Theoretical Foundation for Energy Structure Adjustment

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Abstract

Application of unit fuel consumption has been explored deeply based on the second law analysis of thermodynamics to meet the strategy demand of optimizing energy structure adjustment. Theory of unit consumption analysis has been used in this paper to explore the theoretical foundation of energy structure adjustment. It has been proved that value of fuel exergy varies when two fuel exergy assessment methods are used separately. It can be obtained that coal utilization corresponds to the lowest second law efficiency while H_2 or CH_4 the highest according to the calculations. Thus, to increase the percentage of natural gas in regional energy consumption will lead to higher regional second law efficiency. And theoretical energy saving potential can be obtained from the departure of practical unit fuel consumption (UFC) to theoretical UFC.

Keywords: Energy structure, Energy utilization efficiency, Evaluate, Theory of unit fuel consumption, Fuel exergy

1. Introduction

About 90% of the world energy supplies are provided by fossil fuels, with the associated emissions causing local, regional, and global environmental problems. Long-term projections indicate that world energy demand may increase dramatically, with most of this increase taking place in developing countries, while fossil fuels reserves are limited and gradually decreasing because of the enormous energy consumption in economic growth and social development. This has been reported previously (Marc and Ibrahim, 2001, pp.3-13; GUO, Chai and XI, 2008, pp.38-43). In addition, other energy resources like nuclear energy and renewable energy account for less than 10% of the total energy consumption in the world, although lots of measurements have been carried out to prompt research and application of these energy resources. To solve these problems, researchers suggest more concern and devotion on how to improve energy utilization efficiency for social sustainability.

Zaltu and Arif (2007, pp.1-29) reported that energy structure and its supply modes exert great influence on the efficiency of energy resource utilization. Energy structure is among key factors influencing energy utilization efficiency. Obviously, to adjust the energy structure and its supply modes will be an efficient and effective way to improve the efficiency of energy resource utilization. So the theoretical foundation for adjusting energy structure will be studied here.

Exergy analysis is a key tool in evaluating the efficiency of energy resource utilization, and has been widely used by researchers in assessing how efficiently energy is used in sectors, local, regional systems, discussed previously (Wall, 1990, pp.435-444). Then, what will happen if exergy analysis is adopted in studying the effectiveness that energy structure and its supply modes is used to evaluate the exergy utilization efficiency of regional system? Here, the foundation of adjusting energy structure and its supply modes will be studied.

2. Exergy and Exergy analysis

Exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of the system or flow to cause change, as a consequence of not being completely in stable equilibrium relative to the reference environment. Unlike energy, exergy is not subject to a conservation law. Rather exergy is consumed or destroyed, due to irreversibilities in any real process. Bejan et al. (1996,pp.71-90) reported that the exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

The second law of thermodynamics, i.e., exergy analysis, takes the entropy portion into consideration by including irreversibilities. It's a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems. During the past decades, exergy related studies have received tremendous amount of attention from various disciplines ranging from chemical engineering to mechanical engineering, from environmental engineering to ecology and so on, discussed by Ibrahim (2002,pp.137-149). The exergy method is useful for improving the efficiency of energy resource use, for it quantifies the locations, types, and magnitudes of wastes and losses. In general, more meaningful efficiencies are evaluated with exergy analysis identifies accurately the margin available to design more efficient energy systems by reducing inefficiencies. Many engineers and scientists suggest that thermodynamic performance is best evaluated using exergy analysis because it provides more insights and is more useful in efficiency improvement efforts than energy analysis.

Exergy analysis has been used not only in assessing the energy resource efficiency of process and links in practical systems, which has been reported previously (Irfan, Nevin and Ibrahim 2010,pp.:451-460; Leyla, Arif and Ibrahim, 2007,pp.1185-1192; Samuel and Silvio, 2008,pp.153-162), but also of sectors and regional systems, because the latter combines micro thermodynamic and macro decision making and research about this gradually become a trend. Tens of countries have carried out energy resource efficiency evaluation researches based on exergy analysis for sectors, local and regional systems and society. The approaches used to analyze energy utilization of countries or societies may be grouped into three types, namely Reistad's approach, Wall's approach and Sciubba's approach, discussed in Zaltu and Arif (2007, pp.1-29). There are some differences when compared the three approaches.

