

Chapter 2

Relationship Between Energy Efficiency and the Economic System: Measuring Energy Efficiency

In recent years, more and more attention has been paid to the problems of energy efficiency and energy savings. There has been substantial academic research on energy efficiency and most of this research has been beneficial. However, there are still some problems or obstacles about the research methods and objectives to be resolved: (1) The lack of awareness and understanding of energy efficiency leads to an improper use of energy data and energy efficiency indicators, which will probably lead to biased judgments and evaluations; (2) the confusion between the goals of energy research and ways to reach them, including the exogenous and endogenous factors as well as the analyses and results lead us to simply set our goals as “reducing energy consumption” and “decreasing energy consumption per unit of output.” If so, then in the long term, from an integrated perspective, energy efficiency will not be improved. Instead, there will be losses in other aspects of the economy and society; and (3) the lack of attention toward basic theories, assumptions, and relationships and the advantages and disadvantages of various indicators of energy efficiency leads to a casual use of the energy efficiency indicators, which will bias our judgments and evaluations.

According to the above phenomena, this chapter will discuss the following questions (Liao and Wei 2010b; Wei and Liao 2010):

- What is the meaning of energy efficiency?
- What is the relationship between energy efficiency and the economic system?
- What indicators of energy efficiency exist now? What are their basic theories and the scope of their applications?
- According to economic theory, can we provide some new indicators and ways to measure energy efficiency?

2.1 Reconsideration of Energy Efficiency and Its Relation to the Economic System

2.1.1 Understanding Energy Efficiency

“Efficiency” usually refers to the rationing of output to input. The World Energy Council (WEC 2006) pointed out that energy efficiency is the rationing of energy service output to energy input. In practice, we sometimes use relative efficiency to compare different subjects horizontally or to compare a subject with itself in different time periods. Sometimes, we also use the rationing of the target consumption quantity and the actual consumption quantity. The closer the ration is to one, the more efficient it is. Improving energy efficiency is to use as little inputs as possible to gain the largest quantity of service outputs. The general understanding of the definition of energy efficiency has reached a consensus nowadays. But the real sense of the meaning of energy efficiency is still in doubt.

Energy efficiency is not an isolated measurement. It has a close relationship with the economy, society, environment, technology, and many other domains. Sometimes, simply trying to reduce energy consumption or decrease energy consumption per unit of output may lead to a decrease in energy in the short term using a limited perspective, but the energy efficiency is not improved actually from the long and integrated perspective. This approach could even lead to losses in other aspects of the economy and society. Because of the different understandings of economic efficiency, arguments like the Rebound effect and Jevons paradox have taken place. Papers were published in some famous magazines, such as *Science* (Cherfas 1991; Madlener and Alcott 2009; Sorrell et al. 2004).

Energy is not only an important necessity but also a kind of strategic materials. Chemical resources are non-renewable. The utilization of fossil fuels can result in environmental problems, the destruction of the ecology, changes in climate, and other kinds of public problems. Thus, we should use the cost–benefit principle, the ensure-supply principle, and the sustainable utilization principle to solve our energy problems. The concept of energy efficiency focuses on the contribution made by the consumed energy toward the development of society as a whole. In the different phases of a developing community, the people have different levels of understanding about their individual contributions:

- (1) In a macro view, the meaning of energy efficiency is not confined to thermodynamics and engineering technologies. Instead, it includes the economy, society and environment, including sustainable development. From the producer’s viewpoint, the producer’s goal is to gain benefits and use energy effectively in his own way. From the consumer’s viewpoint, the consumer often uses energy by considering its cost and efficiency, even though his habits and education are very important factors in terms of energy demand. The government also has its responsibility to develop strategies according to the

various functions of different energies and the relationship between different energies.

- (2) Even though some regular energy efficiency indexes may not show it, the improvement of energy efficiency can be seen from the improvement of equipment and many other aspects. Some energy-consuming activities give people a more satisfactory service despite the cost of consuming lots of energy. Nevertheless, such activities are considered efficient. For example, an airplane flight can cost more than travel by ship over equal distances, but this does not mean that a plane is relatively less efficient. In this case, we mean that a plane travels much faster than a ship. Several ways can help us increase energy efficiency. We can reduce the burning of fossil fuels by reducing the weight of a plane. By installing windows with double-paned glass in place of single-paned glass, one can reduce the electricity used in air-conditioning. Using lower-cost plastic to substitute for higher-cost iron products is another good way to use energy more efficiently. All of the above activities are seen to improve energy efficiency, even though they cannot be included in the energy efficiency index.
- (3) Although some activities do not bring about changes in the output of some products, they contribute to sustainable development. This is one kind of energy efficiency improvement. One of the basic reasons for us to improve energy efficiency is the scarcity of natural resources. Most of the energy we use today is fossil fuels, which have a limited storage infrastructure. If the technologies allow us to use solar energy freely, the problems about energy scarcity will no longer exist. If we can use solar energy instead of fossil fuels, the negative effect on the environment will be reduced. In this way, energy efficiency will be improved, but this improvement will not show up in the regular index.

2.1.2 Measuring Energy Efficiency

The energy efficiency index plays an important role in formulating and analyzing policy strategies. The level of energy efficiency cannot cover all the information related to energy efficiency. In practice, we use a one-dimensional index to describe energy for the sake of convenience. Even though it cannot include all aspects of energy, such an index is acceptable as long as it covers most information and does not include significant mistakes. But sometimes, this index is unacceptable because there are different results and conclusions based on different views and evaluation methods or indexes, especially when comparing different regions and countries. In many cases, we use energy consumption per unit of output and energy consumption per unit of added value to calculate the consumption levels and derive a statistical view. The information we get using this approach is rather narrow, so it should not be used to make effective decisions. Therefore, using the wrong index may lead to

inappropriate responses and regulations, which are discussed more extensively in publications like *Science* (Larrick and Soll 2008).

- (1) All energy efficiency measuring indexes have certain assumptions. Each of these indexes has its advantages, disadvantages, and applicable fields. Simply from a mathematical view, the definition of energy efficiency and how to measure it relates to the rationing of service output to energy input. However, both input and output are multidimensional vectors having elements with different qualities. Some service outputs, such as human life, cannot be measured by money. We cannot simply use division to calculate the vectors. If we have to divide them, some measures must be used to calculate the service output and energy input. A common way to do this is the weighted sum of all of the elements. In this process, some loss of information is unavoidable. For example, if we put in n kinds of energy and the sum of the energy inputs is E , we usually use the first law of thermodynamics and a weighting factor λ_i , which is considered as the power of each kind of energy. If we also use the second law of thermodynamics, the value of λ_i will be different. The regular method is as follows:

$$E = \sum_{i=1}^n \lambda_i e_i \quad (2.1)$$

Different fields are calculated in different ways. Thus, there are different indexes to measure energy efficiency. Each index is based on certain assumptions. All of them have advantages and limitations. If all of these prerequisites are not true, then there will be relatively great deviations and even greater miscalculations. All of these biases will lead to wrong decisions. In practice, the method we use relies on the accuracy of the obtained information. In recent times, the normal energy efficiency measuring indexes include the following: energy consumption per GDP, the sum of energy consumption, energy consumption per value added, energy consumption per production unit, and energy consumption in the process of production. All of these indexes are based on certain assumptions.

