Study on impact of energy price comparison on energy saving benefits of heat pump in North China

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Abstract. As to the heat pump technology applying in the HVAC engineering, the relationship between energy saving rate (ESR) and electricity cost saving rate (ECSR) of heat pump should be a positive correlation in theory. But in the actual energy price system, due to the fluctuating energy price comparison, the relationship between them is of less coordination. Moreover, despite the high ESR, the economic benefit of ECSR is lost. In this paper, via the case analysis under the condition of average technical and economic parameters in North China, the critical point rate of economic benefit of ECSR in energy price comparison among prices of residential electricity, steam-coal, and residential natural gas is found, which is about 2:3:8. Also, a viewpoint as well as a method is suggested to promote the wide usage of heat pump, balance energy supply structure, save energy consumption, and reduce emissions by optimizing the energy price comparison, which is feasible and desirable to raise the price comparison between residential electricity and natural gas, and reduce the price comparison between residential electricity and steam-coal in a certain extent.

1. Introduction
Energy is the important material basis and driving force of the survival then development of human society. So far, the energy structure has not been essentially changed, which is still primarily based on fossil fuels, including the auxiliary application of clean and renewable energy in many fields. Threatening the sustainable energy development, energy structure problems mainly have two aspects: One is the serious harm to environment such as acid rain and greenhouse effect caused by the utilization of fossil fuels; the other is the contradiction between the growing energy demand in human society and the increasing difficulty of exploiting finite fossil fuels in terms of technology and policy.

In order to solve the above troubles, many studies on the techno-economic performance of heat pump have been conducted in recent years. Sahraie et al. [1] have simulated and optimized the thermo-economic and thermodynamic properties of a two-stage irreversible heat pump from the perspective of employing Fuzzy and LINMAP and TOPSIS decision-making approaches to obtain the Pareto frontier. Lazzarin and Noro [2,3] implemented an economic analysis of a gas engine heat pump
coupled to two condensing boilers, which was connected to the district heating grid in Vicenza, Italy. Lambert and Beyene [4,5] made a thermo-economic comparative analysis between a solar thermal cooling system and a solar electric cooling system for 24 cities across US Sunbelt (south of 37°N). Thygesen and Karlsson [6] have simulated and analyzed three solar-assisted ground source heat pump systems with regards to economics and energy. Blum et al. [7] made the techno-economic and spatial analysis of vertical ground source heat pump systems in the state of Baden-Württemberg, South Germany. Yazdi et al. [8] have researched the exergy, economic and environmental performances of a heat pump to cool the input air from a gas turbine compressor both in Yazd whose climate is arid and Tehran whose climate is temperate, Iran. Li H and Yang HX [9,10] conducted experiments then energy and exergy analysis on a multi-functional solar-assisted heat pump system proposed to supply domestic hot water and space cooling in Hong Kong. Wu et al. [11] have carried on a year-round simulation and techno-economic analysis of heating system with air source absorption heat pump under weather conditions of four cities in China. Wu et al. [12] have also studied annual economic performance of heating system with compression-assisted air source absorption heat pump.

The application of heat pump technology can reduce the energy consumption during cooling and heating, relieve the tense energy situation, and decrease environmental pollution, which has significant social and economic benefits. Even so, there are still possibilities existing in the discordant and fluctuating energy price system to cause the loss of economic benefits of heat pump, from the artificial other than technical factors perspective. It means that even though the application of heat pump is energy-saving, this kind of behavior may not be money-saving. The purpose of this paper is to find reasons and explore effective measures to eliminate the adverse impact of energy price comparison and promote the usage of heat pump widely as well as quickly in North China.

2. Primary energy rate of heat pump

Heat pump is a kind of high-efficiency and energy-saving equipment used to improve heat grade for heating. Heat pump uses the low-grade heat from nature or manufacturing process emissions as a low-temperature heat source, through a small amount of high-grade power consumption of compressor or other forms, thus improves the heat grade of low-temperature heat to apply to heating users of high-temperature heat source. Taking electric vapor compression heat pump most widely used as an example, its energy balance model is shown in Figure 1.

