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The research on the index system of extended energy efficiency evaluation

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Abstract. Energy problem has been the focus of attention. Energy efficiency evaluation is an important part of energy conservation and emission reduction, but the evaluation system of energy saving measures and its effect is not perfect. Firstly, a more perfect and scientific energy efficiency evaluation system is established. The kinds of energy are classified. The concepts of extended system, global system, transfer extended system and local extended system are put forwarded. The connection of the two energy efficiency evaluation indices, energy consumption ration and energy utilization efficiency, was analyzed. On this basis, the concept of energy consumption transfer and energy consumption feedback is introduced, and its significance is expounded.

1. Introduction

With the continuous growth of energy consumption and the shortage of primary energy, low-carbon economy has become a popular topic all over the world. China has also done a lot of work in energy saving and make progress emission reduction, but compared with the international advanced level, there is still a large gap[1-3]. Therefore, during the “Thirteenth Five-Year Plan” period in China, energy issues continue to be the focus of public attention, and effective energy-saving and emission-reduction measures cannot be procrastinated[4]. However, before taking effective measures to save energy and reduce emissions, it is necessary to fully understand the energy components and the energy flow process. Based on the understanding, it is also necessary to have a scientific and reasonable evaluation system. At present, the research on energy efficiency evaluation technology is deepening at home and abroad, but there is not a complete set of energy efficiency evaluation system, so it is difficult to give a comprehensive evaluation of the energy-saving effect of various energy-saving measures[5-8]. However, with the gradual attention of China's energy problems and the further promotion of energy conservation and emission reduction, a comprehensive and accurate evaluation of energy efficiency is an inevitable trend. Ref. [9-10] extracts the universally adaptive indicators from the various aspects of the regional integrated energy system and the smart grid, and then uses the methods of analytic hierarchy process, network analysis and anti-entropy to evaluate the energy efficiency of the system. Ref. [11-12] has preliminarily explored the index selection of energy efficiency evaluation index system and put forward an energy efficiency evaluation system based on energy utilization efficiency and energy consumption ratio. It is suitable for horizontal comparison in multiple occasions. It makes up for the shortcomings of the traditional indefinite energy efficiency evaluation index and imperfect system. But the energy consumption mentioned is only considering the local energy utilization, when there is energy transfer and feedback situation in the system, from the local point of view it is an effective energy saving measure. From the point of view of extended



system, it may be found that the energy loss is not really reduced. Therefore, it is more accurate and comprehensive to analyze the energy transfer and energy consumption feedback within the extended system, which will further improve the whole energy efficiency evaluation system.

2. Global energy efficiency evaluation system

2.1. Energy classification

In a production process unit, the total energy input to accomplish the target operation is called input energy, denoted by E_{in} ; the input energy is divided into effective energy and ineffective energy, respectively expressed by E_{ef} and E_l ; the effective energy is converted into the required energy called output energy, denoted by E_{out} , according to the conservation of energy $E_{ef} = E_{out}$.

Ineffective energy is divided into direct ineffective energy and indirect ineffective energy. Indirect ineffective energy is divided into attendant indirect ineffective energy and prerequisite indirect ineffective energy, denoted by E_{l-b} , E_{l-id} , E_{l-bid} and E_{l-nid} . The direct consumption generated by effective energy in the target object is called the attendant ineffective energy. The energy consumption in transmitting and converting the effective energy is called prerequisite indirect ineffective energy. The ineffective energy that increases with ineffective energy or other factors is called attendant indirect ineffective energy, as shown below:

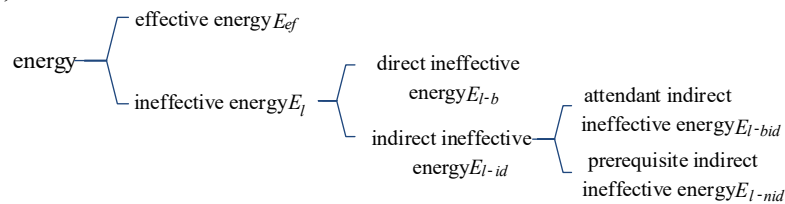


Figure 1. Classification of energy.

