International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 0205

Understanding the evolution and driving factors of energy service efficiency: from energy source to final service

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ABSTRACT

Most of the current energy efficiency models focus on the primary-secondary-useful energy conversion chain of energy system, however, ignore the chain of useful energy to final service. In fact, what people need is not energy itself, but the energy service it provides. Therefore, this paper extends the analysis boundary of energy efficiency model to final service, to reveal the evolution and the driving factors of energy service efficiency. Firstly, we divide the energy system into six stages to conduct societal exergy analysis, which are energy source, transformation, end-use conversion device, useful energy, passive system and final service. And the whole scenario of energy flow and conversion is mapped in Sankey diagrams. Then, we use LMDI (Logarithmic mean Divisia Index) decomposition method to comprehensively understand factors driving the change of energy service efficiency. Efficiency and structure factors of each stage are incorporated into a novel LMDI decomposition identity to quantify their relative contributions. A case study of China during 2005-2015 reveals that: a) the energy service efficiency in China, from energy source to final service, has increased from 3.7% in 2005, to 4.1% in 2010, and 4.8% in 2015. It shows an increasing trend, but still at a very low level with huge losses. b) The efficiency improvement of each stage, especially that of end-use conversion device and the power and heat generation sector, makes the greatest contribution to the increase of overall energy service efficiency. c) There are large passive losses in passive systems, especially in the passive system of building. The energy efficiency improvement of passive systems has big potential and deserves more attention in the future.

Keywords: energy efficiency, energy service, driving factors, societal exergy analysis, LMDI, Sankey diagram

1. INTRODUCTION

Improving the energy efficiency of energy system has been considered as a no-regret action to mitigate climate change while meeting people's increasing demand for final service. Data from IEA shows that the improvement of energy efficiency in recent years has played a significant role in energy saving and carbon emission reduction [1]. To better guide future energy efficiency improvement by policymaking, the first step is to have a comprehensive assessment of the overall energy efficiency of the entire energy system, including its evolution and driving factors.

While energy efficiency is generally understood as the ratio of the useful output to the energy input of a process, according to different definitions of the useful output, the assessment indicator of energy efficiency of the entire energy system can be roughly divided into two categories, which are energy intensity and thermodynamic indicators [2]. The energy intensity is the reciprocal of energy efficiency, and defined as the energy consumption per unit of GDP, which provides a top-down approach to connect energy consumption with economic development. Since the data is easy to obtain and easy to calculate, the energy intensity is the most used indicator to evaluate the overall energy efficiency of energy system. The thermodynamic indicator was measured by thermodynamic units, including the first-law energy efficiency and the second-law energy efficiency (or exergy efficiency). Thermodynamic indicators provide a bottom-up approach to observe the energy efficiency change of various energy stages and energy technologies progress underlying energy system. However, energy intensity can't fully reflect the technological progress in various fields, which will lead to a lack of attention on some key technologies with significant potential for energy efficiency improvement. With more and more attention paid to deep improvement of energy efficiency in various technical

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

fields, thermodynamic indicators are more suitable assessment indicators to observe the technological progress and are supposed to be given more attention.

The down-top analysis of thermodynamic indicators divided the entire energy system into several stages into several stages including energy input, energy conversion, and energy utilization, and then aggregate these stages to evaluate the performance of overall energy efficiency. Most of bottom-up analysis of energy efficiency focus on the primary-secondary-useful energy conversion chain of energy system. However, it is all known that people do not desire energy itself but the "energy services" it provides, such as thermal comfort [3]. Loss not only occurs in the conversion process from primary to useful energy chain, but also in the process of providing energy services. Therefore, to comprehensively understand the overall energy efficiency of the entire energy system, it is necessary to extend the boundary of down-top analysis of energy efficiency to energy service.

To fill this research gap, this paper firstly extends the existing down-top analysis boundary to final services to assess the evolution of overall energy efficiency, and then develops a multi-factor decomposition method to understanding factors driving the change of energy service efficiency.

2. METHODS AND DATA

This section is divided into 3 sub-sections. Section 2.1 introduces societal exergy analysis used to evaluate the energy service efficiency. Section 2.2 introduces the LMDI decomposition method used to quantify relative contributions of different driving factors. Section 2.3 introduces data used for case study of China.