- (2) Energy service output includes both beneficial elements (+) and harmful components (-). According to energy efficiency, energy services will not only include useful components (+) but also consider negative components (-). The key to calculating energy services is to balance its contribution to maintain and encourage the sustainability of the economy, society, and environmental systems. Ideally, we can calculate the net energy service output. The concept of service and output varies. Service is a multidimensional vector, even though it is constructed in terms of both production and services, with different internal characteristics. In the case of the available monetary measurement techniques, we usually see the price as the weight of total production. In the macroscopic measurement of a country or region, service output is based on the country's GDP while for a particular industry or department, service output

is based on the total production value or a value-added index. For a specific product, we use a yield index to represent its service output. Because of the different service outputs in different countries, the consumption of energy among countries will be very different, even though the total production value, value added index, or the level of development are the same. In many cases, the service outputs will differ significantly because of the objective constraints.

- (3) The energy input is heterogeneous. Various energies cannot be substituted with alternative energies. From the perspective of energy input, the energy efficiency in terms of size and advantage also depends on how to measure the amount of energy inputs. For the same energy-service quality, we can also have different structures of energy input. Similarly, in terms of energy use per unit of production, the quantity of energy consumption will be different if one uses coal versus natural gas. In the production of hydropower and other renewable energy resources, we sometimes use the heat (caloric) method as the conversion coefficient, and we sometimes use the electric power generation method. Moreover, various types of energy cannot be replaced completely. In the accounting of energy input, the scientific method is not only to consider all kinds of energy embodied in energy consumption but also to consider their respective prices and costs, as well as the possible substitution of alternative energies. Otherwise, the energy input data will sometimes be very different, and these differences will affect the results of any research on the energy economic system.
- (4) The resource endowments and initial and developmental stages will vary among countries. It is difficult to make an accurate and quantitative comparison of China's energy consumption per unit of GDP with that of the developed countries. At present, the results vary in terms of an international comparison of unit outputs of power consumption. According to the indexes from the World Bank (2009) and IEA (2009), which use the exchange rate method, China's energy consumption per unit of GDP is more than four times that of the United States. In contrast, according to purchasing power parity (PPP), China's consumption is only 70 % higher than that of the United States. Nordhaus (2007), a professor at Yale University, has raised some issues between the 3E modeling data conversion method and the Superlative-PPP method. According to Nordhaus (2007), the resulting data differences are related to the quality of the basic data, caliber of the statistics, quality of the energy and raw material and data availability, and the means by which the data were acquired.

2.1.3 Energy Efficiency and the Economic System

Most of the direct use of energy is commercial. Energy efficiency is reflected in all aspects of the energy value chain, including energy extraction, processing, conversion, storage, final demand, and recycling, as well as in terms of national

production, distribution, trade, and consumption. Thus, to study a country or region’s energy problems, we should first study how energy fits into the economic system. Energy saving should also consider both the costs and benefits, as pointed out by Joskow and Marron (1993a, b), whereby the different ways to save energy have different costs. A reduction in the output per unit does not necessarily equal to a reduction in the cost and an increase in efficiency. Some regions spend a great deal of money on various environment-friendly and efficient buildings to maintain a positive image, but such gains may not make up for their losses.

2.1.3.1 Structural Heterogeneity and Element Substitution

Structural heterogeneity includes the economic structure (industry, demand, disposition of income, region, urban and rural, ownership and price, and the structure of various factors or elements, especially energy). Energy is heterogeneous because the different types of energy cannot be substituted for one another. Factor substitution includes elasticity of capital, labor, and land, as well as the elasticities of oil, coal, electricity, and other energy.

The study of energy economics will result in a number of combined heterogeneous structures and factors, and a resulting loss in information, if we only study the total data without a structural analysis of how the components are integrated. Because of this loss, the reliability of the scientific research will be reduced. In recent times, product and energy structural differences in the measurement of energy efficiency have gradually caught the attention of the public, but the heterogeneity of the economic structure is still not reflected in the measurements.

Structural heterogeneity and factor substitution have some common connections, but they are also distinct. Both emphasize the internal system of the various components of the differences. The former is mainly from a statistical accounting perspective while the latter is mainly from an economic perspective. The following Fig. 2.1 shows their relationship:

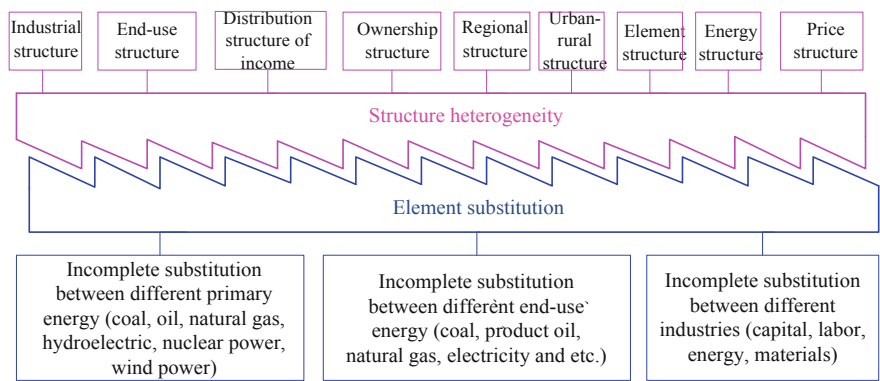


Fig. 2.1 Structural heterogeneity and factor substitution, including energy

2.1.3.2 Factor Production Rates and Energy Efficiency

For a very long time, manufacturing has been the major energy-consuming sector. Energy is an important element in terms of production. Economic growth cannot exist without energy inputs. The source of economic growth mainly includes the factors of investment (capital, labor, and resources) and the growth of total factor productivity (including human capital accumulation). Therefore, in terms of growth of total factor productivity, we can formulate an analytical structure of energy efficiency and an economic system to analyze energy efficiency and the energy structure, economic growth and economic structure, and technological development. This will enable an in-depth discussion about the influence of energy efficiency.

In the determination of the sources of economic growth and the theoretical discussion of the quality of economic growth, most of us use the product–capital–labor model, which means that the total growth of the combined factors (the common speed of technological development) equals the economic growth rate minus the weighted capital (or capital service) and labor (or labor service) investment growth rates. Such business accounting seldom considers the industrial structure. The inputs only include capital and labor, with the implicit assumption that the natural resources or energy for economic growth have no effect. Economic growth is essentially an evolving process by sector. Without a sector analysis, it is difficult to explain why and how the process happened (Rostow 1959). A study of energy requirements and energy efficiency cannot be separated from those of the total economy and, in particular, when studying the economic structure because the total represents the overall picture, but the structure represents the specific content.

To discuss the relationship between economic growth and energy efficiency in terms of both technological development and product structure, we use the method to calculate the sector production rate (Jorgenson et al. 1987; Jorgenson and Stiroh 2000), like $Y = KLEM$ (output = capital, labor, energy, materials¹), which is different from the calculation of the total production rate. For a certain production sector i in a certain period, to gain an output, Y_i , we need to include four factors: capital (K_i), labor (L_i), various energy sources $\{e_{i1}, e_{i2}, \dots, e_{is}\}$ $\eta_c < 1$, and raw materials (M_i). The function is:

$$Y_i = A_i \cdot f_i(K_i, L_i, M_i, e_{i1}, e_{i2}, \dots, e_{is}) \quad (2.2)$$

A_i refers to the technology level of sector i . The technological improvement here is Hicks neutral. The function f_i meets the regularity condition and homogeneous conditions. We can see that the energy and other elements are separate.

$$\exists X_i \in \{K_i, L_i, M_i\},$$

¹Material means intermediate inputs except energy, including intermediate production and services.

$$\frac{(\partial f_i / \partial e_{iu}) / (\partial f_i / \partial e_{iv})}{\partial X_i} = 0 \quad (u \neq v) \quad (2.3)$$