3. Unit fuel consumption analysis of energy utilization and energy saving potential

Unit fuel consumption analysis (UFCA) proposed by Professor Song Zhi-ping (1992, pp.15-21), is a analysis method for energy system based on exergy and exergy economics. It belongs to exergy analysis. According to second law of thermodynamics, the exergy balance equation for any energy use process could be stated as follows:

$$B^s \cdot e_f = P \cdot e_p + \Sigma B_i \cdot e_f \tag{1}$$

where ef, ep stand separately for specific exergy of fuel and product, with unit kW·h/kg, P is product, Bs is standard coal consumption and ΣB_i is the sum of additional fuel consumption corresponding to exergy consumption of links in a process.

Apparently, (1) could be written as:

$$b = \frac{B^s}{P} = \frac{e_p}{e_f} + \frac{\Sigma B_i}{P} = b^{\min} + \Sigma b_i \tag{2}$$

$$b^{\min} = e_p / e_f \tag{3}$$

Where $b_{\min}$ is theoretical unit fuel consumption (TUFC) of a product, depending on natural qualities of a product not production process, Σb_i is the sum of additional unit fuel consumption, depending on production modes and flow path.

Second law efficiency (e.g., exergy efficiency) for energy use could be attained according to (1):

$$\eta_{ex} = \frac{P \cdot e_p}{B^s \cdot e_f} = \frac{e_p / e_f}{B^s / P} = \frac{b^{\min}}{b} \tag{4}$$

As is known, second law efficiency is the fundamental efficiency of energy use process. Equation (3) makes it possible for second law efficiency to apply statistics analysis, which is an important development for second law analysis, more details referred to Zhou's (2008, pp.42-44; 2004,pp. 1219-1226).

According to (2) and (4), theoretical energy saving potential could be derived:

$$\Delta b_{\max} = b - b^{\min} \tag{5}$$

The value of theoretical energy saving potential makes it definitely to tell us what is the object we've devoted to, however, it doesn't mean it's easy to calculate this value. For example, the unit fuel consumption(UFC) of power supply for the most advanced 1000MW super-critical coal-fired generation sets so far is about 280 g/(kW·h), which means quantity of energy saving potential, compared to 122.9 g/(kW·h) which is the theoretical unit fuel consumption. Nevertheless, this potential is very hard to be excavated. Other generation systems like combined cycles and fuel cells should be integrated while to break through the present situation.

According to Statistics Express of China Electricity Council, the average UFC of electricity for electric networks is 342 g/(kW·h). It's easy to dig the real energy saving potential comparing with that of 1000MW super-critical coal-fired generation sets. The real energy saving potential is defined as the ratio of real unit fuel consumption to advanced UFC for product in the world:

$$\Delta b_{re} = b - b^{ad} \tag{6}$$

Song (1985, pp.399) reported that energy saving and emission reduction viewed from end product and its unit fuel consumption, explored the problem of establishing unified evaluation indicator system, which provided the foundation of energy saving potential analysis for energy-consumed devices, companies and region systems.

But there is still shortage in applying UFC based on end-use product aiming at energy structure adjustment, since theoretical energy saving potential calculated by (5) varies from different unit fuel exergy e_f in (4) and thus different b_{min}.

Scientific measures for adjusting energy structure could be presented only by comprehensively analyzing the basic theory and real energy saving potential, which will prompt national economic structure adjustment and low-carbon economy development.

4. Fuel exergy

Fuel exergy is the maximum work theoretically according to the definition in thermodynamics, and fuel exergy could be approximatively expressed:

$$e_f^0 = q_{h,f}^0 + T_0 \Delta s_R^0 + R_M T_0 \sum_{pr} \alpha_j \ln \frac{p_0}{p_{0j}} \tag{7}$$

Where subscript j stands for reactant except of fuels and resultants of standard reaction, pr stands for fuel combustion resultants, p_{0j} is sub-pressure of resultants in air. T_0, p_0 stand for air temperature and pressure in ambient condition separately, $q_{h,f}^0$ is gross heat of the fuel, Δs_R^0 is standard reaction entropy, which could be calculated:

$$\Delta s_R^0 = \sum_j \alpha_j s_j^0 \tag{8}$$

where s_j^0 is absolute entropy of resultants, referred to Wu's (2010, adopted). Table 1 listed basic thermal physics qualities of some pure fuels, from Zhou, Hu and Song (2006, pp:549-552).