2.2. Extended Energy Efficiency and Global Energy Efficiency

Conventional energy efficiency evaluation generally targets a single enterprise or a single device, but in terms of the entire energy system, there is no object of isolated island operation. Therefore, considering the energy efficiency of the object, other objects related to the target object should be taken into account to obtain the energy efficiency and energy consumption ratio in the extended range, so as to objectively and comprehensively reflect the energy saving situation brought by the specific energy saving measures. Therefore, the concept of extended energy efficiency and global energy efficiency is proposed.

The object considered in this article is defined as the target object. The object which provides energy for the target job is defined as the pre-object. The system consisting of the target object and the preceding object is called the extended system. The extended ineffective energy of the extended system is the sum of the target ineffective energy E_l and the preceding ineffective energy E_{l-pre} , denoted by $E_{l-extended}$.

When there are multiple pre-objects in the target object, the defined target object is a 1-level object, the pre-object of the 1-level object is called a 2-level object, and the pre-object of the (n-1)-level object is called a n-level object by analogy. An energy supply system that defines n-level objects is called a n-level extended system. A n-level extended ineffective energy in the n-level extended system is sum for energy consumption of each level object and the target object, denoted by $E_{l-extendedn}$. The effective energy of the extended system is called extended effective energy, which is denoted by $E_{ef-extended}$. The extended system ineffective energy is referred to as extended ineffective energy and denoted by $E_{l-extended}$. The extended system input energy is referred to as extended input energy and is denoted by $E_{in-extended}$.

By introducing the above multi-level extended system, the first object in the system will be the initial object. This paper defines the entire energy flow system from the initial object to the target object as a global system. The effective energy, ineffective energy, and input energy of the global system are called global effective energy, global ineffective energy, and global input energy, respectively denoted by $E_{\text{ef-initial}}$, $E_{\text{l-initial}}$ and $E_{\text{in-initial}}$. The description of the extended system and the global system, as shown in Figure 2.

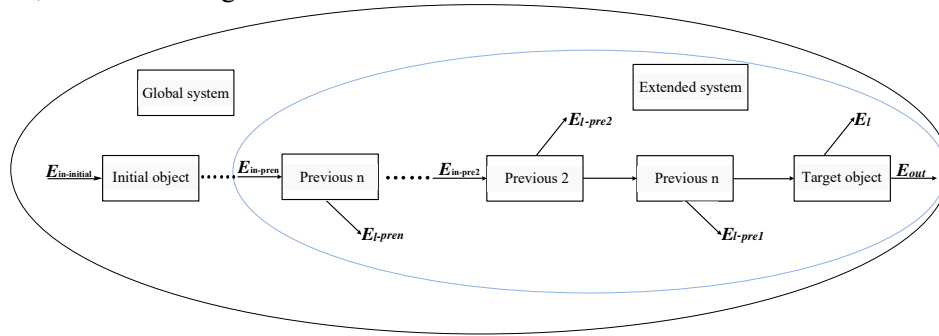


Figure 2. Extended system and global system.

2.3. Energy efficiency and energy consumption ratio

Energy efficiency is the ratio of effective energy to input energy, denoted by η .

Energy consumption ratio is the ratio of ineffective energy to effective energy, denoted by h .

$$\eta = \frac{E_{\text{ef}}}{E_{\text{in}}} \times 100\% = \frac{E_{\text{out}}}{E_{\text{in}}} \times 100\% \quad (1)$$

$$h = \frac{E_{\text{l}}}{E_{\text{ef}}} \times 100\% = \frac{E_{\text{l}}}{E_{\text{out}}} \times 100\% \quad (2)$$

The energy efficiency of the extended system is the ratio of the effective energy of the extended system to the input energy of the extended system, denoted by η_{extended} .