Thus, the production function can be expressed as:

$$Y_i = A_i \cdot f_i(K_i, L_i, E_i, M_i) \quad (2.4)$$

Within the above function,

$$E_i = g_i(e_{i1}, e_{i2}, \dots, e_{is}) \quad (2.5)$$

If we assume that

$$Q_i = f_i(K_i, L_i, E_i, M_i) \quad (2.6)$$

the function g_i also meets the regularity condition. Make the total differential to Eq. 2.6

$$dQ_i = \sum_{X_i=K_i, L_i, E_i, M_i} \frac{\partial f_i}{\partial X_i} dX_i = \sum_{X_i=K_i, L_i, E_i, M_i} \lambda p_i \cdot dX_i \quad (2.7)$$

where g_i is the price of X_i and λ is a Lagrangian multiplier:

$$\lambda = \frac{\partial f_i / \partial X_i}{p_i} = \frac{Q_i}{\sum_{X_i=K_i, L_i, E_i, M_i} p_i X_i} \quad (2.8)$$

The Eq. 2.7 can be changed to:

$$Q_i \cdot d \ln Q_i = \sum_{X_i=K_i, L_i, E_i, M_i} \lambda p_i X_i \cdot d \ln X_i \quad (2.9)$$

Based on Eqs. 2.8 and 2.9,

$$d \ln Q_i = \sum_{X_i=K_i, L_i, E_i, M_i} \frac{p_i X_i}{\sum_{X_i=K_i, L_i, E_i, M_i} p_i X_i} \cdot d \ln X_i \quad (2.10)$$

Suppose that

$$\alpha_{K_i} = \frac{p_i K_i}{\sum_{X_i=K_i, L_i, E_i, M_i} p_i X_i}, \quad \alpha_{L_i} = \frac{p_i L_i}{\sum_{X_i=K_i, L_i, E_i, M_i} p_i X_i}, \quad \alpha_{E_i} = \frac{p_i E_i}{\sum_{X_i=K_i, L_i, E_i, M_i} p_i X_i},$$

$$\alpha_{M_i} = \frac{p_i M_i}{\sum_{X_i=K_i, L_i, E_i, M_i} p_i X_i}. \text{ Obviously, these four equations represent the cost component of the various factors.}$$

According to Eqs. 2.4 and 2.10, we can get the function of the production sector i :

$$\begin{aligned} d \ln Y_i &= d \ln A_i + d \ln Q_i \\ &= d \ln A_i + \alpha_{K_i} d \ln K_i + \alpha_{L_i} d \ln L_i + \alpha_{E_i} d \ln E_i + \alpha_{M_i} d \ln M_i \end{aligned} \quad (2.11)$$

where $\alpha_{K_i} d \ln K_i$, $\alpha_{L_i} d \ln L_i$, $\alpha_{E_i} d \ln E_i$, and $\alpha_{M_i} d \ln M_i$ refer to the contributions of capital, labor, energy, and raw materials, respectively. $d \ln A_i$ represents the contribution of the total production growth rates of the factors for sector i to the sector's total output. The growth rate of the total factors for the whole economy, $d \ln A$, equals the sum of the various factors.

$$d \ln A = \sum_i w_i \cdot d \ln A_i \quad (2.12)$$

With the weight expressed as $w_i = \frac{P_i Y_i}{PV}$,² $P_i Y_i$ is the total value of a particular sector. PV is the total increase, which means the total GDP of a country. To improve the growth rate of a country's economy, the growth rate of the sum total of the underlying factors needs to increase.

For a specific production sector, whether or not it can reduce the consumption per unit depends on whether we can use the growth rate of the total factors of production, including the capital and material increases, as efficiently as possible to replace the energy increase. However, whether we can achieve this goal depends on the relative price changes of energy and the other factors, as well as the alternative elasticities, including those of the production sector itself. If the price of energy rises and prices of other factors decrease, the output per unit of energy consumption will decline; that is, the savings in energy come first over the savings in capital, labor, and raw materials.

For example, during the production of iron, we need to consume both the ore and energy, which can be substituted by each other. To produce a ton of the same quality of pig iron, the energy consumption is different when using high-grade ore versus poor-grade ore. If the price of iron ore is increasing, the iron and steel companies may be inclined to consume more energy and less ore. If the price of iron ore is decreasing, the iron and steel companies may be inclined to consume less energy and more ore. Not only is energy a substitute for the other factors, but the various types of energy have different elasticities among them; that is, the alternative elasticities among different types of energy are different. According to the concepts of energy efficiency, it is difficult to support a particular method's advantages and disadvantages.

Within a certain period of development, each alternative's use of energy, capital, raw materials, and other production factors is relatively weak because of technical and economic constraints. For a number of categories, the relationship between

²The sum of these weights is generally greater than 1 (because the sum of total output is greater than the total value added).

energy and capital is complementary. Capital deepening is the process of rapid growth in energy consumption. Thus, for a specific category i , in order to decrease its energy demand per unit of output, we should rely more on the growth rate of output and $d \ln A_i$, instead of $d \ln E_i$. This also represents an improvement in economic quality. A category's total rate of increase includes not only the speed of progress for science and technology but also softer factors like the efficiency of resource allocation to improve the situation, the positions of various government functions and so on.

At different development stages, the total factor productivity growth rate for different sectors may have a different bias. For example, to produce the same quality and quantity of a product, a company can save a lot of labor and raw materials by introducing a new kind of production method. However, this change may save little energy or even no energy at all. In this case, the relevant policy incentives can encourage enterprises to strengthen their energy conservation technologies and research and development efforts. In the process of industrialization, technical progress is often a type of energy consumption (Liao 2008).

According to Eq. 2.12, for the entire national economy to improve the macro energy efficiency, it is not enough to only depend on the total factor productivity growth rate ($d \ln A_i$). We must also rely on the adjustment of the industrial structure (i.e., adjusting $w_i w_i$). We must reduce the consumption of the energy-intensive sectors and decrease the proportion of energy-intensive sectors in the national economy. Broadly speaking, the adjustment of the industrial structure includes the overall structural adjustment, including the individual product structural adjustments. For example, one can reduce the energy consumption in the iron and steel sector by decreasing the ratio of steel and iron and increasing the ratio of continuous casting and the steel rolling rate. As a result of its relevance to industry, such an adjustment is often progressively and dynamically pursued. Moreover, it has a close relationship with final demand. In the long term, the structure of residential consumption plays a key role. Such consumption has significantly affected how industrial structure has evolved. In the upgrade stage of the residential consumption structure, houses, automobiles, household appliances, and other high energy consumer goods begin to enter the household. This entry may drive the industrial structure in the direction of energy-intensive development (Wei et al. 2006). Comparative advantage and the foreign trade structure have a guiding role on the evolution of the industrial structure. The income distribution structure will also affect the final demand structure, thereby affecting the industrial structure (Liao 2008).

The mathematical analysis is mainly in the neoclassical economic analysis framework. The growth rate of energy consumption is mainly based on the economic growth rate and growth quality. The quality of economic growth can be generalized as the various factors of production inputs (and their combinations) that promote economic growth. The quality of economic growth is not only present in the contribution of the total factors to the growth of the economy but also in the contribution to the growth in output from the production and industry structures, and from the relationships between the different industries. The quality of economic

growth is closely related to the hard features, such as the specific technical equipment and management level, as well as the soft features, such as the legal and economic systems, and the fixed agendas of the various government functions.

