$$

$$\overline{N}=\frac{\sum_{i=1}^{n} I_i}{\left(\sum_{i=1}^{n}\Delta E_{\mathrm{IS}i}\cdot p-\frac{\sum_{i=1}^{n} I_i}{m}\right)\times(1-\Gamma)+\frac{\sum_{i=1}^{n} I_i}{m}} \tag{9}$$

where N_i is the static investment payback period of IS mode i; $\overline{N}$ is the average value of all IS modes; p is the price of standard coal, which is 950 RMB per ton. In addition, m is the depreciable life of IS equipment and 10 years is taken as the average value; Γ is the tax rate whose value equals to 25 %.

NPV and IRR of IS

In finance, the NPV of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values of the individual cash flows of the same entity (Lin and Nagalingam 2000) formulated in Eqs. (10) and (11). NPV may be used to assess the advantages and disadvantages of each IS mode. If the NPV is higher than zero, each IS mode is practicable. A larger NPV indicates a better IS mode and more benefits from the investment.

A higher IRR of an IS mode formulated in Eqs. (12) and (13) indicates that a certain mode is more suitable to undertake. IRR is the rate of pay. Thus, a larger IRR value is preferred (SBEP 1996).

$$\mathrm{NPV}_{\mathrm{IS}i}=\sum_{j=1}^{m=10}\frac{\left(P_i-\frac{I_i}{m}\right)\times(1-\Gamma)+\frac{I_i}{m}}{(1+\Pi)^j}-I_i \tag{10}$$

$$\overline{\mathrm{NPV}}=\sum_{j=0}^{m=10}\frac{\left(\sum_{i=1}^{n}P_i-\frac{\sum_{i=1}^{n} I_i}{m}\right)\times(1-\Gamma)+\frac{\sum_{i=1}^{n} I_i}{m}}{(1+\Pi)^j}-\sum_{i=1}^{n} I_i \tag{11}$$

where $\mathrm{NPV}_{\mathrm{IS}i}$ is the NPV of IS mode i and $\overline{\mathrm{NPV}}$ is the average value of NPV of all IS modes. P_i is the financial savings of IS mode i; Π is considered the current bank rate, whose value is 5.8 %.

$$\mathrm{IRR}_{\mathrm{IS}i}=i_1-\frac{\mathrm{NPV}_1(i_1-i_2)}{(\mathrm{NPV}_1-\mathrm{NPV}_2)} \tag{12}$$

where i_1 is the discount rate when NPV approaches zero from the positive direction namely NPV_1; i_2 is the discount rate when NPV approaches zero from the negative direction namely NPV_2.

$$\overline{\mathrm{IRR}}=i_1'-\frac{\overline{\mathrm{NPV}}_1\left(i_1'-i_2'\right)}{\left(\overline{\mathrm{NPV}}_1-\overline{\mathrm{NPV}}_2\right)} \tag{13}$$

where i_1' is the discount rate when NPV approaches zero from the positive direction namely $\overline{\mathrm{NPV}}_1$; i_2' is the discount rate when NPV approaches zero from the negative direction namely $\overline{\mathrm{NPV}}_2$.