2.1 *Societal exergy analysis*

The societal exergy analysis has been widely used to provide a physically based framework to assess the economy-wide energy efficiency. Instead of only considering the quantity of energy in first-law energy efficiency, the "ability of work" of energy is also considered in this method, which is also known as exergy. It enabled the understanding of the historical trend of energy efficiency improvement and the observation of priority actions of energy efficiency improvement.

It has been given in previous studies about the specific steps of the societal exergy analysis, as summarized in Figure 1. This section only introduces key features of each step.

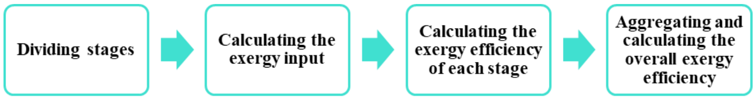

Fig. 1 Steps about the societal exergy analysis

1) This paper divides the SESs into six stages in the order of energy flow, that is the energy source, transformation, end-use conversion device, useful energy, passive system, and final service, as shown in Figure 2. Each stage is further divided into several sectors, for example, end-use conversion device is divided into fifteen categories of technical devices, including diesel engine, coal burner, and so on.

We extend the analysis boundary to include final services, and introduce the passive system learning from Cullen and Allwood's research [4]. Unlike conversion devices, passive systems do not actively or intentionally convert energy to another form but instead hold or trap the useful energy for a time, to provide a level of final service. For example, the car body holds kinetic energy to provide a transport service, and the room traps light to provide illumination.

2) Chemical exergy is usually used to calculate the exergy input of energy system. Chemical exergy can be obtained by multiplying fuel's low heating value (LHV) and exergy factor λ.

$$Ex_{chemical} = \lambda * LHV$$

3) In most practical situations, data of exergy efficiency is not easy to find while the first-law energy efficiency η is easier to get. Thus, exergy efficiency ε can be obtained by multiplying the first-law energy efficiency η and the quality factor ν.

$$\varepsilon = \eta \times \nu$$

4) The energy service efficiency of the entire energy system can be calculated as follws.

$$\boldsymbol{\varepsilon}_{primary-service} = \frac{\sum_{n} \boldsymbol{U}_{n}}{\sum_{i} \boldsymbol{Ex}_{chemical,i} - \sum_{i} \boldsymbol{Ex}_{non-energy,i}}$$

where the numerator is the sum of the energy delivered to final service ***n***. The denominator is the sum of the chemical exergy input from different energy source ***i*** excluding the exergy that flows to non-energy use.

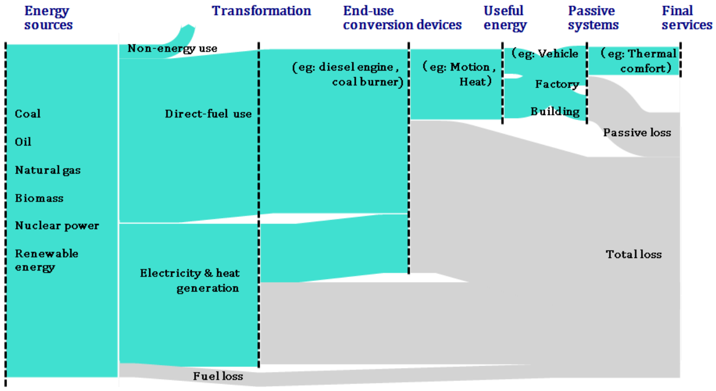

Fig.2 Stage division of energy system

2.2 LMDI decomposition method

LMDI (Logarithmic mean Divisia Index) decomposition method is a kind of method of index decomposition analysis (IDA) that used for the analysis of driving factors of energy system under development, which was first proposed by Ang and Choi in 1997 and solved the residual term problem that existed in the previous IDA methods. LMDI decomposition method firstly establishes a rigorous decomposition identity that decomposes the aggregated variable into the form of the product of several driving factors, and then uses decomposition formulas to decompose the relative contribution of each driving factor. For example, energy consumption is decomposed into the product of total economic output, sector structure, and sector energy intensity.

According to the LMDI decomposition guide proposed by Ang, decomposition steps are shown as follows.