There is much difficulty to precisely calculate fuel exergy because fuel exergy in (7) is derived under the assumptions of ideal gas, and the composition of real fuels varies and is much different from ideal gas. To simplify the calculation of fuel exergy, researcher Zoran Rant, from Slovenia, who firstly brought up the concept of exergy, suggested some ways to evaluate fuel exergy for gas, liquid and solid fuels according to the gross heat and low heat value of fuels.

$$e_f^0 = \begin{cases} 0.950\, q_{h,f}^0, & \text{for gas fuel} \\ 0.975\, q_{h,f}^0, & \text{for liquid fuel} \\ q_{l,f}^0 + r_{f,g} \cdot x, & \text{for solid fuel with moistue content x} \end{cases} \tag{9}$$

Where $r_{f,g}$ is latent heat of vaporization of water in ambient temperature.

Exergy is the capacity of work for working medium in thermodynamics, and electricity is the best quality of work and is considered as 100% exergy, thus there's much intuitive for converting fuel exergy to equivalent electricity.

$$e_f^e = \frac{e_f^0}{3600} \quad [\text{kW·h/kg}] \quad (10)$$

According to (4), the specific exergy of fuels vary because of different kinds of fuels, which means second law efficiency could be different. If high quality clean energy is used improperly, additional consumption will occur although its high thermal efficiency. For example, although the thermal efficiency (first law efficiency) of natural gas used in boiler is larger than normal coal-fired industrial boiler, in some area natural gas is directly used in heat supply for residents in winter, which results low efficiency. Moreover, wrong decisions which were unpractical and lacked long-term insight have been made during power industry development history. The reasons of making lapse are superficially resource and environment conditions, but the real and fundamental reason is that the evaluation of energy utilization efficiency is only carried out using the first law of thermodynamics, and the second law efficiency (4) is the nature respond to energy utilization. So far, thermal efficiency of energy utilization defined in nation regulation is based on the low heat value of standard coal, which ignores the difference of resource qualities could different energy efficiency. It means that the adjustment of energy structure lacked scientific theory guidance, and this should be changed as soon as possible.

5. Specific exergy and theoretical unit fuel consumption of electricity and heat

5.1 specific exergy of electricity and heat

Electricity and heat are mainly two modes of energy use, and almost each product would consume directly or indirectly these two energy. Here, only the specific exergy of electricity and heat are explored, those of other products could be determined by thermodynamics.

specific exergy of electricity:

$$e_p = 1 \quad [\text{kW·h/kW·h}] \quad (11)$$

For heat production, when average thermodynamics temperature of desired heat is $\overline{T}_h$, Zhou (2007) considered that the specific exergy could be:

$$e_p = (1 - \frac{T_0}{\overline{T}_h}) \quad [\text{kW·h/kW·h}_\text{h}] \quad (12)$$

Or, $$e_p = 278(1 - \frac{T_0}{\overline{T}_h}) \quad [\text{kW·h/GJ}] \quad (12a)$$

where T_0 is ambient temperature.

5.2 Theoretical unit fuel consumption of electricity and heat

Thus, theoretical lowest UFC of standard coal, fuel oil and natural gas for electricity generation could be:

$$b_e^{\min} = e_p / e_f^e = 1 / e_f^e \quad [\text{kg/kW·h}] \quad (13)$$

If the fuels listed above are used to supply heat, the corresponding theoretical lowest UFC are:

$$b_h^{\min} = \frac{e_p}{e_f^e} = \frac{278}{e_f^e}(1 - \frac{T_0}{\overline{T}_h}) \quad [\text{kg/GJ}] \quad (14)$$

LHV is widely used in energy statistics in China, and therefore, all energy consumption should converted as low heat value (LHV) of fuels, and the theoretical lowest UFC of electricity generation and heat supply($b_e^{\min ce}$ and $b_h^{\min ce}$), based on LHV, would be equal to values from (13) and (14) times corresponding conversion factor to standard coal.