Case study

Brief introduction of the XF IP

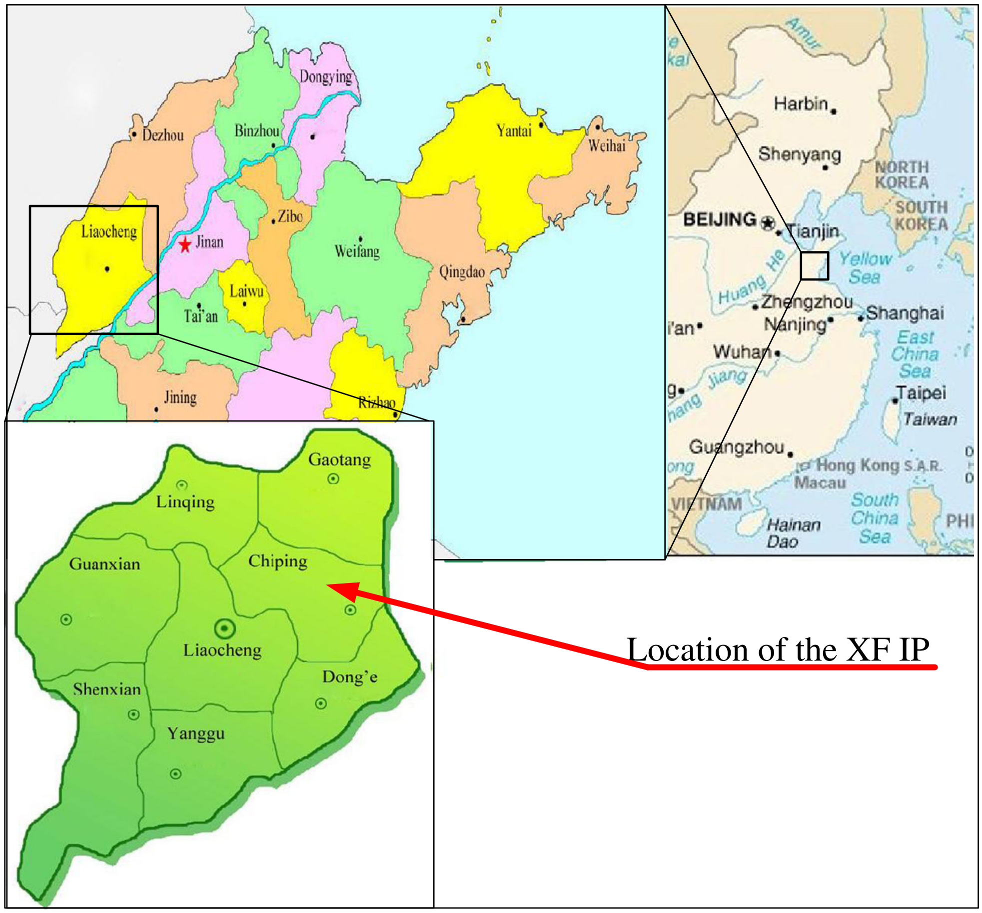
Founded in 1972 and located in the Chiping Economic Development Zone in Liaocheng City, Shandong Province (Fig. 1), the XF IP is a development at the base of a thermal electric power (EP) plant. The XF IP has 13 key enterprises that comprise an IS system of thermoelectricity, alumina, electrolytic aluminum, aluminum processing, caustic soda, calcium carbide, carbon processing, PVC, monosodium glutamate, and so on. The XF IP owns 208 enterprises containing the largest local thermal EP plant in China. Three large production bases are designated for aluminum processing, aluminum powder production, and prebaked anode production. The fixed assets of this IP have reached RMB 77 billion, adding RMB 0.66 billion to the fiscal revenue of local governments. The GDP has thus reached 14.04 billion RMB.

Data collection and content computation

The required data were mainly acquired from the clean production reports of enterprises in the XF IP and from documents provided by the local Environmental Protection Agency (EPA). In 2012, we conducted field investigations and obtained other data. The principal contents of the field investigations included information about production engineering and equipment, equipment investments, newly built IS modes, energy-savings, and the investments to each IS mode. The survey population included the production managers, financial managers, workshop directors, and technology development departments of each enterprise. The EPA of the XF IP was also covered.

With the available data, the computed content consisted of the total energy consumption (steam and EP) in each plant of the XF IP, direct energy-saving through IS between two production processes within one plant and IS mode between two plants, the amount of energy-savings between plants, as well as the heating system. When EP from EP plant was sufficient for every enterprise in the XF IP, redundant EP

Fig. 1 Location of the XF IP



would be transferred to the grid for sale. Conversely, EP was transferred to the XF IP from the grid as needed. Figure 2, which shows the boundary of the system, reveals the details of the computed contents.

Energy flow in industry chains

Survey data indicated that the main energy used by the XF IP was EP (Geng et al. 2010) and steam. Electrolytic aluminum, aluminum processing, caustic soda, and calcium carbide plants were the primary enterprises that consume EP. The alumina, medium-density fiberboard (MDF), and monosodium glutamate plants basically consumed steam. Table 1 displays the energy consumption of each enterprise. The alumina, electrolytic aluminum, MDF, caustic soda, and calcium carbide plants are the principal enterprises that consume energy, accounting for 98.74 % of the total energy consumption in the XF IP.