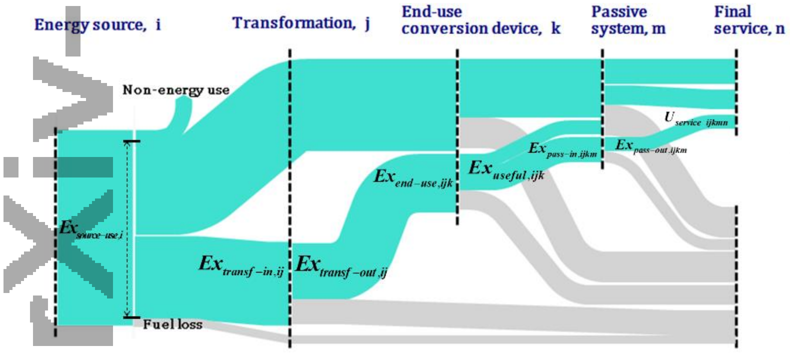

Fig. 3 Schematic diagram of LMDI decomposition

1) Firstly, a novel LMDI decomposition identity including all six driving factors is established. As shown in Fig. 3, according to the order of energy flow, the efficiency and structure factors of each stage are incorporated into the same LMDI identity.

$$\varepsilon_{primary-service} = \sum_{ijkmn} \frac{U_{service-ijkmn}}{Ex_{source-tot}}$$

$$= \sum_{i}\sum_{k}\sum_{k}\sum_{m}\sum_{n} \frac{Ex_{source-use}}{Ex_{source-tot}} \times \frac{Ex_{source-use,i}}{Ex_{source-use}} \times \frac{Ex_{transf-in,ij}}{Ex_{source-use,i}}$$

$$\times \frac{Ex_{transf-out,ij}}{Ex_{transf-in,ij}} \times \frac{Ex_{end-use,ijk}}{Ex_{transf-out,ij}} \times \frac{Ex_{useful,ijk}}{Ex_{end-use,ijk}}$$

$$\times \frac{Ex_{pass-in,ijkm}}{Ex_{useful,ijk}} \times \frac{Ex_{pass-out,ijkm}}{Ex_{pass-in,ijkm}} \times \frac{U_{service-ijkmn}}{Ex_{pass-out,ijkm}}$$

$$= \sum_{ijkmn} \varepsilon_{source} S_{source,i} S_{transf,ij}$$

$$\varepsilon_{transf,ij} S_{end-use,ijk} \varepsilon_{end-use,ijk}$$

$$S_{pass,ijkm} \varepsilon_{pass,ijkm} S_{service,ijkmn}$$

2) Then, assuming that the overall energy service efficiency changes from time ***0***, $\varepsilon^{0}_{primary-service}$, to time ***T***, $\varepsilon^{T}_{primary-service}$. The change rate of these six driving factors are characterized in the following.

$$D_{tot} = \frac{\varepsilon^{T}_{primary-service}}{\varepsilon^{0}_{primary-service}} = D_{source-coe} D_{source-str} D_{transf-str} D_{transf-eff}$$

$$D_{end-use-str} D_{end-use-eff} D_{passive-str} D_{passive-eff} D_{servive-str}$$

3) Finally, contributions of six driving factors are quantitatively decomposed by following formulas.

$$D_X = \exp\left(\sum_{ijkmn} \frac{(\varepsilon^{T}_{ijkmn} - \varepsilon^{0}_{ijkmn}) / (\ln \varepsilon^{T}_{ijkmn} - \ln \varepsilon^{0}_{ijkmn})}{(\varepsilon^{T} - \varepsilon^{0}) / (\ln \varepsilon^{T} - \ln \varepsilon^{0})} \ln \frac{\varepsilon^{T}_{x}}{\varepsilon^{0}_{x}}\right)$$

$$D_X = \exp\left(\sum_{ijkmn} \frac{(\varepsilon^{T}_{ijkmn} - \varepsilon^{0}_{ijkmn}) / (\ln \varepsilon^{T}_{ijkmn} - \ln \varepsilon^{0}_{ijkmn})}{(\varepsilon^{T} - \varepsilon^{0}) / (\ln \varepsilon^{T} - \ln \varepsilon^{0})} \ln \frac{S^{T}_{x}}{S^{0}_{x}}\right)$$

Where D_X represents different driving factors in step (2), x represents different stages.