6. Analysis of fuel exergy

The theoretical lowest UFC of electricity generation and heat supply (other products are similar) is different because fuels used have different qualities. The higher qualities of fuels have, the lower of theoretical lowest UFC for a product is, according to (13) and (14). And in terms of (4), more scientific energy utilization technologies are needed to be developed in order to reach high second law efficiency.

For example, for fuel oil and natural gas, viewed from the second law efficiency, if these two kinds of fuel are used in electricity generation, gas-steam combined cycle or even fuel cell technology is needed in order to reach higher exergy efficiency; thus, it's an improper mode of energy use if these two kinds of fuel are directly used in heat supply.

Obviously, the second law efficiency analysis based on energy utilization is important in guiding theoretically energy structure adjustment and energy utilization efficiency improvement.

Nevertheless, the value of fuel exergy is very difficult to be calculated because of complex composition of practical fuels. For example, oil, which mainly consists of alkane, arene, alkene, cyclane, doesn't have molecular formula. Even light oil products whose main components are pentane and hexane doesn't have molecular formula. Here, pure material fuels like H2, CH_4, C, and $C5H_{12}$, are chosen as examples in order to clearly understand fuel exergy and its impact on the second law of energy utilization.

Values of fuel exergy, corresponding gross heat, theoretical lowest UFC for electricity generation are obtained from (7) and listed in Table 2. In general, value of fuel exergy under atmospheric environment is higher than the gross heat value of the fuel except H2, which is probably connected with water assembly parameters, because only water has phase change and lead to big error when H2 is assumed to be ideal gas.

The fuel exergy for electricity generation is larger while the quality of fuel is higher if these pure material fuels are used to generate electricity, e.g. the number of fuel needed for power generation is less. Therefore, C is the fuel with the highest second law efficiency, others are less efficient. In other words, more advanced technologies are demanded in order to achieve more efficient energy utilization when other kinds of fuel are used. For example, the second law efficiency for oil-fired boiler than that of coal-fired boiler while the energy efficiency between these two kinds boiler is the same. The situation that fuel oil is widely used in other fields gives a big attack in its application in power generation less.

Equation (9) is computation method based on manually correction and it fits practical application and people's understanding of fuel quality. The quality of real fuel corresponding to pure material pure listed in Table 3 like coal, oil, natural gas and H_2, is improved step by step when used, while the quality of light oil is equal to that of natural gas.

H_2 fuel produces water when combusted and is considered to be an ideal clean energy resource, therefore, more attention should be paid on the technologies of energy use. It can be concluded from ratios in Table 3 that the second law efficiency of H_2 is 12.9% higher than that of C fuels in order to maintain the equality of these two efficiencies when H_2 is used for power generation.

Of course, different kind of fuel has different qualities. So it's of realistic and theoretical significance to carry out qualities evaluation of fuel for energy structure adjustment.

7. Conclusions

The efficiencies for different fuels used differ largely, for example, the efficiency of coal used is the lowest among several fuels studied above, while that of natural gas is highest. Therefore, when energy demand is determined, we could adjust energy structure in order to achieve the highest energy utilization efficiency.

The higher quality of fuel is, the larger value of specific exergy is, and the less fuel consumed. It should be established on the base of fuel exergy analysis for optimal use of different types of fuel.

It would provide decision support for building scientific and reasonable energy structure combined with research on market regulation systems based on the actual situation of local economy development and actual demand of energy consumption.

Energy utilization efficiency was defined on account of low heat value of standard coal so far in China, which ignores the probability that different quality of energy resource may produce diverse energy efficiency. Energy structure adjustment lack scientific theoretical guidance, which is badly in need of change.

It must be declared that the fuel exergy for simple and pure matter could be easily obtained according to part 5, thus its lowest TUFC for electricity generation and heat supply and the value of energy saving could also be attained. It would take lots of effort to analysis how to obtain the fuel exergy of different kinds of compounds since the compositions are unstable and complex.

References

GUO Ju-e, Chai Jian and XI You-min. (2008). Effect of the primary energy consumption structure change to the energy use per unit of GDP. *China Population, Resource and Environment*, 1, 38-43

Ibrahim Dincer. (2002). The role of exergy in energy policy making. *Energy Policy*, 30, 137-149.