Energy flow between industry chains was studied by analyzing the material flow within the industry chain. Energy-saving channels through IS in XF IP were determined as follows: (1) the energy of materials at high temperature was utilized between industrial processes, (2) waste heat and steam were recovered between different processes, and (3) energy was saved by sharing infrastructures. A closely linked IS network that saved energy emerged because of the three modes of IS in the XF IP.

Utilizing energy of materials at high temperature

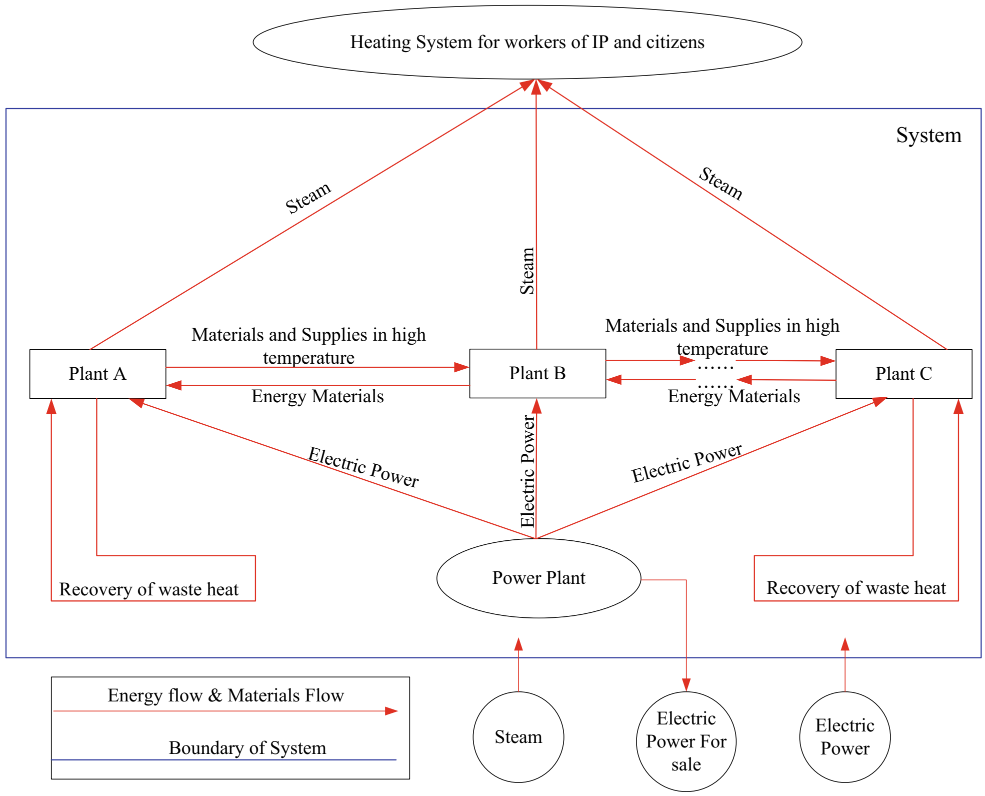
(1) Utilizing energy of thermokalite (UET in this work)

Owing to the geographic proximity of the industrial clusters in the XF IP, thermokalite (90 °C, 42 %) is pipelined to the alumina plant directly after being produced in the caustic soda plant. Compared with liquid caustic brought from outside, a temperature contrast of 65 °C is observed. Such a high temperature can help the alumina plant save 44,800 t of stream (0.2 MPa, 133 °C) with consideration of the amount of caustic soda (0.45 Mt) per year and the specific heat capacity of the liquid caustic (4,200 kJ kg^{-1} $°C^{-1}$).

(2) Utilizing energy of hot calcium oxide (UEH in this work)

The temperature of calcium oxide from the furnace is 200 °C to 250 °C, which decreases to 160 °C with a temperature contrast of 135 °C when calcium oxide is delivered to the calcium carbide factory through a conveyor belt that is resistant to elevated temperatures. Notably, 0.211 kW h of EP may increase the temperature of calcium oxide by 1 °C. Thus, 1 t calcium oxide at 160 °C enables the calcium carbide factory to save

Fig. 2 System boundary



28.94 kW h EP, which decreases to 28.49 M kW h when 1 Mt calcium oxide is delivered to the calcium carbide factory in this manner.

