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Whether it is economical to use combined heat and power (CHP) system for the efficient utilization of associated petroleum gas in oil extraction sites in China: A cost-benefit analysis considering environmental benefits

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The efficient use of associated petroleum gas with combined heat and power (CHP) systems in oil extraction sites has proven to be technically feasible, but its economic inefficiency continues to deter oil companies from using CHP, given that simple fuel cost reductions do not yield significant positive returns in the face of large investments in purchasing and maintaining CHP. This research constructs a cost-benefit analysis model, which includes the monetized environmental benefits generated by CHP. A pilot experiment operated in a certain oilfield in Shandong province shows that the annual difference between the reduction in fuel costs and the investment in purchase and maintenance of CHP is only about ¥210,000 per device. However, when environmental benefits including health benefit and low-carbon benefit are included in the model, the annual environmental benefits of a single equipment update can be about ¥760,000, and the overall annual net benefits will reach about ¥970,000. It is concluded that the application of CHP in oil extraction sites is economically efficient, taking into account the environmental benefit it can produce. The research results will help oil companies use CHP to make more contributions to carbon and air pollutant emission reduction. However, considering that a large number of CHP systems can form a distributed energy structure, the proposed model still has limitations.

KEYWORDS

cost-benefit analysis, associated petroleum gas, combined heat and power (CHP) system, environmental benefit, health benefit, low-carbon benefit

1 Introduction

Oil extraction sites in oilfields are ideal scenarios for applying combined heat and power (CHP) systems. It is because a) Oil extraction sites have both electricity and heat needs. There is a large amount of electrical equipment at the site, and the temperature of the freshly extracted crude oil once it enters the site needs to be maintained at around 70°C for subsequent transportation (Osintsev et al., 2019); b) CHP can use associated petroleum gas as fuel, which reduces the cost of fuel. Previously, oil extraction sites burned associated petroleum gas directly into the atmosphere through torches (Rajović et al., 2016); c) The use of CHP can reduce the emission of carbon dioxide, nitrogen oxide, and PM2.5 (Shi et al., 2022). It is because the source of electricity has changed from a coal-fired thermal power plant to CHP fueled by associated petroleum gas (Ekaterina et al., 2017; Zhu et al., 2019), meanwhile the source of heat has changed from the original heating equipment to CHP with a higher process level (Berg et al., 2019). However, previous studies have only focused on discussing whether it is technically feasible to use CHP to achieve efficient use of associated petroleum gas, neglecting whether the scheme is economical.

Regarding the application of CHP in other application scenarios (e.g. school, shopping mall, and office building), previous studies have shown that considering the high cost of purchasing and maintaining CHP, making them economical requires stringent conditions, including low operating power and low fuel prices (Ghorbani et al., 2016; Amber et al., 2018; Yang et al., 2019; Hossein et al., 2021). Although oil extraction sites can use low-cost associated petroleum gas as fuel for CHP, it is still difficult to offset the investment cost by reducing fuel costs alone, leaving oil companies unable to operate CHP at normal power levels to fully meet the sites' thermal and electrical needs. In short, if only fuel cost reduction and investment in purchase and maintenance of CHP are included in the cost-benefit calculation, it is difficult for CHP to be economical at normal power.

Previous studies have demonstrated that CHP is eco-friendly (Maurovich-Horvat et al., 2016; Perea et al., 2016; Cora et al., 2019). At the same time, China's "Dual Carbon" goals put forward higher requirements for enterprises' contribution to carbon emission reduction (Guo et al., 2022). Therefore, the environmental benefits of CHP cannot be ignored. This research monetizes the environmental benefit arising from the use of CHP and incorporates it into the cost-benefit analysis model. Through this model, this research analyzes whether the use of CHP in oil extraction sites can be economically operated at the required operating power in the face of high investment in purchase and maintenance of CHP, considering its environmental benefits and fuel cost reduction. To prove that the total benefits of using CHP are significantly higher than the investment in purchase and maintenance of CHP, a pilot experiment from an oilfield in Shandong Province is used as a case study.

This article is organized as follows: theoretical models to quantify the benefits and costs of applying CHP are presented in Section 2; empirical results are presented in Section 3; the conclusion proved by empirical findings and discussions on potential extensions and limitations of the theoretical models are presented in Section 4.