2.1.4 Energy Efficiency and Energy Conservation

In many documents, including government policy documents, “improving energy efficiency” and “conservation of energy” are used interchangeably. They do not distinguish between the two definitions. The newly revised Energy Conservation Law points out that saving energy is the means of strengthening energy management. We should take feasible and reasonable measures that the environment can bear, including all linkages of energy production and energy consumption, to reduce consumption, losses, waste, and pollution emissions and to make effective and reasonable utilizations of energy. In the book entitled *Basic Terms in Energy*, edited by the National Energy Base and Standard Technical Management Committee (1991), energy conservation refers to the scientific management and use of advanced technology in each link for improving the utilization of energy. The two definitions of energy conservation include both narrow and broad definitions. “The Encyclopedia of Energy” in Gibbons et al. (2004), published by Elsevier Company, defines “energy conservation” as “on the basis of not decreasing the quality of life, a scientific method used to reduce energy consumption through technology and policy changes.”

- (1) In general, energy improvement equals energy conservation, but they are different. The meaning of energy efficiency is broader. Energy efficiency focuses more on energy services while energy conservation focuses on the reduction in energy consumption. Energy efficiency focuses on the meaning within energy economics, such as social benefits, while energy conservation focuses on the real and physical meanings.³ In addition, energy efficiency focuses on systems analysis while energy conservation sometimes focuses on local (regional) analysis. Though the two concepts have some differences in terms of practical issues, we often use them without any strict limitations. In the energy economics model or the energy macroeconomic policy target, energy-saving often means the fall in unit GDP energy consumption rather than a specific reduction in absolute volume. In the specific energy model construct, the target function is different, so there are different results. The function is also related to the model system of boundary demarcations. Energy conservation without consideration of the cost is unacceptable.

³This is consistent with profit maximization and cost minimization in the new classical economic theory. But due to reasons such as information asymmetry and incentives, they are incompatible and sometimes inconsistent.

We assume that “improving energy efficiency” is better than “increasing energy efficiency.” The language of management science and systems science describes the former as a multi-objective programming problem and the latter as a single-objective programming problem.

- (2) In general, we usually transform the multi-objective problem into a single objective problem as a result of the problems with various data sources and measurements. If we consider energy heterogeneity and incomplete alternative to calculate the amount of energy use, the result will support our decision function. Energy efficiency is not a static or short-term objective, and it should be considered from a dynamic or long-term perspective. Therefore, to agree with the meaning associated with the scientific language, the improvement of energy efficiency becomes a dynamic programming problem.

2.2 Indicators and Measurement of Energy Efficiency

The energy consumption’s connotation is that the contributions made by consumed energy to maintain and promote the social economy and environmental system should be through sustainable development. Energy efficiency is usually expressed as the ratio of energy service output to energy input. But there are different methods to determine the quantity of energy input and service output in different industries. Hence, we have different indexes. The current or historical levels of energy efficiency are objective calculations, but it is not usually possible to use an index that completely covers all aspects of the information that should be included in energy efficiency (because of limited information and data availability). In practice, and for the sake of convenience, we use a one-dimensional index to describe energy efficiency. This index cannot cover all of the information, but most information can be included in the index, at least partially, to meet our needs so that it can be considered an acceptable index. Sometimes, a particular index cannot give us the information we need, so we need to create other indexes. Each index is based on certain assumptions (e.g., homogeneity and comprehensive alternative assumptions) with certain advantages and disadvantages. If these assumptions cannot meet our demands, they may result in great inaccuracies in terms of our understanding and measurement of energy, resulting in errors in calculations, biased judgments, and bad decisions.

This chapter will conduct a systematic analysis of the energy efficiency measuring indexes, outline the problems associated with these indexes and reach various conclusions. We discuss the basic theories and hypotheses, relationships and limitations, and some things to consider when using these indexes. The seven indexes are energy macro-efficiency, energy physical efficiency, energy thermodynamics efficiency, energy value efficiency, energy allocation efficiency, energy utilization efficiency, and energy economic efficiency.

2.2.1 *Energy Macro-efficiency*

Nowadays, we usually use energy consumption per unit of GDP, a macro index called “energy intensity,” to measure country, regional, or industrial energy efficiency levels. We define its reciprocal as macro-efficiency, e_m (energy macro-efficiency). The lower the increase in energy consumption per unit of GDP, the higher is the energy macro-efficiency. The output of energy is expressed by the outputs from economic activities. Energy input is expressed as the consumption of primary energy. The increased value per unit of power consumption is related to the development stage, economic structure, technical level, energy price, social culture, geographical location, climate conditions, resources, and other factors. During the past two centuries, the UK, United States, and other developed countries have shown a rise in per unit GDP energy consumption during the process of industrialization that peaked before falling. The later a country entered the industrial state in the industrialization process, the lower was the unit value of GDP energy consumption. Sometimes, there was no increase in consumption per unit of GDP, which was mainly a result of the progress of technology and the advantage of being a backward country that arrived much later in the process of industrialization.

In certain documents, we sometimes define the reciprocal of the energy consumption per unit of GDP as the “energy production rate.” Strictly speaking, the two definitions are of very different calibers. When calculating energy consumption per unit of GDP, we include the direct use of energy by households. However, when calculating the energy production rate from the viewpoint of calculating GDP in the production method, the direct use of a household’s energy will be excluded (as in the difference between GDP per capita and labor productivity, the former refers to the entire population while the latter calculation only includes the number of laborers). In China, since the direct energy use of households is low, the difference between the energy production rate and the reciprocal of the energy consumption per unit of GDP is very small. In the horizontal and vertical comparison between regions, a significant bias will usually not happen.

When big differences do not occur in the energy input structure, the measurement of energy efficiency based on energy consumption per unit of GDP is easy and there is relatively less probability that this measurement of efficiency will change. When the energy input structure changes a lot, incomplete substitutes among various energies may lead to some bias in the results. (For more information, please refer to Liao 2008 and Liao and Wei 2010a.) However, macro energy efficiency relating to economic growth mainly relies on such underlying assumptions relating to energy consumption and technological progress. In fact, economic development relies on other factors, which have different types of substitutes. Hence, the energy macro-efficiency index is a partial measure that does not consider the substitute elasticity between energy and other alternatives. Discussion about these concepts can be found in Liao (2008). To overcome or reduce these limitations, we should sometimes use other energy efficiency indicators. From a microeconomic viewpoint, it is inappropriate for some documents to regard energy efficiency as “energy

economic efficiency” (the concept and measure of the efficiency of the energy economy will be given later).

From the view of the production method used to calculate GDP, GDP is the total increase in value for all fields of activity and the associated increase in energy consumption. Each industry can be further decomposed to the product level. Hence, as long as we can secure the data, the macro energy-efficiency changes will inevitably be decomposed into the changes in the industrial structure and the changes in the energy efficiency, which are commonly referred to as the structure share and the efficiency share. The Divisia index method is by far the best index decomposition method. The Törnqvist index method is a processing form that uses discrete approximations. Diewert (1976) pointed out that for the linear logarithmic homogeneous function and unit cost function, Törnqvist’s quantity index and price index are accurate. According to the definition, considering only the energy used in production, energy macro-efficiency meets the assumption of the linear homogeneous function. Even though the Divisia index can decompose macro-efficiency into different levels, it is just a decomposition of the total data from top to bottom to a large degree. The information we gain is limited; thus, the support for the resulting decisions is weak. The goals relating to energy conservation are known worldwide and include two parts: reducing the proportion of the energy-intensive industries (or the proportion of the energy-intensive products) and increasing the speed of improvements in technology. However, the product structure and technology levels are largely endogenous. They represent the results, not the reasons behind the actions.