(3) Remaking calcium carbide furnace and recovering off-gas (RFRG in this work)

Depending on whether burner gas is burning in the furnace, calcium carbide furnaces can be classified as either an internal combustion type or closed type. The latter has a cover on top of the furnace, which isolates the furnace from air. In a closed furnace, the inside does not burn, such that minimal energy is lost, and the off-gas (CO, 75 to 85 %) can be gathered for use as fuel or to produce other chemical products.

The original calcium carbide furnace in the XF IP was half-closed and it was remade in 2008 into a closed furnace, after which 16 closed furnaces were placed in

Table 1 Statistics of each enterprise's energy consumption of the XF IP in 2011

Name of enterprise	EP[a]/MkW h	Ratio of EP/%	Steam[b]/Mt	Ratio of steam/%	Total energy consumption/Mtce	Ratio of total energy consumption/%
Electrolytic aluminum	10,800	70.18	/	/	1.33	35.45
Alumina	1,357.14	8.82	17.14	79.75	1.64	43.92
Monosodium glutamate	167.86	1.09	0.71	3.32	0.08	2.2
MDF	305.14	1.98	2.66	12.36	0.27	7.12
Carbon	77.04	0.5	0.09	0.41	0.02	0.45
PVC	130.74	0.85	0.41	1.9	0.05	1.37
Caustic soda	912.86	5.93	0.23	1.07	0.13	3.53
Calcium carbide	1,433.57	9.32	/	/	0.18	4.71
others	204.56	1.33	0.26	1.19	0.06	1.26
Total	15,388.91	100	21.5	100	3.74	100

[a] The coefficient of conversing EP to standard coal is 1.229 Ht/MkW h

[b] Parameters of low-pressure steam: 0.2 MPa and 133 °C. The coefficient of converting steam to standard coal is 11.6 t/t

the XF IP (eight 30,000 kV sets and eight 25,500 kV sets). Moreover, each 30,000 kV furnace produces 2,300 Nm^3/h to 3,800 Nm^3/h of off-gas, of which 2,680 Nm^3/h can be gathered. Furthermore, each 25,500 kV furnace produces 1,920 Nm^3/h to 3,160 Nm^3/h of off-gas, of which 21,440 Nm^3/h can be gathered. Thus, 39,328 Nm^3/h of off-gas (2,740 Cal/Nm^3), 75 to 85 % of which is CO, is gathered from the 16 furnaces. After being purified, the off-gas is used as fuel to fire calcium oxide instead of coal, which saves 0.1217 Mtce per year. Moreover, the use of off-gas as fuel cuts down the consumption of budgust and EP by 0.27 t and 50 kW h, respectively, when producing 1 t of calcium oxide compared with traditional production engineering. Calcium carbide unit consumption is reduced by 150 kW h, and 5,520 tce is saved annually in the XF IP calcium carbide plant.

(4) Manufacturing electrolytic aluminum liquid into ingot blank directly (MEAL in this work)

Electrolytic aluminum liquid (810 °C) is delivered directly by a special tank car and pipelined from the electrolytic aluminum plant to the aluminum processing factory, which eliminates the remelting of aluminum and significantly reduces the energy consumed when processing aluminum. First, 1,000 kW h EP is consumed when remelting aluminum. Thus, 0.1217 Mtce is saved when 0.99 Mt of electrolytic aluminum liquid is used in the XF IP.

Recovering waste heat and steam

(1) Recovering waste heat through remolding boilers in the EP plant (RWH in this work)

To guarantee the quality of the steam from the boiler, along with boiler security and stability, the EP plant discharges sewage (110 to 130 °C out of the expansion tank) continuously, which is the key factor affecting the efficiency of the boiler in the EP plant. Discharging hot sewage directly and continuously not only wastes heat, but also damages the wastewater recycling system. Considering the features (steady, high temperature) of hot sewage, the XF IP remade the discharge system of boilers to recover heat from the sewage. Such heat is used as steam in the heat supply network, through which 2.025 Mt of steam is saved for a total of 0.1746 Mtce annually. A portion of the steam from the EP plant pours in from the MDF plant, thus creating an IS relationship among the EP plant, the MDF plant, and other enterprises with no strict requirements for steam quality.