![Figure 1. Heat pump in the energy balance model](image)

Electric vapor compression heat pump is an equipment transforming electricity into heat. The relative scale between benefits and costs of heat pump is evaluated by COP in the thermodynamics as follows:

$$COP = \frac{Q_H}{W}$$

where $Q_H$ is the heating capacity and $W$ the quantity of consumed work.

The expression of COP is the comparison rate between thermal energy and mechanical work, so the economic feasibility of transforming mechanical work into thermal energy must be considered in certain conditions of energy price comparison and device availability. From the thermal power point of view, the COP expression cannot explain the rationality of heat energy utilization in theory. To this issue, the introduction of primary energy rate (PER) of heat pump is essential. The meaning of PER is
that the quantity of consumed work \( W \) in the COP expression can be converted into equivalent primary energy consumption of thermal power generation as follows:

\[
\text{PER} = \frac{Q_H}{W} \eta_p
\]  

(2)

where \( \eta_p \) is the efficiency of thermal power generation.

Analyzing the Formula (2), it is feasible to compare PER with the thermal efficiency of boiler. Both the techno-economic analysis of heat pump and boiler can be based on the conversion and utilization efficiency within transforming the chemical energy of fossil fuel combustion into heat energy. Their specific energy utilization processes are shown in Figure 2.

Figure 2. Energy utilization process comparison between (a) boiler and (b) heat pump

Illustrated in Figure 2, the chemical energy of fossil fuel combustion is directly used for heating in the energy utilization process of boiler, thus the thermal efficiency must be less than one. Concerning the energy utilization process of heat pump, the chemical energy of fossil fuel combustion is \( \frac{W}{\eta_p} \), which is used for thermal power generation through boiler and steam turbine power generation system. Electricity generated from thermal power generation system drives heat pump to consume the work \( W \) and improve the low-grade heat. The heat pump process ends up with the heat \( Q_H \) for heating. Because the energy utilization process of heat pump is by way of electricity transmission and driving the compressor to use the low-grade heat from low-temperature heat source, \( \frac{W}{\eta_p} \) is just an idealized expression of primary energy consumption quantity of heat pump to facilitate comparative calculation, which has ignored the influence of efficiency of electricity transmission and utilization. There is no unified evaluation method whether the usage of low-temperature heat source is calculated on the energy consumption of heat pump or not, and how to estimate the low-temperature waste heat discharged from steam turbine. But crucially in terms of the conversion process from chemical energy to heat energy, the PER of heat pump and thermal efficiency of boiler are comparable [13].

3. Energy saving rate of heat pump

Energy saving benefits of heat pump are generally evaluated by two indicators which are energy saving rate (ESR) and electricity cost saving rate (ECSR). The calculation of ESR refers to the comparison of primary energy consumption between different equipments. Meanwhile, the count of ECSR is the comparison of electricity economic efficiency of end users. The ESR of electric vapor compression heat pump shows the comparison of primary energy consumption between heat pump and traditional coal-fired boiler, as well as between heat pump and gas-wall boiler, under the same thermal load condition. Under the condition of the same heating quantity \( Q_H \) of heat pump as boiler, the ESR of heat pump is calculated as:

\[
\lambda_h = \frac{E_b - E_h}{E_b}
\]  

(3)
where $\lambda_h$ is the ESR of heat pump; $E_h$ and $E_b$ are the quantity of primary energy consumption of heat pump and boiler respectively.

The thermal efficiency of boiler $\eta_b$ is estimated as:

$$\eta_b = \frac{Q_H}{E_b}$$  \hspace{1cm} (4)

Using the PER of heat pump and the thermal efficiency of boiler, the ESR of heat pump is shown as follows:

$$\lambda_h = 1 - \frac{\eta_b}{\text{PER}}$$  \hspace{1cm} (5)