When comparing nations, the value of the economic products must be transformed into the same currency because of the international monetary system. The normal methods are MER, PPP, and so on. Ideally, PPP is the most suitable method, but it is hard to calculate (of course, there are also problems with the method itself). The results are not completely accurate as the method is not comprehensive and uses broad data. For example, according to the exchange rate method, China’s energy consumption per unit of GDP in 2007 was 5.78 tons per 1000 USD, which is 3.8 times that of the OECD countries. According to the World Bank’s data, it was only 2.75 tons per 1000 USD, which is 1.7 times that of the OECD countries. Comparing the data from the World Bank (2009) and IEA (2009) with our data, we can see that under two different exchange rate methods, developed countries are located near the 45° line, but China, India, and other developing countries are far from the line. Figure 2.2 describes the energy consumption per unit of GDP in the BRICs and some OECD countries.

Nordhaus (2007), a professor from Yale University, introduced the Superlative-PPP method, which falls between the two methods mentioned above, to model the global energy, economic, and environmental problems aimed at solving the problems in the PPP method, which is based on exchange rates and world prices. In December 2007, the World Bank published a study to compare the results of the International Comparison Program (ICP) across the world and it subsequently modified the PPP coefficients. Even though the data are more exact through such modifications, the PPP calculations for China continue to have some problems

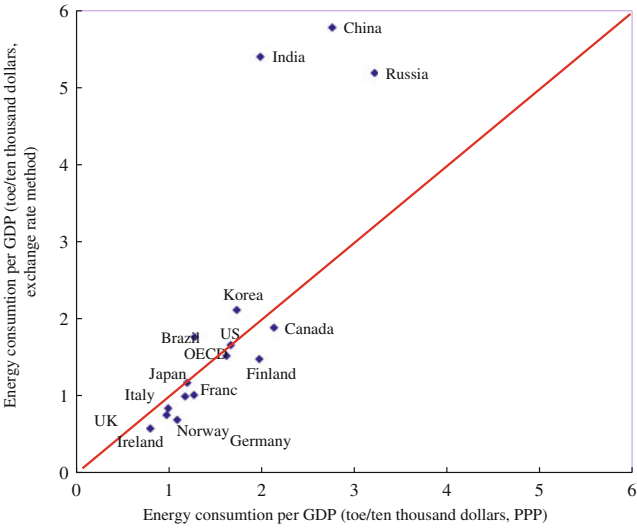


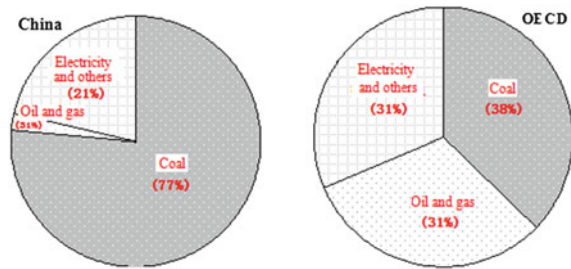
Fig. 2.2 The energy consumption per unit of GDP in the BRICs and some OECD countries (2007). *Data sources* World Bank (2009), IEA (2009) and authors’ calculations

because of some constraints between the theoretical method and the basic data. The degree of market integration in the developed countries is relatively high and the conversion system is accurate when one uses the PPP data to compare the unit GDP energy consumption in the developed countries; thus, the results are relatively accurate and reliable. However, when using the World Bank’s PPP data for China to compare its energy consumption per unit of GDP with the developed countries, the ordinal number is relatively meaningful, but the cardinal number is meaningless.

2.2.2 Energy Physical Efficiency

We usually define the energy consumption per unit of product and the energy consumption during the production process as the physical energy efficiency, e_p (energy physical efficiency); some examples include the total energy consumption per ton of steel production, comparable energy consumption per ton of steel, tons of steel consumption, power consumption, energy consumption per ton of cement, etc. It is common practice that the technical indicators do not include the magnitudes of value. This approach has been widely introduced and will not be discussed any further here. Energy efficiency is a suitable measure of comparison between the different production structures of an enterprise. It responds to the micro-economy and technical equipment level of management. At present, many companies and industry associations in China promote the “benchmark” based on energy consumption per unit of product. In the “Tenth Five-Year Plan” period,

Fig. 2.3 Energy structure of the iron and steel sector in China and the OECD countries (2007). Data sources IEA (2009c) and authors' calculations



China's energy macro-efficiency appeared to decline (using the coal consumption method). But the main energy consumption's physical efficiency continued to decrease, especially in products requiring raw materials such as iron, steel, cement, and glass.

We need a unified measure when we compare energy consumption per product and energy consumption during the production process between countries and enterprises. For example, we still have a long way to go to catch up with the developed countries in terms of calculating the energy consumption per ton of product. The items included in the energy consumption calculations for Japan include solid fuel, gas fuel, electricity, oxygen, and steam, but the items for China also include compressed air, nitrogen, water, and other mediums besides those in Japan. If the blast furnace uses blowers, then the air flow is included when calculating total energy consumption. According to the thermal equivalent method, the unit energy consumption is high for our main products. In addition to our use of technical equipment, other important reasons for this result include the quality of raw materials and the energy consumption structure. If one does not take these factors into account, then one may overestimate China's energy-saving potential. For example, using the thermal equivalent method, energy consumption per unit of product in China's iron and steel industry is higher than that in the developed countries, where the iron ore includes a higher proportion of poor quality ore. Figure 2.3 shows that China's energy consumption structure in the iron and steel industry in 2007 was 77 % coal while that for the developed countries was only 38 % coal. When using the physical efficiency indicators, the energy inputs sometimes vary relatively more, so the conclusions will be different than those found when using the heat equivalent, coal consumption method. One also needs to consider various alternatives that do not completely replace the original energy sources.

2.2.3 Energy Thermodynamics Efficiency

Energy physical efficiency refers to e_d (energy thermodynamics efficiency). The calculation is based on the theory of thermodynamics. Based on different steps in energy flow, it can usually be divided into energy exploitation, processing, storage and transportation, and terminal utility efficiency. The physics of energy efficiency

can also be classified as the first law of thermodynamics efficiency and the second law of thermodynamics efficiency. According to the first law of thermodynamics, energy physical efficiency in China has improved a lot during the past twenty years. In 2005, the energy extraction efficiency, intermediate linkages utilization efficiency, and final use efficiency were 33.2, 68.4, and 53.9 %, respectively. The total physical efficiency was 13 %. According to data from the NBS-DE and NBS-DCS, China's power stations' and power plants' heating efficiency was 40.24 % and their coking efficiency was 97.78 %. The efficiency of coking oil was 97.17 %.

According to the second law of thermodynamics, energy conversion has a direction. According to the theorem of the Carnot cycle, a cycle consists of two isothermal processes and two adiabatic processes known as the Carnot cycle efficiency: $\eta_c = (T_1 - T_2)/T_1$. In practice, since the absolute temperature of a true high-temperature, T_1 , heat source cannot be infinite, the absolute temperature of a low-temperature, T_2 , heat source cannot be zero. Hence, $\eta_c < 1$. Heat cannot be completely converted into mechanical work. Based on the second law of thermodynamics, the calculated thermal efficiency can be even lower. The energy physical effects' calculation is more complex and also involves more knowledge of thermodynamics, which has been introduced already. We will not discuss this in depth.

2.2.4 Energy Value Efficiency

Due to the heterogeneity of the various types of energy or quality differences, the same equivalent of the effects will be different. In some areas or businesses, although their energy consumption is low, they consume mostly high-quality energy (such as natural gas, a net transfer of electricity), whose cost is not low. To calculate the total number, we can use the thermal equivalent coefficient as the weight of the various types of energy and we can also calculate the total in terms of weighted prices. In this way, we can calculate the energy efficiency value, e_v . If the energy used in the production of outputs can also be measured by value, we can compare the energy efficiency value and the other indexes for different countries and find out the reasons why they are different (e.g., low energy prices and different energy structures); that is, why differences exist between the macro-efficiency and physical efficiency of different countries. In the calculations of the magnitude of energy consumption in different countries or regions in terms of value, one needs to be consistent in terms of what is included in the calculations (e.g., in terms of VAT, output taxes, transportation costs, etc.). When we compare energy efficiency values vertically, the value of energy efficiency will be different because of changes in energy prices. Therefore, the value of energy efficiency is more suitable in terms of a horizontal comparison. The advantage of the value of energy efficiency approach is that it is not influenced by the international comparisons of countries in terms of the exchange rate or PPP.