(2) Recovering steam from the productive process of PVC (RS in this work)

In the PVC plant, a graphitic synthetic furnace is used to synthesize chlorine hydride. This process produces steam (0.2 MPa, 133 °C), which meets the steam demand of caustic soda and PVC devices at 0.27 Mt per year.

(3) Recovering off-gas from calcinator in the carbon plant (ROG in this work)

The ZTE Carbon Company remade calcinatory #9, #10, and #11 by establishing three steam furnaces to recover off-gas (0.2 MPa, 133 °C, 0.04 Mt), which satisfies the heating requirements of the company and gas house. Moreover, the excess steam is sold to the heat supply network of the city.

Sharing infrastructures (SI in this work)

The XF IP insists on development through a combination of producing, providing, and consuming. Thus, each factory (the electrolytic aluminum, alumina, chemical, and calcium carbide plants) has a self-contained, complete EP plant nearby to cut down the EP wastage (equal to 60 MkW h EP) in the circuit by reducing tension and boosting voltage.

Table 2 shows the energy saved by each IS mode. The IS network in the XF IP is displayed in Fig. 3. The heating system, which supplies heating for workers and townspeople, was not in the IP area; however, the spare steam (0.2 MPa, 133 °C) from enterprises in the XF IP was considered in this study. Approximately 1.18 Mt steam was transferred to the heating system, as shown in Fig. 3.

Results and discussion

Energy-saving indexes of IS in the XF IP

In 2008, the XF IP did not have IS chains. Thus, we use 2008 as the base year. All of the IS chains in the XF IP were completed in 2011, which was the target year. The energy consumption in 2011 was completed by retaining the energy consumption level in 2008, which was called scenario analysis (Tian and Jin 2012), as shown in Table 3.

$$\Delta E_{\mathrm{e}} = \sum_{k=1}^{n} \mathrm{e}_k \cdot M_k - E_{2008} \quad (14)$$

where ΔE_{e} is the increase in energy attributed to economic development as defined previously, e_k is the production level of enterprise k in 2008, and M_k is the scale of enterprise k in 2011.

As shown in Table 3, the predicted energy consumption for 2011 was 5.0885 Mtce. When compared with the actual

Table 2 Modes and energy savings of each IS chain

Source	Receiving company	Materials with energy	The amount of energy-saving/tce
Chlor-alkali plant	Alumina plant	Thermokalite 90 °C	3,900
Lime factory	Calcium carbide factory	Calcium oxide 160 °C	3,500
Calcium carbide factory	Lime factory	Rich in CO	121,700
Calcium carbide factory	Calcium carbide factory	Closed heating furnace	5,500
Electrolytic aluminum plant	Aluminum processing factory	Electrolytic aluminum liquid	121,700
EP plant	Electrolytic aluminum plant and other plants	Infrastructure	7,400
EP plant	MDF plant and EP plant	Low-pressure steam	174,600
PVC plant	MDF plant and system of supply heating	Low-pressure steam	23,300
Carbon plant	Carbon plant and system of supply heating	Low-pressure steam	3,500
Total	465,100		

consumption for 2011, which was 3.7444 Mtce, this finding indicates that the amount of energy saved is 1.3441 Mtce, of which 0.879 Mtce is from NIS, and 0.4651 Mtce is from IS. The energy consumption for 2008 was 3.662 Mtce. Energy consumption rose to 1.4265 Mtce from 2008 to 2011 as a result of the economic development in the XF IP. Thus, we can calculate three indexes: comprehensive energy-saving index, energy-saving index of IS, and contribution rate of energy saved through IS.

$$C_e = 0.9422; \quad C_{IS} = 0.326; \quad W_{IS} = 34.6\%$$

The energy-saving index of IS, contribution rate of energy saved through IS, fractional energy saving, and cut rate of