The average thermal power efficiency is 39% in 2015, China [14]; the thermal efficiency of coal-fired boiler is about 60% [15] and for gas-wall boiler is 80-96% [16]; the average COP can reach more than three for air source heat pump coupled with low-temperature hot water floor-heating system in the whole heating season [17]. What have been mentioned above are the average technical parameters in North China. For certain and calculation, the thermal power efficiency is 39%, the thermal efficiency of coal-fired and gas-wall boiler is respectively 60% and 88% average, and the COP of heat pump is three. Results calculated in Formula (5) and gained by these parameters are that, the ESR of heat pump comparing with primary energy consumption of coal-fired boiler is about 48.7%, and the ESR comparing with gas-wall boiler is about 24.8%. Results also show that under the same thermal load condition, the application of heat pump is effectively able to save the corresponding rate of non-renewable energy consumption, and reduce the corresponding rate of carbon emissions.

4. Electricity cost saving rate of heat pump

As one kind of heating equipment energy-saving and emissions-reducing, heat pump will replace boiler for heating in some conditions. Its economic benefit is affected by many factors, such as the change of investment and operating cost, the change of life cycle and depreciation of equipment. Only from the aspect of electricity cost saving rate (ECSR) of heat pump comparing with the heating operating cost of coal-fired and gas-wall boiler, this article discusses the economic feasibility of heat pump as a substitute for energy-saving and environment-protecting technology.

When the heating load is same, the economic feasibility of heat pump can be computed according to Formula (6):

$$\eta_h = \frac{m_b - m_h}{m_b}$$  \hspace{1cm} (6)

where $\eta_h$ is the ECSR of heat pump; $m_h$ is the electricity cost of heat pump and $m_b$ the fuels cost of boiler.

Combining with the thermal efficiency $\eta_b$ of boiler, the ECSR $\eta_{hc}$ of heat pump comparing with fuels cost of coal-fired boiler and the ECSR $\eta_{hg}$ comparing with gas-wall boiler can be got respectively as follows:

$$\eta_{hc} = 1 - \frac{Q_c \eta_b}{3600\text{COP}} \cdot \frac{c_p}{c_c}$$  \hspace{1cm} (7)

$$\eta_{hg} = 1 - \frac{Q_g \eta_b}{3600\text{COP}} \cdot \frac{c_p}{c_g}$$  \hspace{1cm} (8)

where $Q_c$ is the calorific value of steam-coal, kJ/kg, and $Q_g$ for residential natural gas, kJ/Nm$^3$; $c_p$ is the price of residential electricity, CNY/kW·h, and $c_c$ for steam-coal, CNY/kg, and $c_g$ for residential natural gas, CNY/Nm$^3$. 
The average technical parameters in North China above used for calculation are also given here. Namely, the thermal efficiency of coal-fired and gas-wall boiler is respectively 60% and 88% average, and the COP of heat pump is three. Here more adds the calorific value $Q_c$ of steam-coal Q5500 commonly used in thermal power plant, whose national general standard is 5,500 kcal/kg or 23,022 kJ/kg [18], and the calorific value $Q_g$ of residential natural gas whose national general standard is $3.8 \times 10^4$ kJ/Nm$^3$ [19]. Moreover, the average economic parameters in North China include the average Free-On-Board price $c_c$ of steam-coal Q5500 in the Qinhuangdao Port, which is 0.415 CNY/kg [20], the national average price $c_g$ of residential natural gas 2.48 CNY/Nm$^3$ [21], and the average price $c_p$ of residential electricity in North China 0.485 CNY/kWh [22].

According to Formula (7) and (8), results show that comparing with gas-wall boiler, the ESR of heat pump is 24.8% and the ECSR is 39.5%, while comparing with coal-fired boiler, the ESR is 48.7% and the ECSR is -49.5%. The results reveal that the operation of heat pump is more energy-saving and money-saving than utilization of gas-wall boiler. Even though the operation of heat pump is more energy-saving than that of coal-fired boiler, the former is much more expensive than the latter. Namely, heat pump has to spend 49.5% more money on heating operating cost to save 48.7% energy consumption. Energy saving loses electricity cost saving for heat pump in this case which severely lowers the energy-saving benefits and market value of heat pump.