Using comparable input-output tables based on the 48 sectors defined by OECD and major developing countries, we calculated the values of energy efficiency in

Table 2.1 A comparison of the efficiency of the energy value in China and the major developed countries (2005)

Country	Energy consumption	GDP	Energy value efficiency		Energy macro-efficiency	
			Absolute ratio	Indexation	Absolute ratio	Indexation
France	1.62	17.26	10.63	1.10	6.75	1.27
Germany	2.34	22.45	9.58	0.99	7.28	1.37
Italy	1.51	14.30	9.50	0.98	8.78	1.66
Japan	552	4996	9.05	0.94	7.30	1.38
US	12.9	124.2	9.66	1.00	5.30	1.00
China	37.45	186.26	4.97	0.51	3.11	0.59

Energy value efficiency is calculated according to the input-output table for the OECD in 2009. Value is in domestic currency units (100 billion). Energy macro-efficiency data is from the World Bank. The index used is US = 1

China and the major industrialized countries in 2005 (data for the UK and Canada are missing). To make accurate comparisons, energy consumption amounts are calculated at producer prices (final energy demand). The results are outlined in Table 2.1. We can see that the U.S. energy macro-efficiency is obviously lower than that of four other countries, but the country’s energy efficiency is not less than that of other countries; it is sometimes even higher. This result is partly because the various final energy prices are generally lower than those in other countries (Table 2.2), regardless of the estimations using either the exchange rate or PPP methods. In 2005, China’s energy value efficiency was 50 % of that for the developed countries.

From the dynamic point of view, the value of energy efficiency can also be defined as the ratio of the service output for the full life cycle of the equipment to energy costs. For example, the price of energy-saving lamps may be very high, but in the long term, we save more energy and actually improve the energy value by using them (part of this substitution achieves equivalence by replacing energy with capital).

2.2.5 Energy Allocation Efficiency

The energy allocation index mentioned above is based on some common experiences, statistical knowledge or thermodynamic knowledge. The index relies little on knowledge of the economy. Now we use mathematical economic theory to determine the index of energy allocation efficiency, e_a . Allocation of resources, which is an economic system and price mechanism problem, has a close relationship with the ability to motivate users in terms of the importance of reducing energy consumption. Energy allocation efficiency, e_a , is related to various material prices. It reflects the ways to reduce the cost of materials by changing their combinations under a certain relative price system.

Table 2.2 Final energy prices in major developed countries, including tax (2005)

Country	Unleaded gasoline (USD/l)		Residential natural gas consumption (USD/m ³)		Industrial electricity (USD/kWh)		Industrial light fuel oil (USD/kl)		Commercial motor vehicle diesel (USD/l)	
	Exchange rate	PPP	Exchange rate	PPP	Exchange rate	PPP	Exchange rate	PPP	Exchange rate	PPP
France	1.442	1.257	0.55	0.48	0.050	0.043	563.3	491.1	1.062	0.926
Germany	1.519	1.411	–	–	0.084	0.078	559.7	519.7	1.143	1.061
Italy	1.515	1.408	0.77	0.71	0.174	0.162	1084.4	1007.3	1.147	1.066
Japan	1.131	0.961	1.16	0.99	0.123	0.104	439.5	373.5	0.745	0.633
US	0.626	0.626	0.46	0.46	0.057	0.057	427.7	427.7	0.633	0.633
China	0.47	–	0.22	–	0.073	–	–	–	–	–

France, Germany, Italy and US is #95 unleaded gasoline, Japan is regular unleaded gasoline. China's price is the average price for 36 cities and industrial electricity represents the large-industry price

To directly analyze the resource allocation, we use a two-dimensional yield line analysis method. As shown in Fig. 2.4, OYY' is the equality yield line, which means the minimum combination of the two elements, e and x , to produce the same amount of y with the technology level unchanged.

The combination of the factors of production is based on the principle of cost savings or the quest for profit. In a given production level, y , and element price levels (p_e, p_x), the minimum cost of the elements is:

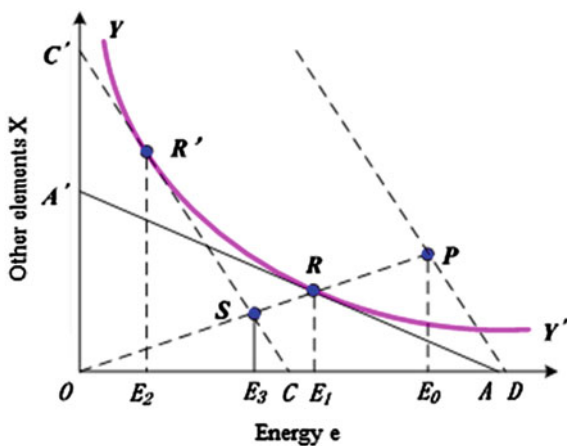
$$\begin{aligned} \text{The objective function: } \min & ep_e + xp_x \\ \text{Constraints: } & y = f(e, x) \end{aligned} \quad (2.13)$$

whereby you can obtain the best combination of elements, $R(e^*, x^*)$. The yield on a tangent, AA' , is the point R , where

$$\frac{f'_e(e^*, x^*)}{f'_x(e^*, x^*)} = -\frac{p_e}{p_x} \quad (2.14)$$

The relative price level of the various factors of production is a key factor of the determinants in the investment structure. If the actual relative price level, p_e/p_x , is distorted, the price is relatively low. Thus, the slope of the tangential line is relatively low and a corporation will choose point R to be the combination of production elements. The slope of the straight line, CC' , reflects the relative price level of the elements in response to both opportunity costs. That is the tangent with the isoquant at point R . For the whole society, the best combination of elements of such a configuration should be at R' . The potential savings in energy is $\Delta e = OE_1 - OE_2 = E_2E_1$. This is due to factor price distortions and a low factor allocation. We define the total element allocations as

Fig. 2.4 Energy allocation efficiency diagram



$$E_a = \frac{|OS|}{|OR|} \quad (2.15)$$

When the three points coincide, the allocation efficiency is at its highest. If the energy price level is low, in which the slope, AA' , is too small, then the investment income that the enterprise uses to save energy and improve energy efficiency is not as good as for other aspects of the investment gains. Thus, an enterprise's selection of raw materials for its infrastructure, technological transformation, and equipment renewals will not be too much to improve energy efficiency in the first place. For example, the iron and steel enterprises need to consume iron ore and energy in the production process. If energy prices are low (below the shadow price), then the businesses will tend to minimize their cost by purchasing low-grade iron ore and consuming multiple types of energy; that is, replacing some of the iron ore with energy. Due to the low cost of energy for the entire national economy, the country's industrial structure may trend towards energy-intensive development. Within the specific industry, this response could lead to higher energy inputs with a higher proportion of energy consumption related to households and a lower relative proportion related to other inputs. A reasonable price level will include not only energy extraction, processing, conversion, and storage costs but also the costs of non-renewable resources and pollution controls pertaining to the environment (most of the present energy consumption is non-renewable fossil fuels). The above analysis is based on two dimensions using a two-factor analysis. However, the analysis of many elements in multidimensional space can also reach the same conclusion.