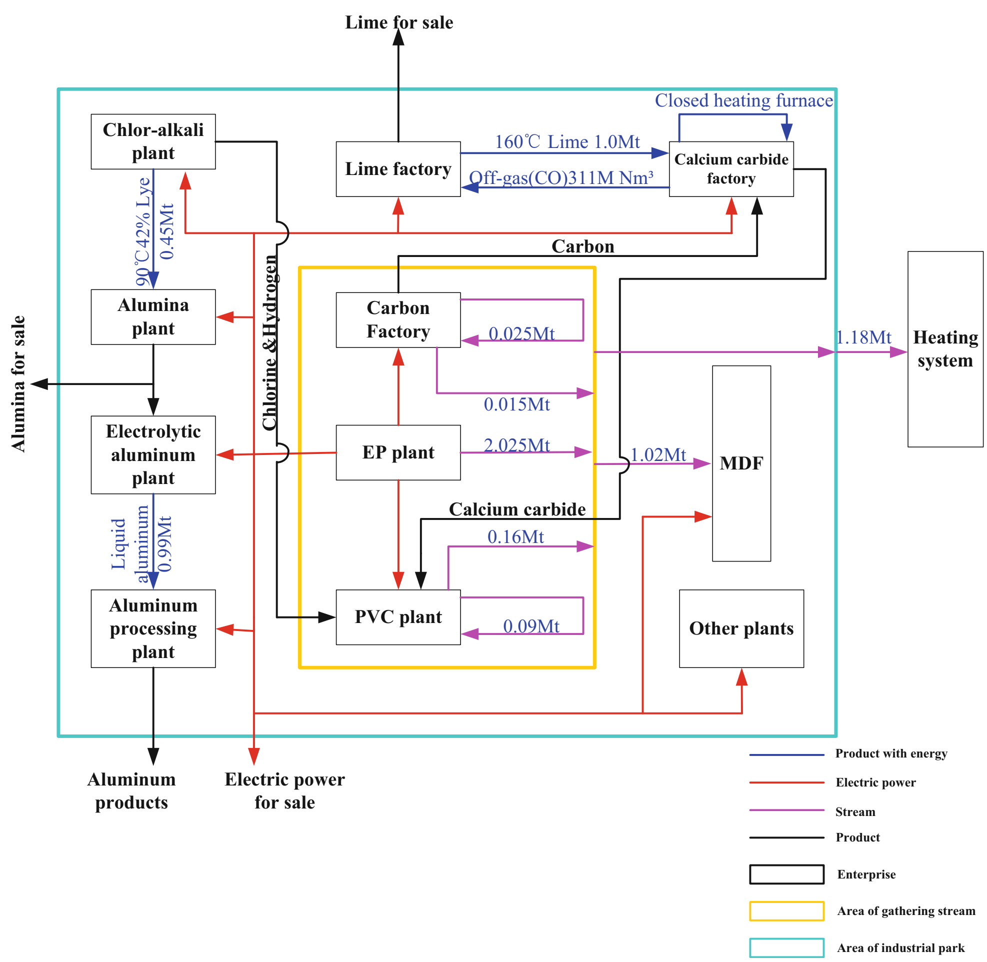


Fig. 3 Net of IS based on cascade utilization of energy in the XF IP

Table 3 Predicted consumption of energy in 2011 based on scenario analysis

Product	EP plant	Alumina plant	Electrolytic aluminum plant	Caustic soda plant	PVC plant	Calcium carbide	Carbon plant	Aluminum processing factory
Scale/Mt	11,823[a]	4.5	0.68	0.45	0.55	0.3	0.35	0.5
Comprehensive energy consumption per unit products kgce/t	23.6[b]	429	1,715	391	250	1,470	72.7	1,865.87
Consumption of energy /Mtce	0.279	1.9305	1.166	0.176	0.1375	0.441	0.0254	0.9329
Total /Mtce	5.0885							

[a] The measurement unit of EP is MkW h

[b] Comprehensive energy consumption per unit product of EP indicates the consumption of energy needed to produce 1 kW h, the measurement unit of which is gce/kW h

energy consumption per GOV were calculated to assess the effect of energy saved through IS. The highest value of C_e in developed countries is 1.11, whereas the lowest value is 0.86. However, the C_e of China is significantly lower than that of developed countries at approximately 0.6, except in1995 to 2000, when the economic growth rate of China slowed, and C_e was 1.18. The C_e of the XF IP is 0.9422, approaching that of developed countries, and the C_{IS} of the XF IP is 0.326 with a percentage of 34.6 %, thus indicating the availability of IS modes in the XF IP.