2 Theoretical models

A model for quantitative analysis of the economic benefits of using CHP is expressed as follows:

$$Eentire = \sum_{i=1}^{n} Ehealth_i + Elowcarbon_i + Efuelcost_i - Csite_i$$

where $Eentire$ is the entire economic benefit of replacing the existing supply program of electricity and heat with CHP at oil extraction sites. $Ehealth_i$ is the health benefit due to reduced emissions of air pollutants, considering that fewer people will become ill or die from air pollutants; $Elowcarbon_i$ is the low-carbon benefit due to the reduction of greenhouse gas emissions; $Efuelcost_i$ is the cost reduction value caused by the use of associated petroleum gas as fuel in CHP; $Csite_i$ is the investment in purchase and maintenance of CHP. Different subscripts of variables mean different periods reflected by the data, considering that the demand for heat will vary greatly with seasonal changes, it would be more accurate to use monthly or quarterly data. When analyzing, annual operation-related data from the target equipment and data from publicly available databases (e.g. Statistical Yearbooks of governments, National Health Commission) should be obtained.

2.1 Monetary quantification of health benefit

Switching from coal-fired power plants to CHP that burns associated petroleum gas has resulted in lower PM2.5 emissions and lower rates of respiratory and cardiovascular disease caused by an excessive level of PM2.5 in the air, resulting in health benefit. According to the environmental health value assessment theory (Huang et al., 2013; Du et al., 2021a), the following model is built:

$$Ehealth_i = Risk_{in} * C_{in}$$

where $Risk_{in}$ is the health risk change of the health effect endpoint n, which needs to be calculated by the environmental health risk assessment method (Jung et al., 2010; Faisya et al., 2018; Putri et al., 2019; Sandra et al., 2021; Thu et al., 2021); C_{in} is the value corresponding to the change in health risk per unit of health effect endpoint n, which needs to be obtained through an environmental health value assessment method (Gentry et al., 2016; Mori et al., 2019; Kim et al., 2022).

The change in health risk is based on the epidemiological "exposure-response relationship" and combined with the relative risk model using Poisson regression. Thus, the following formula is constructed:

$$Risk_{in1} = Risk_{in0} \times exp\ (\beta \times q_{ci})$$
$$Risk_{in} = P_i \times (Risk_{in1} - Risk_{in0})$$

where P_i is the number of exposed population; q_{ci} is the change in PM2.5 concentration after the power supply and heating methods of the pilot experimental site are changed; $Risk_{in1}$ and $Risk_{in0}$ are the health conditions under two concentration levels of PM2.5 (c and c_0), respectively. This research uses $Risk_{in1}$ calculated by Du (Du et al., 2021b); β is the exposure-response relationship coefficient. Previous researchers have analyzed and proposed the exposure-response relationship coefficient applicable to different regions of China (Kan et al., 2004; Xie et al., 2009; Lu et al., 2016).

For the economic loss caused by the premature death of residents caused by PM2.5, this research adopts the Value of a Statistical Life Method (VSL) to evaluate. Xie's method based on the choice experiment estimated the VSL of Beijing residents in 2010 (Xie, 2011). It is denoted as VSL_{io} and the following formula is constructed:

$$VSL_{i1} = VSL_{io} \times (Income_{i1} \div Income_{i0}) \times elasticity$$

by adjusting VSL_{i0}, we can get the latest VSL_{i1} of the residents in the oilfield. Furthermore, $Income_{i1}$ represents the *per capita* disposable income of the oilfield area; $Income_{i0}$ is the *per capita* disposable income of Beijing (Beijing Municipal Bureau of Statistics, 2010); elasticity is the income elasticity of residents.