In Formula (7) and (8), the thermal efficiency of boiler, COP of heat pump, and calorific value of fuels are all relatively stable technical parameters in a certain region and during a certain period, which are not primary causes directly affecting ECSR of heat pump. Average prices of residential electricity, steam-coal, and residential natural gas are crucial economic parameters within spontaneous economy market regulation and political active intervention both at home and abroad. Their energy price comparison $c_p/c_c$ between residential electricity price relative to heat pump and fuels price relative to boiler is decisive for ECSR, including $c_p/c_g$ between the price of residential electricity and natural gas, and $c_p/c_c$ between the price of residential electricity and steam-coal. What has been shown in Figure 3 is the impact of energy price comparison $c_p/c_c$ on ECSR $\eta_h$ of heat pump in North China. Under the aforementioned computational condition of average technical and economic parameters in North China, the critical point rate of economic benefit of ECSR in energy price comparison among prices of residential electricity, steam-coal, and residential natural gas is found, whose $c_p : c_c : c_g$ is about 2:3:8. On the basis of this critical point rate, the lower the rate is, the higher ECSR is, and $\eta_h$ is in the profit interval, which is favorable for popularizing heat pump; while the higher the rate is, the lower ECSR is, and $\eta_h$ is in the deficit interval, which is unfavorable for heat pump. The reason why ECSR comparing with coal-fired boiler is negative is because $c_p/c_c$ is 1.17 more than 0.67, whose $\eta_{hc}$ is within the deficit interval, so heat pump loses economic benefit. The $c_p/c_c$ should be controlled beneath 0.67 in order to popularize heat pump heating technology of energy-saving benefits in the central heating areas using coal-fired boiler.
Figure 3. Impact of energy price comparison $c_p/c_b$ on ECSR $\eta_h$ of heat pump in North China

Although the energy price comparison $c_p/c_b$ between residential electricity price relative to heat pump and fuels price relative to boiler is lower, the ECSR $\eta_h$ is higher. The low $c_p/c_b$ within the profit interval must be controlled within a certain range to ensure a safe and orderly economic market. Because when $c_p/c_b$ is low to a certain extent, economic market would spontaneously transform heating behavior from fossil fuel combustion into electrical heating entirely. It would lead to unbalancing the structure of energy supply as well as energy import and export, and threatening energy economy security of China. It would also threaten other social stability factors such as stable average employment rate in related fields. Nowadays, the overall situation of electricity supply in China is still relatively tense. Through the reasonable behavior of market economy and government regulation, it is feasible and desirable to raise the price comparison $c_p/c_g$ between residential electricity and natural gas, and reduce the price comparison $c_p/c_c$ between residential electricity and steam-coal in a certain extent, in order to balance energy supply structure and promote the sustainable utilization of heat pump which is energy-saving and environmentally friendly. However, meeting the demands of residents, enterprises, government and other various interests farthest, the best energy price comparison solution remains to be determined via the hearing finally.

5. Conclusions
The application of heat pump can obtain certain ESR, reduce emissions and protect environment. It is quite significant for solving energy and environment problems in China.

Under the condition of average technical and economic parameters in North China, the example shows the electricity cost comparison among the air source heat pump coupled with low-temperature hot water floor-heating system, traditional coal-fired boiler and gas-wall boiler. The results explain that the critical point rate of economic benefit of ECSR in energy price comparison among prices of residential electricity, steam-coal, and residential natural gas is about $2:3:8$. Based on it, the lower the rate is, the higher ECSR is, and ECSR is in the profit interval, vice versa. Even if heat pump has energy-saving advantages, the corresponding economic benefit may not come along with the energy price system which is not harmonious.

Through the reasonable behavior of market economy and government regulation, it is feasible and desirable to raise the price comparison $c_p/c_g$ between residential electricity and natural gas, and reduce the price comparison $c_p/c_c$ between residential electricity and steam-coal in a certain extent, in order to balance energy supply structure and promote the sustainable utilization of heat pump which is energy-saving and environmentally friendly. However, meeting the demands of residents,
enterprises, government and other various interests farthest, the best energy price comparison solution remains to be determined via the hearing finally.

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