According to the definition of the comprehensive energy-saving index (Dan et al. 2010), if C_e >1, the effect of the energy saved through IS and NIS will catch up with and surpass the incremental consumption of energy attributed to economic development, such that the amount of total energy consumption in IP is ultimately reduced. If C_e <1, the effect of the energy saved through IS and NIS is less than that of the incremental consumption of energy attributed to economic development, whereas the amount of total energy consumption in IP ultimately increases. In sum, a larger value of C_e indicates greater energy saved and more advanced modes of IS and NIS. A larger value of C_{IS} results in a better effect of the energy saved through IS in the IP.

Based on the section on energy flow in industry chains, the amount of energy saved through IS in the XF IP was determined to be 0.4651 Mtce, and the actual consumption of energy in 2011 was 3.7444 Mtce. The energy consumption in 2008 was 3.662 Mtce. Thus, η_{IS} is equal to 12.42 %, whereas η_{NIS} is 23.47 %, which indicates that the amount of energy saved through IS comprises 12.42 % of the actual total energy consumption, whereas that saved through other methods comprise 23.47 %. Industrial technology innovation could only contribute 12 to 14 % to energy saving (Liu et al. 2010), and its investment is much higher than that of IS. D is equivalent to 43.24 %, which will be 14.41 % if averaged over the 3 years from 2008 to 2011.

The amount of energy saved through the use of IS modes was determined to be 0.4651 Mtce. The energy-saving index and fractional energy savings of IS were 0.326 and 12.42 %, respectively, thus contributing 34.6 % to the comprehensive energy-saving index and reducing energy consumption per GOV by 43.42 % from 90.9 tce/MRMB in 2008 to 51.6 tce/MRMB in 2011. Owing to IS and other energy-saving measures, the comprehensive energy consumption per unit of the electrolytic aluminum plant, alumina plant, calcium oxide plant, and other factories achieved a world-class level that is more advanced than the domestic level. The consumption rate of energy sources in China is increasing at an average annual rate of 9.98 % (Jiang and Lin 2012; Liao et al. 2013; Rao et al. 2011). IS in China is in its infancy, but its energy-saving advantages are remarkable based on the analysis in this paper.

Moreover, the IS mode based on materials is likely to contribute to indirect energy savings. For example, waste materials from plant A could replace the raw materials of plant B, which may save energy for manufacturing raw materials (Boons et al. 2011; Trokanas et al. 2014). The advantage of IS modes in IPs or EIPs would be obvious if indirect energy savings are considered. The computing paradigm of indirect energy savings through IS modes based on materials is complex, and the initial data are difficult to access. Therefore, this paper preferentially discussed direct energy savings.

Financial indexes of IS in the XF IP

According to the investigated data and the formulas introduced above, the financial indexes of IS are determined and displayed in Table 4.

Table 4 demonstrates that the IS input–output ratio is small, with an average value of 406.2 RMB/tce, which is 57.2 % lower than the price of standard coal. This finding implies the high economic benefits of IS. The low investment (less than 0.1 MRMB, disregarding the alteration of new devices) provides an edge to IS, which generally needs no large-sized devices apart from pipelines that carry steam and materials with energy. In addition, the dynamic investment, or the cost of maintenance and management after construction, is low, which indicates the practicability of IS for enterprises or IPs that have limited floating capital. The static investment payback period of IS is short term, with a maximum value in the

Table 4 Financial indexes of IS in the XF IP

Reforms of IS	Investment M RMB	Energy-saving tce	Input–output ratio RMB/tce	Static investment payback period/month	NPV M RMB	IRR %
RFRG	133	127,200	1045.597	21.8	42.336	55.62
RWH	10	174,600	57.274	1.2	721.609	984.62
RS	5	23,300	214.592	4.5	93.285	264.55
Remaking of Net of Steam	40	/	/	/	/	/
ROG	0.74	3,500	211.429	4.4	10.426	268.55
MEAL	0.068	121,700	0.559	0.01	5.086	100,673.46
UET	0.054	3,900	13.846	0.3	16.256	4,065
UEH	0.046	3,500	13.143	0.3	14.591	4,282.39
SI	/	7,400		/	/	/
Total & Average	188.908	465,100	406.189	8.5	1,789.961	140.96