For outpatient and inpatient expenses, this research uses the cost of disease method to estimate the formula as follows:

$$C_{in} = Cp_{in} + GDP_i \times T_{in}$$

where C_{in} is the total cost of disease caused by PM2.5 to health effect endpoint i; Cp_{in} is the medical expense per unit case of health effect endpoint i; GDP_i is the daily average of *per capita* gross national product in oilfields; T_{in} is the time lost due to illness for health effect endpoint i. The selected health effect endpoints affected by PM2.5 in this research are premature death, hospitalization for respiratory diseases, hospitalization for cardiovascular diseases, medical outpatient clinics, pediatric outpatient clinics, acute bronchitis, chronic bronchitis, and asthma (Du et al., 2021a). Among them, the disease cost method is not suitable for chronic bronchitis due to the difficulty in determining the duration of the disease. This research refers to the result of Viscusi, which is set to be 32% of VSL (Viscusi et al., 1991).

2.2 Monetary quantification of low-carbon benefit

Using CHP to generate electricity, the power generation energy is changed from coal to associated petroleum gas, and carbon dioxide emissions are reduced, hence low-carbon benefit is generated (Maurovich-Horvat et al., 2016; Cora et al., 2019).

The product of reduced greenhouse gas emissions and carbon trading price is used as the monetized low-carbon benefit. It is calculated as follows:

$$Elowcarbon_i = \left(R_i + R_i^{'}\right) \times P$$

where R_i represents the CO_2 emission reduction caused by changing the power supply source of the pilot experimental site; $R^{‘}_i$ represents the NOx emission reduction caused by changing the heating source of the pilot experimental site; P is the carbon trading price.

The formula for calculating CO_2 emission reduction in the pilot experiment is as follows:

$$R_i = e_{i1} \times Q_{i1} - e_{i2} \times Q_{i2}$$

where R_i represents the CO_2 emission reduction caused by changing the power supply source of the pilot experimental site; e_{i1} is the power carbon emission coefficient of CO_2 during coal-fired power generation; Q_{i1} is the power supply; e_{i2} is the carbon emission coefficient of CO_2 when the associated petroleum gas is burned after the use of CHP; Q_{i2} is the total amount of natural gas consumed.

The critical emission temperature of nitrogen oxides is 1,400 °C, and the higher the temperature, the more nitrogen oxides will be produced. While the original heating equipment burns at temperatures above 1,400 °C, CHP uses low-temperature combustion technology. It can control the combustion temperature at around 1,300°C (Yao et al., 2022). Therefore, compared with the original heating equipment, CHP reduces the emission of nitrogen oxides and produces low-carbon benefit. The formula for calculating NOx emission reduction is as follows:

$$R^{‘}_i = (v_{i1} \times T_{i1} - v_{i2} \times T_{i2}) \times GWP$$

where $R^{‘}_i$ represents the NOx emission reduction caused by changing the heating source of the pilot experimental site; v_{i1} represents the NOx emission rate when the original heating equipment continues to produce heat; T_{i1} represents the annual operating time of the original heating equipment; v_{i2} represents the NOx emission rate when using CHP; T_{i2} represents the annual operating time of CHP; GWP represents the global warming potential value of NOx, which is used to convert NOx into the corresponding CO_2 Emissions.

2.3 Cost reduction due to the use of oil associated petroleum gas

The emission standards of air pollutants in various regions of China are becoming increasingly strict. Considering that the new pollutant emission standards have been implemented, even oil companies have not opted for the plan to introduce CHP (i.e. the “renewal plan”), it is also necessary for oil companies to apply the plan that using low nitrogen burner and flue gas treatment equipment to meet emission standards (i.e. the “improvement plan”). Therefore, the formula for calculating the cost reduction is as follows:

$$Efuelcost_i = Pextra_i + V_{i2} \times P_{i2} + V_{i3} \times P_{i3} - V_{i1} \times P_{i1}$$

where $Efuelcost_i$ represents the value of cost reduction for the renewal plan compared with the improvement plan; $Pextra_i$ represents the cost of installing low-nitrogen burners and flue gas treatment equipment for the original heating equipment; V_{i1} represents the total amount of associated petroleum gas required under the renewal plan; P_{i1} represents the cost of using associated petroleum gas; V_{i2} represents the total amount of electricity purchased under the improvement plan; P_{i2} represents the purchase price of electricity; V_{i3} represents the total amount of natural gas of original quality required under the improvement plan; P_{i3} represents the purchase price of natural gas of original quality.