Irfan Kurtbas, Nevin Celik and Ibrahim Dincer. (2010). Exergy transfer in a porous rectangular channel. *Energy*, 35, 451-460.

Leyla Ozgener, Arif Hepbasli and Ibrahim Dincer. (2007). Exergy analysis of two geothermal district heating systems for building applications. *Energy Conversion and Management*, 48, 1185-1192.

Marc A. Rosen and Ibrahim Dincer. (2001). Exergy as the confluence of energy, environment and sustainable development. *Exergy In*t. J.1,3-13.

Samuel José Sarraf Borelli and Silvio de Oliveira Junior.(2008). Exergy-based method for analyzing the composition of the electricity cost generated in gas-fired combined cycle plants. *Energy*, 33(2): 153-162.

Song Zhiping and Wang Jiaxuan. (1985). *The Principle of Energy- Saving*, Electric Press, 399.

Song Zhiping. (1992). Consumption Rate Analysis: Theory and Practice. *Proceedings of the CSEE*. 12, 15-21.

Wall G. (1990). Exergy conversion in the Japanese society. *Energy,* 15, 435-44.

Wu Zhi-quan, Zhou Shao-xiang, An Lian-suo and Shi Hai-lin. (2010). Energy saving and emission reduction evaluation system based on unit fuel exergy of end-use product. *Chinese Journal of Power Engineering*, adopted.

Zafer Utlu and Arif Hepbasli.(2007). A review on analyzing and evaluating the energy utlizaiton efficiency of countries *Renewable and Sustainable Energy Reviews*, 11,1-29.

Zhou Shaoxiang, Hu Sangao and Song Zhiping. (2006). Comparison of the Theory of the Unit Fuel Consumption Analysis and the Method of Structural Coefficients. *Journal of Engineering Thermophysics*, 27, 549-552.

Zhou Shaoxiang, Hu Sangao and Song Zhiping. (2008). Specific Fuel Consumption Analysis and Efficiencies of Energy Utilizations, *China Energy*, 30, 42-44.

Zhou Shaoxiang. (2004). The Unified Benchmark Evaluating the Thermodynamic Performance of Energy Utilization Systems. *Proceedings of 17th ECOS International Conference*, Guanajuato. México, 1219-1226.

Table 1. mole mass, gross heat and low heat value and absolute entropy of pure fuels

fuels	RMW**	$q^0_{h,f}$	$q^0_{l,f}$	s^0_R	CF***
unit	kg/kmol	MJ/kmol	MJ/kmol	k/(mol·K)	-
H_2(g)	2.0159	286.0	240.80	130.57	4.07569
CH_4(g)	16.043	890.001	799.599	186.15	1.70059
C_5H_{12}(l)	72.151	3515.702	3244.402	262.7	1.53429
C(s)	12.0112	406.898	406.898	5.740*	1.15588

Note: g, l, s stand for gas, liquid, solid collection condition separately;

*-carbon dates of graphite structure; **- relative molecule weight; ***- factors that particular fuel converts to standard coal

Table 2. exergy values of different fuels from Eq. (7)

fuel	e^o_f	e^e_f	$e^o_f / q^0_{h,f}$	$b_e^{\min ce}$	ratio*
unit	MJ/kg	kW·h/kg	-	kg_{ce}/(kW·h)	-
H_2	138.60	38.50	0.9769	0.1059	1.150
CH_4	57.73	14.37	0.9326	0.1183	1.029
C_5H_{12}	47.89	13.30	0.9828	0.1153	1.056
C	34.18	9.49	1.0089	0.1218	1

Table 3. exergy values of different fuels from (9)

fuel	e^o_f	e^e_f	$e^o_f / q^0_{h,f}$	$b_e^{\min ce}$	**ratio***
unit	**MJ/kg**	**kW·h/kg**	**-**	**kg_{ce}/kW·h**	**-**
H_2	134.78	37.44	0.95	0.1089	1.129
CH_4	52.702	14.64	0.95	0.1162	1.058
C_5H_{12}	47.509	13.20	0.975	0.1163	1.057
C	33.877	9.410	1	0.1229	1

Note: *- is ratio of the theoretical lowest unit fuel consumption for a specific fuel to the theoretical lowest unit fuel consumption of C.