The energy consumption ratio of the extended system is the ratio of the extended ineffective energy to the extended effective energy, denoted by h_{extended} .

$$\eta_{\text{extended}} = \frac{E_{\text{ef}}}{E_{\text{in-extended}}} \times 100\% \quad (3)$$

$$h_{\text{extended}} = \frac{E_{\text{l-extended}}}{E_{\text{ef}}} \times 100\% \quad (4)$$

The global energy efficiency of the global system is the ratio of the effective energy of the global system to the input energy of the global system, denoted by η_{initial} .

$$\eta_{\text{initial}} = \frac{E_{\text{ef}}}{E_{\text{in-initial}}} \times 100\% \quad (5)$$

The global energy consumption ratio of the global system is the ratio of global ineffective energy to global effective energy, denoted by h_{initial} .

$$h_{\text{initial}} = \lim \frac{E_{\text{l-pre1}} + E_{\text{l-pre2}} + \dots + E_{\text{l-pren-1}} + E_{\text{l-pren}} + E_{\text{l}}}{E_{\text{ef}}} = \frac{E_{\text{l-initial}}}{E_{\text{ef-initial}}} \times 100\% \quad (6)$$

Energy utilization efficiency and energy consumption ratio are the basis for measuring the energy utilization and energy consumption. The relation between the two is:

$$h = \frac{1}{\eta} - 1 \quad (7)$$

$$\eta = \frac{1}{h+1} \quad (8)$$

The energy in this paper is different from the defined power P (unit kW) of efficiency in the traditional sense. The E in energy efficiency and energy consumption ratio in this paper represents energy (unit J). The energy in the energy efficiency evaluation system in this paper is an integral of power in time. The input energy in this paper should be all energy input from the time energy is supplied until the stop of supply. The effective energy should be the energy used during the period from the start of action to the stop action.

$$E_{\text{in}} = \int_{T_{\text{start}1}}^{T_{\text{end}1}} p_{\text{in}} dt = \int_0^{T_1} p_{\text{in}} dt \quad (9)$$

T1-Period of energy supply.

$$E_{\text{ef}} = \int_{T_{\text{start}}}^{T_{\text{end}}} p_{\text{ef}} dt = \int_0^{T_2} p_{\text{ef}} dt \quad (10)$$

T2-Period of energy utilization.

3. Transfer energy consumptiono

For some cases, the input energy of the target object includes two parts: one part is directly delivered to the local by the pre-object, which is called direct input energy, denoted by $E_{\text{in-d}}$; the other part is delivered through some form of conversion and indirectly forwarded. The energy transferred from the level object is indirectly transmitted energy, which is called indirect energy input. It is denoted by $E_{\text{in-ind}}$. The relation between two parts are shown in the following formula:

$$E_{\text{in}} = E_{\text{in-direct}} + E_{\text{in-indirect}} \quad (11)$$

The energy consumption during the indirect energy-conversion is called indirect conversion energy consumption, denoted by $E_{\text{I-convert}}$. As shown in Figure 3:

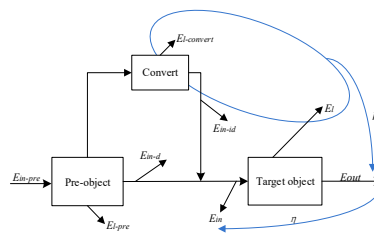


Figure 3. Indirect conversion of energy.

When considering the energy efficiency, a reasonable analysis is to use the total input of the pre-object as an input indicator, and the indirect conversion energy consumption and the local energy consumption are used as energy consumption indicators. This is the energy consumption of the target object during the whole process of energy utilization.