2.4 Investment in purchase and maintenance of CHP

The initial investment cost of CHP is higher than that of existing heating equipment. At the same time, the operation stability of CHP is less than that of the existing heating equipment, the maintenance cost of its operation is also higher than that of the existing heating equipment. Therefore, this research analyzes the increased investment cost of energy supply plan renewal from two directions: equipment investment cost and operation cost:

$$Csite_i = EICentire_i + EOMCentire_i$$

where $EICentire_i$ represents the difference between the annual discounted value of the equipment investment cost; $EOMCentire_i$ represents the difference between equipment operation and maintenance costs.

Given that most of the equipment investment cost is a one-time investment at the beginning of the period, this research uses the following formula to amortize the equipment investment cost for each year according to the service life of the project or equipment and the social discount rate:

$$EIC = \frac{IIC \times R \times (1+R)^T}{(1+R)^{T-1}}$$

where EIC represents the annual discounted value of the equipment investment cost, R is the social discount rate, and T is the service life of the equipment. IIC is the one-time initial investment cost of purchasing equipment. Hence:

$$EICentire_i = EIC_{i1} - EIC_{i2}$$

where EIC_{i1} represents the sum of the annual discounted value of the equipment investment cost of CHP, and EIC_{i2} represents the sum of equipment investment of the original heating equipment’s annual discounted value of cost.

$$EOMCentire_i = EOMC_{i1} - EOMC_{i2}$$

where $EOMC_{i1}$ represents the sum of operation and maintenance costs of CHP, and $EOMC_{i2}$ represents the sum of operation and maintenance costs of the original heating equipment.

3 Case analysis

Since 2021, a pilot experiment about CHP has been conducted at an oil extraction site in an oilfield in Shandong province. The pilot experiment continued for more than a year until mid-2022. After obtaining 1-year data from the pilot experiment and other publicly available data, this research introduced the data into the model constructed in Section 2 and obtained the following results.

To operate CHP continuously for 1 year at an oil extraction site to replace the previous heat and electricity supply system requires an investment of about ¥560,000 in purchase and maintenance. Correspondingly, CHP can generate about ¥730,000 in health benefit, about ¥30,000 in low-carbon benefit, and about ¥770,000 in fuel cost reductions over a year (Table 1).

Table 2 shows the details of the health benefit.

In the face of high investment in purchase and maintenance of CHP, if only the fuel cost reduction is counted as the benefit, the application of CHP can only generate a net benefit of ¥210,000, that is, a net interest rate of 27.3%. However, if the environmental benefits produced by CHP are taken into account in the cost-benefit analysis, the overall net benefit can reach ¥970,000, with a net interest rate of 63.4% (Figure 1).

In conclusion, the pilot experiment in an oilfield in Shandong Province has demonstrated that it is economical to replace the previous heat and electricity supply system with CHP at an oil extraction site after incorporating environmental benefits into the cost-benefit analysis.

4 Discussion

Previous studies on the prospect of combined heat and power for public use have shown that the high investment in purchase and maintenance of combined heat and power causes stringent conditions to make it economical, including low operating power and low fuel price. Although low fuel price can be achieved by using associated petroleum gas as fuel for oil extraction sites, keeping combined heat and power operating at low power is not

TABLE 1 Summarized benefits of applying CHP.

Category	Benefit (yuan)
Health Benefit	732,875.21
Low-carbon Benefit	29,032.59
Cost Reduction due to the Use of Oil Associated Petroleum Gas	767,461.21
Investment in Purchase and Maintenance of CHP	-556,853.20

TABLE 2 Monetary quantification of health benefit.