XF IP of 22 months. The minimum value is only 1 month. The average payback period in the XF IP is 8.5 months, which indicates that the XF IP began to earn profit 8.5 months after the construction of all IS modes. However, the short static investment payback period mainly depends on the IS modes and the characteristic structures of the enterprises within the XF IP.

The NVP of each IS mode is greater than zero, the minimum value is 10.426 MRMB, whereas the maximum value is 721.61 MRMB. The average value is 1,789.96 MRMB. The IRR of each IS mode is also greater than zero, with an average value of 140.96 % in the XF IP, which demonstrates the economic viability and benefits of IS in the XF IP.

The indexes of the static investment payback period of IS (IS input–output ratio and the NPV and IRR of IS) were used to analyze the economic feasibility of IS. The case of the XF IP proved the low amount of investment required (with some IS modes requiring no investment) and the short-term static investment payback period, which should promote the popularization of IS in IPs or EIPs. The IS input–output ratio in the XF IP was 406.2 MRMB/tce, which is 57.2 % lower than the price of standard coal. The NPV and IRR of IS in the XF IP were high, thereby suggesting the high economic benefits of IS (Wen and Meng 2014).

The economic viability and benefits of IS largely rely on the geographical proximity (Jensen et al. 2011) between enterprises in the XF IP. Familiar IS patterns in other IPs may not generate significant energy-savings. For instance, the UEH case, which paid 0.046 M RMB for a conveyor belt between the lime plant and calcium carbide factory, could save 3,500 tce with an IRR of 4,282.39 %. Except for the expenses of the transport unit, no front-end investment was needed in the UEH case. The MEAL case invested 0.068 M RMB for the construction of a pipeline between the electrolytic aluminum plant and aluminum processing factory, as well as the transportation cost for special tank cars, which could result in total energy savings of 121,700 tce.

Final discussion

The adopted evaluation methodology was utilized to investigate the energy saved through IS and economic feasibility of IS by analyzing the material flow within the industry chain. The proposed index system is easy to be operated and may help IPs and EIPs to make a strategic decision when designing IS modes. The method also has deficiencies, such as the boundedness of the energy-saving index, which could be applied only if no expansion scale occurs in enterprises. Moreover, the selected indexes, particularly the financial indexes were insufficient. This paper discussed the investment of constructing IS modes but neglected the running cost, maintenance charge, labor cost, as well as the investment variety of IS devices and their performance period, some of which were unstable and difficult to obtain. This condition gives rise to difficulties in quantifying research on the energy-saving efficiency of IS from the economic perspective. Therefore, the selected financial indexes would reflect the significant economic benefits of IS to a certain extent. Fortunately, the proposed indexes system in the paper would improve the evaluation methodology of IS energy saving efficiency to a certain degree.

Conclusion

The following conclusions were drawn after conducting the research:

1) By analyzing the material flow in the industry chain, this paper studied the energy flow among industry chains in the XF IP. Three energy-saving channels using IS were found in the XF IP: (a) utilizing the energy of high-temperature materials among industrial processes, (b) recovering waste heat and steam between different processes, and (c) saving energy by sharing infrastructures. A closely linked IS

network that saves energy was created considering the three IS modes in the XF IP, which provided significant economic benefits to the enterprises.

2) Despite the fore-mentioned deficiencies, the implication of the proposed index system cannot be ignored. The value of each energy-saving index of IS illustrates that IS's energy-saving advantages are noteworthy, even though IS in China is in its infancy. Moreover, the financial indexes help to analyze the economic feasibility of IS, and IS modes would provide significant economic benefits to the enterprises in an IP or EIP. The proposed methodology quantifying the energy-saving efficiency of IS may help IPs and EIPs to make a strategic decision when designing IS modes. Overall, IS could lead to use of energy with high efficiency and lighten the financial burden of enterprises in IPs or EIPs.

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