The target energy efficiency is:

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}} \times 100\% \quad (12)$$

The target energy consumption ratio is:

$$h = \frac{E_l + E_{l\text{-convert}}}{E_{\text{out}}} \times 100\% \quad (13)$$

By taking some measurements, the energy converted indirectly from the pre-object is no longer provided by the pre-object, but is provided by another new productivity object, then we say that the target object has more than one pre-object. That is, the original indirect input energy is transferred to a new pre-object. This new pre-object is called transfer object. The energy provided by the transfer object is called the transfer input energy, denoted by $E_{\text{in-tra}}$, which is:

$$E_{\text{in}} = E_{\text{in-d}} + E_{\text{in-tra}} \quad (14)$$

The energy consumption caused by the transfer object in providing the transfer input energy is called transfer consumption, denoted by $E_{l\text{-tra}}$. As shown in Figure 4:

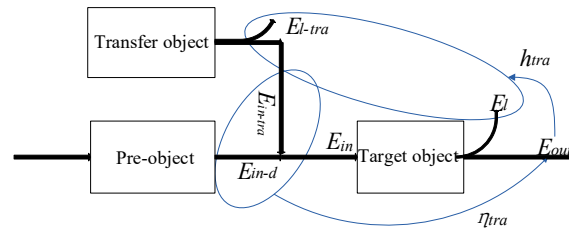


Figure 4. Transfer energy consumption.

When the energy conversion shown in Figure 4 occurs, the analysis according to Figure 3 is unreasonable. We consider not only the consumption of the target object, but also the transfer consumption when the transfer object transfers the input energy to the target object after the energy transfer occurs. This is also a reasonable way to consider energy transfer and utilization within an extended range.

This paper defines that a system that does not include a transfer object is a local extended system, and a system that includes a transfer object is called a transfer extended system.

When the energy transfer occurs, the energy utilization efficiency of the target object in the transfer extended system is the ratio of the target effective energy to the sum of the direct input energy and the transfer input energy:

$$\eta_{\text{tra}} = \frac{E_{\text{out}}}{E_{\text{in-tra}} + E_{\text{in-d}}} \times 100\% \quad (15)$$

The ratio of energy consumption is the ratio of the sum of the target energy consumption and the transfer energy consumption to the target effective energy:

$$h_{\text{tra}} = \frac{E_l + E_{l\text{-tra}}}{E_{\text{out}}} \times 100\% \quad (16)$$

From that, when energy transfer occurs, the energy efficiency of the system may increase if it only focuses on the local extended system. However, if you aims to the transfer extended system, the original part of the indirect energy consumption still exists, just transferred to other objects, and its energy efficiency has not increased. The process of transferring the original indirect energy consumption to other objects becomes transfer energy consumption. It can be seen that the transfer energy consumption in the local extended system can reduce the local energy consumption and increase the local energy efficiency. However, in the transfer extended system, the energy consumption of the transfer object in providing the transfer input energy cannot be ignored. Therefore, from the perspective of the transfer, energy transfer is not a reasonable plan to improve energy efficiency.

For example, a manufacturing company, consumes a large amount of water vapor each year to complete operations. In order to reduce the energy consumption of steam production, steam is purchased from other companies, and the company becomes the transfer target. If the energy

consumption of the water vapor produced by the transferred enterprise is higher than that of the enterprise, the energy consumption of the production water vapor is transferred to other enterprises during the process of purchasing steam. In the transfer extended system, the actual energy consumption is not reduced. Instead, it entered the transfer object.

4. Energy consumption feedback

In the whole energy system, there is another case that the locally lost energy is recycled in a certain way and re-enters the system as input energy. This article refers to this kind of energy reuse as energy consumption feedback. The part of energy that is recycled in the ineffective energy is called feedback energy, denoted by E_{re} . The consumption that this part of energy generates in the feedback process is called feedback consumption, denoted by E_{l-re} . The energy that is actually recycled out of the consumption portion is called feedback input energy, denoted by E_{in-re} . The feedback input energy is sent to the system, and consumption is also generated in the process of transmission and utilization in the system, called reuse consumption, denoted by $E_{l-reuse}$. The output part produced by the feedback input energy E_{in-re} is E_{out}^* , and the target object output E_{out} includes E_{out}^* and the effective energy conventionally utilized in the system. As shown in Figure 5.