Disease	Health effect endpoint	Health benefit (yuan)
Premature Death	Premature Death	300,162.00
Hospitalization	Respiratory Diseases	1,476.41
	Cardiovascular Diseases	477.66
Outpatient Service	Pediatrics	173.57
	Internal Medicine	458.75
Other Illnesses	Acute Bronchitis	16,771.45
	Chronic Bronchitis	410,541.00
	Asthma	2,814.37
Total		732,875.21

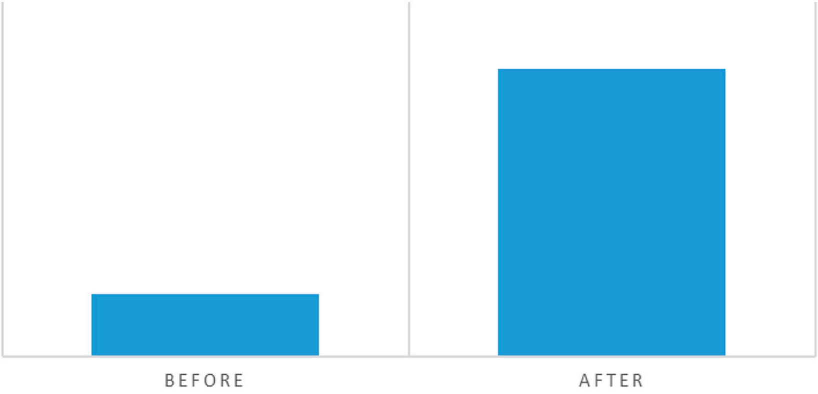

FIGURE 1
Net benefits before and after considering environmental benefits.

acceptable for oil extraction sites. Therefore, if combined heat and power is operating at normal power at oil extraction sites, oil companies are concerned about whether the simple reduction in fuel cost can make the use of combined heat and power profitable.

This research provides a model that includes monetized health and low-carbon benefits, cost reduction value, and investment in purchase and maintenance of combined heat and power. In Sections 2.1, 2.2, this research provides the idea of monetizing the economic benefits generated by combined heat and power. Using data on reductions in the number of respiratory and cardiovascular diseases and deaths among residents, this research calculates the economic benefits of reducing air pollutants (i.e. health benefit). At the same time, from the perspective that oil companies can make profits in the carbon trading market through greenhouse gas emission reduction, this research calculates the economic benefits generated by greenhouse gas emission reduction (i.e. low-carbon benefit). The calculation methods of fuel cost reduction and investment in purchase and maintenance of combined heat and power are presented in Sections 2.3, 2.4, respectively.

The model in this research helps oil companies verify whether the following conclusion holds in a specific oilfield area: When applying combined heat and power to oil extraction sites, if environmental benefits are taken into account in the cost-benefit analysis, combined heat and power can be economical at normal power operating conditions. To verify the feasibility of the model, a pilot experiment of combined heat and power in an oilfield in Shandong Province is used as a case, which successfully proves that the above conclusion is valid in the oilfield in Shandong Province. In sum, the model in this research can guide oil companies when analyzing whether to use combined heat and power in an oilfield. While promoting the reduction of air pollutant emission, the use of combined heat and power as a thermal and power supply solution for oil extraction sites will also help oil companies slow down global warming in terms of deep decarbonization to meet the 1.5°C–2°C target. Moreover, with the expansion of urbanized areas, more oil field facilities that emit pollutants that were originally far away from urban residential areas will directly affect the surrounding residents. In this case, the application of combined heat and power will not only make the oil field facilities that emit pollutants directly profit from the equipment renewal, but also alleviate the tension between them and the surrounding residents due to the emission of pollutants.

This research's model still has limitations. Considering the wide distribution and a large number of oil extraction sites in the entire oilfield area, if the number of sites using combined heat and power is large enough, the economy of scale will be formed (Carvajal et al., 2019), which makes the model in this research need to be revised. Moreover, when the site's heat and power needs are met, there is still a lot of associated petroleum gas left over (Valentin et al., 2020). The ability to integrate combined heat and power at different sites into the same power network, which could provide power not only for the site itself but also for other industrial and even civil facilities nearby (Stoltmann et al., 2019), would also generate additional benefits. Finally, the power network composed of a large number of combined heat and power belongs to a distributed energy structure. Compared with the power network from a single source, the power network with distributed energy structure has a stronger anti-risk ability in the face of power failure (Zeng et al., 2020; Chin et al., 2021; Marcos et al., 2022). The corresponding benefits will also be generated as the number of unexpected production interruptions due to power outages decreases (Kayoung Kim et al., 2017; Karyn Morrissey et al., 2018; Tensay Hadush Meles et al., 2021). For oil companies that want to use combined heat and power on a wider scale, the model needs to be revised.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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