2.3 Data

We conduct a case study of China in 2005, 2010, and 2015. The evolution of energy service efficiency is calculated from 2005 to 2015, and driving effects of factors are quantified during 2005-2010, 2010-2015, and 2005-2015.

Data are mainly from the “China Energy Statistical Yearbook” (2006, 2011, 2016), “Wang Qingyi - Energy Data” (2006, 2011, 2016). Part of the data comes from “The 13th Five-Year Plan for Energy Development” and

“The 13th Five-Year Plan for Renewable Energy Development”.

3. RESULTS AND DISCUSSION

3.1 The evolution of energy service efficiency

After applying the societal exergy analysis to the case study of China, the bottom-up revolution of energy service efficiency of China’s energy system is revealed, including the stages of energy source, transformation, end-use conversion device, useful energy, passive system, and final service. The results are visually displayed in the exergy efficiency Sankey diagrams, as shown in Fig. 4.

By comparing analysis results in 2005, 2010, and 2015, changes of different stages and sectors can be observed as follows:

1) The energy service efficiency of China from energy source to final service has increased from 3.7% in 2005, to 4.1% in 2010, then to 4.8% in 2015. It shows an increasing trend, but it is still at a very low level, which means that only less than 5% of energy ultimately provides energy services people need.

2) Concerning the energy flow from energy source to useful energy that people often studied, the source-useful energy efficiency has also increased from 11.3% to 12.1% and then to 14.3%. End-use conversion device sector and power and heat generation sector have always been main sources of exergy loss. The average exergy efficiency was from 16% to 19% and then to 21%, and from 30% to 34% and then to 35%, respectively. Among them, the industrial coal burner and the coal-fired power and heat generation have always consumed the most and lost the most in their respective sectors.

3) It noted in this paper that the passive loss of passive systems is considerable. Passive systems hold useful energy to provide a level of final service, and are divided into 3 sectors including vehicle, factory and building. The passive loss of building is the most, where over 80% useful energy is wasted without providing needed services. Several factors currently inhibit the deployment of more efficient technical solutions in buildings in China: the variety of building designs; the existence of a large number of old buildings that has caused huge energy losses; people's excessive enjoyment, such as setting the air conditioner to a very low temperature in summer and so on.

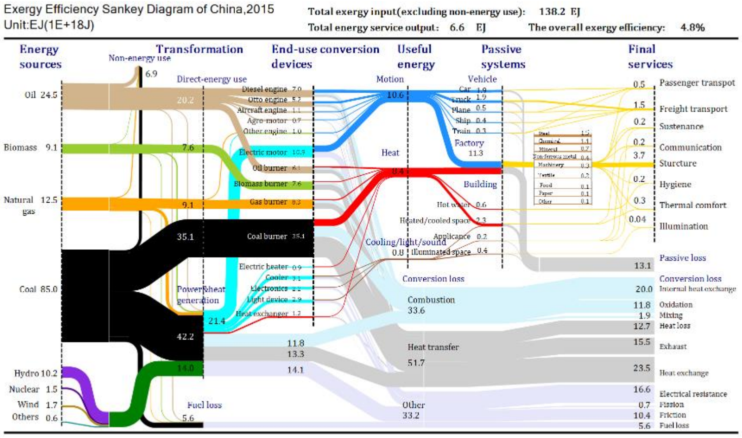

Fig. 4 The exergy efficiency Sankey diagram of China in 2015

3.2 Driving factors of energy service efficiency

Based on results of societal exergy efficiency, LMDI decomposition method is used to quantify the relative contributions of efficiency and structure factors of each stages, as shown in Fig. 5. Main decomposition results are listed as follows:

1) The improvement of efficiency factor of each stage contributes the most to the improvement of overall energy service efficiency, especially the efficiency improvement of end-use conversion devices and power and heat generation sector. Contributions of the adjustment of structure factors is limited and even have negative effects.

This is mainly due to China's continuous promotion of energy efficiency improvement in various technical fields in recent years. On the other hand, since China is still a developing country, the irrational structure of each stage under development has inevitably brought about the effect of “efficiency dilution”.

2) The improvement of end-use conversion efficiency has always been the most important driving factor, contributing 25.6% of the overall energy efficiency growth, and its contribution is far more than others.