The energy allocation efficiency, e_a , is an essential part of total element allocation efficiency, E_a . The analysis of the energy allocation efficiency is as follows:

$$e_a = \frac{|OE_2|}{|OE_1|} \quad (2.16)$$

In calculating the energy allocation efficiency, the first step is to calculate the energy economic efficiency. This calculation will be presented later in this chapter.

Energy is a scarce resource. The energy configuration in various sectors and enterprises can affect energy efficiency. A planned economy is one way to allocate resources, but overall, its efficiency is very low and the choice of point R is likely to deviate from R' , resulting in price distortions (or prices without markets and excess supply).

The main reasons are that (1) planners often do not have sufficient capacity to optimize the allocation of resources. There are various levels of technology and production conditions for the different government departments in different regions. Optimum planning is often difficult in terms of a timely response to various types of resource supplies and an accurate estimate of the shadow prices of the various inputs. (2) A planned economy is not a very effective incentive mechanism. In fact, the producers or planners can calculate the shadow prices and the optimal mix of

resources, but they cannot determine their own corresponding incomes. Therefore, in a planned economy, it is difficult to incentivize the producers and planners to make this effort. (3) A planned economy is not an efficient individual institution. The mistakes made cannot be attributed to any one person. Hence, nobody will be accountable and pay for their mistakes. (4) If planners are not subject to regulations, they may artificially distort resource allocations. In China's past, low energy prices, energy resource allocation, and scheduling were mostly controlled by the country's planning department, where energy resources tended to be assigned to the energy-intensive heavy industrial sectors. This partly caused an imbalance between light and heavy industries that determined the allocation of energy resources, leading to a low level of macro-efficiency.

An open market is the best way to allocate resources. In a market environment where the full responsibilities of property rights are clear and there is complete information and a sound legal system, producers and consumers will adjust their structures of production and consumption according to various inputs and prices to gain more profits. To increase energy services and energy efficiency, we should maximize the usage values of every kind of energy and reasonably allocate energy to various economic and daily activities. Energy resources should be distributed wisely to maximize the value of energy use, which is a requirement of increasing energy services and improving energy efficiency. Because of incomplete information and technological uncertainty, the allocation of resources (OP in Fig. 2.4) cannot totally depend on the market, even though the market is the source of our struggle to use it effectively.

2.2.6 *Energy Utilization Efficiency*

Energy as a factor of production is usually included with the other elements of capital, labor, and raw materials involved in the production process. The energy efficiency of factor allocation is based on various combinations of the elements and it is used to calculate the optimal combination of various elements. The e_u (energy utilization efficiency) can reduce the element requirements under the established element combinations. Assuming that we need the same quality and quantity of products, the combinations of capital, labor, raw materials, and energy can vary, as shown in Fig. 2.4, where R represents the point of actual production when it is connected with the origin, OR, and also intersects with the equal product quantity line at point P. Referring to Farrell (1957) and Färe et al. (1985), they use E_u to represent $\frac{|OR|}{|OP|}$ when studying production efficiency. When points P and R are coincident, the efficiency of the total elements is one, which is the highest value. The element use efficiency is one when the point lies on the isoquant. In most of the mathematical economics literature, the elements' utilization efficiency is also called

their technical efficiency, radial efficiency, or Farrell efficiency (it can also be described by the production possibilities curve). In practice, with the same quantity and quality of inputs, the output may differ. This difference will be represented in the aspects of the elements' utility efficiency. To calculate this efficiency, we need to construct an isoquant, which is a smooth curve that cannot be obtained directly. It is usually estimated based on the envelope formed by the production unit (strictly speaking, this differs from the potential isoquant). We usually use the production unit of an envelope to estimate the isoquant. The method is called data envelopment analysis (DEA). If the utilization efficiency of the energy factor is defined as the "total factor energy efficiency," this meaning is somewhat appropriate (and generally does not cause any misunderstanding).

The energy elements' utility efficiency, e_u , is defined as the ratio of the OR and OP projected distances in the energy axis, E , or $\frac{|OE_1|}{|OE_0|}$. We can use DEA to calculate the isoquant YY' and the energy elements' utility efficiency. Based on the experience of Hu and Wang (2006), the calculation is represented as follows: $X_i = (N, E)$, where E represents the energy and N represent the other elements (Fig. 2.5).

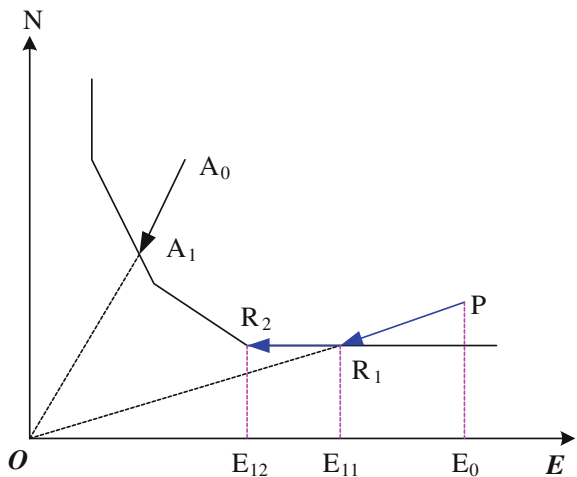
Thus, the energy utility efficiency is

$$e_u = \frac{|OE_{12}|}{|OE_0|} = \frac{\frac{|OR_1|}{|OP|} \cdot |OE_0| - |R_1 R_2|}{|OE_0|} = \frac{\theta \cdot |OE_0| - |R_1 R_2|}{|OE_0|} \quad (2.17)$$

$|OE_0|$ is the compression mapping along the E axis of $|OP|$. θ is the relative value of DEA.

For any production unit O , the relative valid value of DEA is θ_0 . We can calculate the value through linear programming. $|R_1 R_2|$ is a linear programming relaxation variable.

Fig. 2.5 Diagram of energy utility efficiency



$$\begin{aligned}
&\text{The objective function: } \min \theta_o \\
&\text{Constraints: } \begin{cases} \sum_{i=1}^n \lambda_i X_i + S_i^+ = \theta X_o \\ \sum_{i=1}^n \lambda_i Y_i - S_i^- = Y_o \\ \lambda_i \geq 0, i = 1, \dots, n \end{cases} \quad (2.18)
\end{aligned}$$

Within Eq. 2.18 above, S_i^+ and S_i^- are the input and output relaxation variables. Liao (2008) applied this method to calculate China's energy elements' efficiency in different industries in 2006 by considering the differences in the quality of similar elements and comparing them with the biased macro-energy efficiency indicators. Studies have shown that in terms of the 2006 macroeconomic efficiency of China's industrial sector, the energy utility differences were greater than those in terms of energy inputs (by using the coefficient of variation measure) (see Chap. 7). This finding is mainly because the latter calculation considers capital and labor's alternative elasticities. If we also consider the differences among regions, the differences of energy utility efficiency among the regions are much smaller.

In theory, the DEA method is very suitable for the calculation of energy utility efficiency. However, the DEA is very sensitive to the basic data. If the evaluation of an object determines that its value lies in an extreme position, it may have a great impact on the production frontier and thereby affect the results of the other objects being measured. Hence, when we use the DEA method, we need to do some basic analysis of the data included in the object's input index. According to some studies, their calculations show that the energy utility efficiency of a region can be less than 5 % of that for another region. In addition, in terms of production for a certain industry or corporation, energy, capital, labor, and raw materials form the combined input elements. In the process of any calculations, the absence of any one in these four items will influence the results. For a country or region, energy is both an input and an output. Hence, we must define the inputs and outputs clearly so that they are not misrepresented in the calculations.