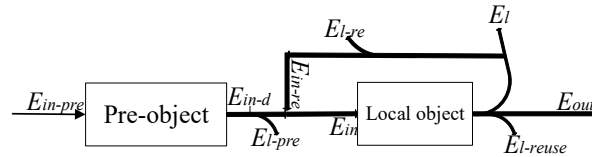


Figure 5. Energy consumption feedback.

The energy utilization efficiency of the target system after energy feedback is:

$$\eta_{re} = \frac{E_{out}}{E_{in-re} + E_{out-pre}} \times 100\% \quad (17)$$

The energy consumption ratio of the target system is:

$$h_{re} = \frac{E_l^* + E_{l-re} + E_{l-reuse}}{E_{out}} \times 100\% \quad (18)$$

The energy utilization efficiency of the extended system after energy transfer is:

$$\eta_{pre} = \frac{E_{out}}{E_{in-pre}} \times 100\% \quad (19)$$

The energy consumption ratio of the extended system is:

$$h_{re} = \frac{E_l + E_{l-re} + E_{l-reuse} + E_{l-pre}}{E_{out}} \times 100\% \quad (20)$$

On the surface, the feedback of energy consumption is to recycle the ineffective energy and reuse it to increase the energy utilization efficiency and reduce energy consumption. However, through the above analysis, the feedback input energy will increase the energy consumption in the process of transmission in the system. For example, the energy E_{l-re} will be generated when the energy is recycled, and it will be added to the input to increase the energy consumption $E_{l-reuse}$, therefore need to be analyzed according to the actual situation, in order to determine whether the energy feedback to the system of energy-consumption ratio reduction and energy utilization efficiency improvement.

The above analysis of the energy transfer and energy consumption feedback situation may exist in the global evaluation system, so it will affect the energy efficiency of the whole system. Therefore, in order to maximize the global energy utilization efficiency and minimize the energy consumption ratio, when considering the energy utilization efficiency and energy ratio of the target object, we should

focus on the global system, and consider the situation of energy transfer and energy consumption feedback.

5. Case analysis

A regional integrated energy system (RIES) As shown in the figure, the RIES consists of a power supply system, a distribution network, energy conversion, energy storage, and end-user. The energy supply system includes renewable distributed power, grid, natural gas and geothermal energy to provide energy for the system. The main task of the distribution network (busbar) is to complete the stable transmission and reasonable distribution of different energy sources. Gas turbines, heat exchangers, gas boilers and ground source heat pumps are used for coupling interaction and mutual conversion between different energy sources. The electric energy storage can complete peak clipping and valley filling. End-user include various types of loads for energy consumption.

There is energy consumption in all processes of energy transmission. Taking each transmission process or device as the target object, the effective energy, the invalid energy and the input energy of each target object are calculated according to the known energy flow condition, thereby obtaining the energy utilization efficiency and the energy consumption ratio of each target object, as shown in Table 1.

Table 1. Energy analysis of each aspect of RIES.

Target	Effective energy (MJ)	Invalid energy (MJ)	Energy efficiency (%)	Energy consumption ratio (%)
Busbar	3316.45	174.55	95	5.26
Charging pile	100	17.65	85	17.65
Electric car	67	33	67	49.25
Electrical load	2100	900	70	42.86
Electrical energy storage	50	8.8	85	17.6
Electric refrigerator	70	70	50	100
Heat absorption refrigeration	30	270	10	900
Cold load	90	10	90	11.11
Gas turbine	350	150	70	42.86
Gas boiler	490	210	70	42.86
Heat exchanger	160	40	80	25
Thermal load busbar	360	40	90	11.11
Ground source heat pump	86.84	130.26	40	150
Heat load	360	40	90	11.11

By calculating the energy efficiency and energy consumption ratio, the energy efficiency evaluation of each process can be carried out, and the energy efficiency low link needs to be improved or the energy flowing through the link needs to be decreased.