Due to the relatively low efficiency of various technical devices in the end-use stages, such as industrial coal-fired boilers, the efficiency improvement of these technical equipment has always been the focus of policy concern. Our analysis confirms that the efficiency improvement of these technical equipment has achieved remarkable results.

3) The energy efficiency improvement of passive systems has huge potential. It can be seen that small

efficiency improvements in passive systems have contributed considerable overall efficiency improvements.

There are large passive losses in passive systems, especially in building. Therefore, the energy efficiency improvement of passive systems deserves more attention. In the next step, actions like increasing the insulation of building exterior walls, using more LED bulbs, improving vehicle streamlines, and reducing vehicle weight, will contribute to reducing passive losses.

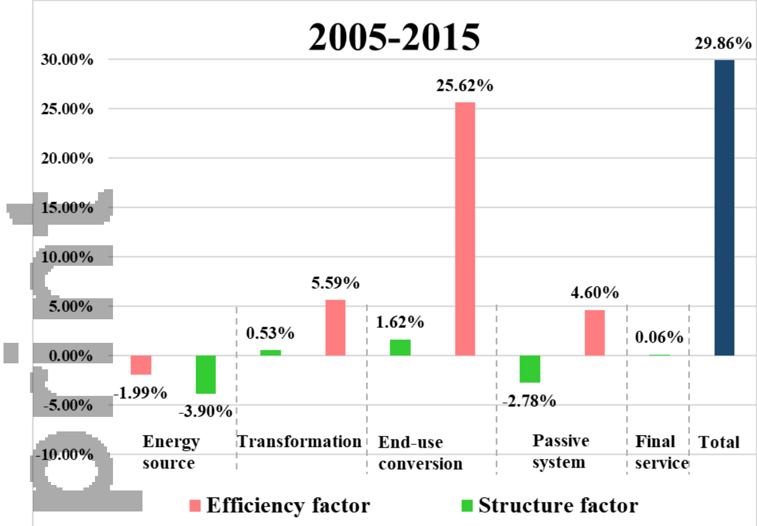

Fig. 5 LMDI decomposition results of driving factors from 2005 to 2015

4. CONCLUSIONS

In this paper, we extend the existing down-top analysis boundary of the overall energy efficiency to passive system and final service, to comprehensively understand the evolution and the driving factors of energy service efficiency from energy source to final service.

Taking China as a case study, the results allow several key insights. a) The energy service efficiency of China from energy source to final service has increased from 3.7% in 2005, to 4.1% in 2010, then to 4.8% in 2015. It shows an increasing trend, but it is still at a very low level and there are huge losses. b) The improvement of the efficiency factor of each stage contributes the most to the improvement of overall energy service efficiency, especially the efficiency improvement of end-use conversion devices and power and heat generation sector. c) There are large passive losses in passive systems, especially in building. The energy efficiency improvement of passive systems deserves more attention.

The policy implications of this study are summarized as follows for future energy efficiency improvement in China. 1) As a developing country, the efficiency improvement of all stages of the energy system should be unswervingly and continuously promoted, especially in the stages of end-useful conversion devices and power and heat generation sectors. 2) Structure factors may bring about the effect of “efficiency dilution”, such as people's increasing demand for thermal comfort service. Efforts should be made to increase energy efficiency management across the entire chain from primary to service, such as accelerating the replacement of low-efficiency heating boilers, increasing insulation of exterior walls of houses, and using ICT technology on the service side to refine thermal management.

This paper provides a technical framework to evaluate the energy efficiency performance of energy system and technical driving factors. Meanwhile, it is noted here that socio-economic barriers also limit the effect of technical efficiency improvement. These include market imperfections (such as lack of adequate financing support and higher perceived costs) and behavioral barriers (for example, consumer preferences and habits, and the well-known rebound effect). Therefore, it is important to incorporate these technical-socio-economic factors into a framework to better guide future policy of energy efficiency.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China [grant number 71690245] and the State Key Laboratory of Power Systems in Tsinghua University [grant number SKLD17Z02].The authors gratefully acknowledge the support of BP in the form of the Phase II and Phase III Collaboration between BP and Tsinghua University, and the support of the Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy, and Sustainable Development.

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