2.2.7 Energy Economic Efficiency

Energy economic efficiency, e_e , is part of the energy cost efficiency, E_e . Energy economic efficiency equals an element's utility efficiency multiplied by its allocation efficiency.

$$E_e = \frac{|OR|}{|OP|} \cdot \frac{|OS|}{|OR|} = \frac{|OS|}{|OP|} \quad (2.19)$$

Energy economic efficiency, e_e , is the result of the entire project on the axis e of OP . Under the situation without relaxation (i.e., Fig. 2.4, in which the medium production line, YY' , is the implicit function P_0 's first derivative of P_0):

$$e_e = \frac{|OE_2|}{|OE_0|} = \frac{|OE_2|}{|OE_1|} \cdot \frac{|OE_1|}{|OE_0|} = e_a \cdot e_u \quad (2.20)$$

Before we calculate the energy economic efficiency, we should first determine the energy efficiency (the former is part of the latter). Färe et al. (1985) and others have raised the idea that we can use DEA to solve the problem of energy efficiency. The objective function is to minimize the total cost. For any given unit O , under the conditions of given capital, labor, raw materials, and the energy vector P_0 , the potential minimum cost can be calculated through the following linear progression:

$$\begin{aligned} &\text{The objective function: } \min P_o \tilde{X}_o \\ \text{Constraints: } &\begin{cases} \sum_{i=1}^n \lambda_i X_i \leq \tilde{X}_o \\ \sum_{i=1}^n \lambda_i Y_i \geq Y_o \\ \lambda_i \geq 0, i = 1, \dots, n \end{cases} \end{aligned} \quad (2.21)$$

$\tilde{X}_o$ represents the objective needs of every elements; that is, when the output is Y_o , to meet the lowest total cost, all elements have the minimum quantities. Y_o is the output.

Economy efficiency:

$$E_e = \frac{P_o \tilde{X}_o}{P_o X_o} = \frac{|OS|}{|OP|} = \frac{|OC|}{|OD|} \quad (2.22)$$

Equation 2.20 can be deduced by the line CC' , which is parallel to the line through point P . CC' is the isocost line. The cost of production at point R' is $|OC|$ while the actual cost of production is $|OD|$. Using DEA to calculate the economic efficiency already exists, so there are no slack variable problems, and no information will be lost. On this basis, we put forward our method of calculating the energy economic efficiency:

Energy Economy efficiency:

$$e_e = \frac{p_e \tilde{E}}{p_e E} \quad (2.23)$$

where P_e is the price of energy. (when only one energy is included, $P_e \in P$; when several types of energy are included, $P_e \subset P$) $\tilde{E}$ is the object energy demand. e_e is the ratio of the object energy cost to the actual energy cost. When the input energy is only one type, $e_e = \tilde{E}/E$. It is obvious that when the economic efficiency is

100 %, the energy economic efficiency is 100 %; otherwise, the solution may not be valid. The allocation efficiency of the energy factor is equal to the ratio of the energy efficiency and energy factor utilization efficiency (provided that in calculating the elements' utilization efficiency, the slack variable is 0).

Besides the DEA method without parameters, we can also use the production and cost functions and the regression analysis method to calculate the elements' utility efficiency, energy allocation efficiency, and economic efficiency. The differences between the energy macro-efficiency and energy economic efficiency are the same as those between the labor efficiency and total elements' efficiency (not considering the energy use by households). Energy macro-efficiency has some bias while energy economic efficiency does not. Moreover, the efficiency calculated by the DEA method is a relative concept. An efficiency of one represents the best among the evaluated objects, but it does not mean that it cannot be improved.

The concept or measure of the efficiency of the energy economy actually combines the energy savings and cost. In the development of energy efficiency policies, decision making by government departments is usually based on macro-energy efficiency or physical efficiency. But if the cost is large, resulting in no reduction in costs or no increase in profits, then it is difficult to motivate energy users to take such initiatives. The government needs to set reasonable incentives (such as in the energy and environment tax systems) for energy users to adopt energy efficiency measures with both cost savings and successful and compatible incentives. This practice will improve not only the macro-energy efficiency but also the efficiency of the energy economy.

2.3 Summary

Energy efficiency is not only a scientific and technical issue but it is also an economic, social, environmental, and development issue. It has highly complex, comprehensive, and systematic problems. China is in the rapid development stage of industrialization and urbanization, so energy resources per capita are relatively inadequate and energy consumption is huge. Higher growth without more certainty in terms of production and consumption will lead to greater environmental pollution. Moreover, carbon dioxide emissions caused by energy development and its uses are increasing and becoming prominent problems. Maintaining rapid economic development, improving the quality of life and energy efficiency, and slowing the growth of energy consumption are extremely important goals for China's current and future energy development.

With research on energy efficiency in China continuing to move forward, we can make the results more scientific and practical by discussing the problems in many ways. (1) Considering the relationship between the total energy supply and demand in various regional economies, we need to pay attention to the structural heterogeneity problems, especially the impact of changes in the energy structure. (2) The

energy structure can be measured by both its physical quantity and its economic value. If we use the latter, China's consumption is mainly oil rather than coal. (3) Depending on the different issues and data, we can use the estimated energy efficiency indicators to avoid single-indicator information bias. (4) To build a computable general equilibrium model based on a particular measurement method, we should consider the various elements within the energy sector, as well as the other elements, and their variable elasticities of substitution.

The amount of energy consumed contributes toward maintaining or promoting the sustainable development of the total economic, social, and environmental systems. Hence, the goal is to promote economic development and the way to reach this goal is to improve energy efficiency, as the processes cannot be changed. The former is the goal while the latter is the means. Energy is an important element of production, so it is interrelated with the other aspects of the economic system. In terms of the macro economy, we cannot use energy consumption per unit of GDP or the value added per unit of energy consumption as the sole indicators of progress. Energy should be included in a comprehensive survey of the entire economic system, which includes comprehensive inspections of each stage of development, the area's natural endowments and the labor base differences under objective conditions. We should combine the savings in energy, the reduction in costs, and the increase in revenues to avoid "one-size-fits-all" evaluations and conclusions.

Energy macro-efficiency, energy physical efficiency, energy thermodynamics efficiency, energy value efficiency, energy allocation efficiency, energy utilization efficiency, and energy economic efficiency are seven indexes to describe energy efficiency. Each of them has a theoretical base, assumptions, relationships, advantages, and limitations. Any single index cannot completely represent a particular energy efficiency level.

Different indexes have different suitable fields of research, measurement methods, and required data. The most common ones are macro-efficiency and energy thermodynamics. Sometimes, we simply set a goal to reduce energy consumption or reduce energy consumption per unit of output because of confusion between the purposes and means of endogenous and exogenous variables, as well as their causes and results. From the static and local points of view, energy consumption has been reduced. From the long-term and global perspectives, energy efficiency has not improved, and it has even caused loss of other aspects of the economic and social systems. Energy conservation could fall into the "doing more harm than good" category. In practice, we should choose some indexes according to certain situations, with special attention to the heterogeneity of different forms of energy and the alternative calculations of data indicators (Liao 2008).

For a country or region, energy economic efficiency is a relatively ideal index. But we need more accurate data, which is usually hard to obtain (even itself with uncertainties), especially when the index uses data to represent the environmental costs and unsustainable energy prices. No matter what kind of data is used, we need to enhance the data caliber as much as possible for both horizontal and vertical comparisons. Although macro-efficiency has some bias, it is suitable for long-term

analyses. In most studies, little attention is paid toward the absolute value of the energy index. We are more concerned about the horizontal and vertical comparisons of energy efficiency, the gap between the energy efficiency of different subjects, and the speed and direction of changes in energy efficiency.

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