For the entire RIES, it is equivalent to constitute a global system, electric vehicle, electric load, heat load and cold load are the target objects, and distributed power, grid, natural gas and geothermal energy are the first test objects. The global energy efficiency indicator of the system can be calculated by the graphical data:

$$\eta_{initial} = \frac{E_{ef}}{E_{in-initial}} \times 100\% = 54.4\%$$

$$h_{initial} = \frac{1}{\eta_{initial}} - 1 = \frac{1}{54.4\%} - 1 = 83.8\%$$

This global energy efficiency evaluation does not only consider the energy utilization of individual equipment and processes, but integrates the energy transfer flow of the entire system, which is a comprehensive assessment of the overall system cost and benefit.

The energy flow extended system of electric vehicles and gasoline engines is shown in Figure 6.

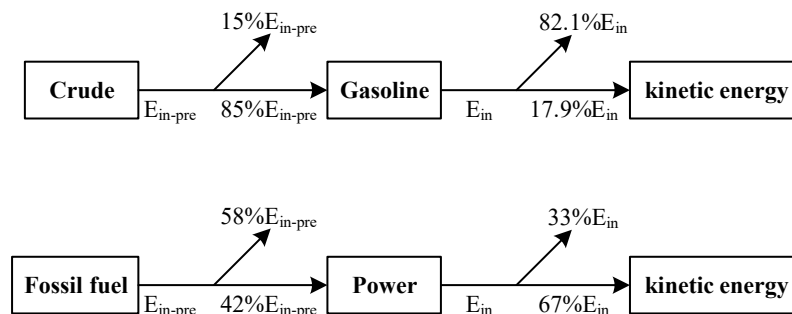


Figure 6. energy flow of car.

Taking the kinetic energy of the car as the target object, when we compare the energy efficiency of the electric car and the petrol car, we need to consider the pre-object associated with the target object to calculate the energy efficiency of the entire extended system.

For petrol cars:

$$\eta_{extended} = \frac{17.9\% \times 85\% E_{in-pre}}{E_{in-pre}} \times 100\% = 15.2\%$$

$$h_{extended} = \frac{1}{\eta_{extended}} - 1 = \frac{1}{15.2\%} - 1 = 560\%$$

For electric cars:

$$\eta_{extended} = \frac{67\% \times 42\% E_{in-pre}}{E_{in-pre}} \times 100\% = 28.14\%$$

$$h_{extended} = \frac{1}{\eta_{extended}} - 1 = \frac{1}{28.14\%} - 1 = 255.4\%$$

Through the extended energy efficiency analysis of the extended system, it can be seen that the energy utilization efficiency of the electric vehicle is higher. Therefore, from the perspective of energy efficiency, electric vehicles should be promoted.

6. Conclusions

The extended energy efficiency assessment indicator system has the following advantages:

The subdivision of energy makes the trajectory of energy flow more obvious, which is beneficial to understanding energy utilization and energy consumption. As a result, subdivision makes it easier to come up with targeted energy-saving tactics..

Compared with the traditional one-sided evaluation method, which examines reduction of energy consumption by a given value or reported fraction, the definition of energy efficiency and energy consumption ratio makes the evaluation of energy efficiency more intuitive and obvious, and it is more widely applicable. Applicable to evaluation under specific conditions, but also suitable for cross-evaluation for a variety of occasions

The proposal of extended energy efficiency and global energy efficiency is a horizontal extension of the assessment method in the traditional sense. The focus is not only on the assessment of the target itself, but also on the energy utilization of the extended system and the global system that are related to the assessment target. The goal is to improve the energy efficiency of the entire global system.

Energy consumption transfer and energy consumption feedback make the system more comprehensive. In the traditional way, the so-called energy consumption reduction is only for the energy utilization of the local target. When there are energy transfer and feedback in the system, there exists some energy saving from the perspective of the target, but when the assessment scope is set as an extended or global system, you may find that there is no real reduction in its energy consumption. Therefore, it is more accurate and comprehensive to analyze the energy transfer and energy consumption feedback within the extended scope or the global scope, and it is also helpful to improve the entire energy efficiency evaluation system.

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