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Promotion of distributed energy systems integrated with district cooling systems considering uncertainties in energy market and policy in China

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Abstract

The distributed energy system has attracted increasing attentions due to its high efficiency and low pollution emissions. The Chinese government has planned to promote the application of distributed energy systems using natural gas to address the atmospheric pollution problem. However, considerable uncertainties exist in energy market and policy, which would significantly affect the economic performance of distributed energy systems and make the promotion challenging. Therefore, this study attempts to investigate the impacts of energy market and policy uncertainties by evaluating the economic performance of a distributed energy system integrated with a district cooling system serving a campus in the cooling dominated area of China. Uncertainties in the following factors are taken into account: the natural gas price, the electricity price, the feed-in tariff, the incentive from the government and the carbon tax. The payback period of the distributed energy system under various uncertainties is analysed. Results show that the economic performance of the distributed energy system is satisfactory when the ratio of natural gas price to the electricity price is less than 3. .If the government plants to promote the DES, the incentive should be not less than 1300 CNY/kW or the carbon tax charged should be not less than 50 CNY/ton.

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1. Introduction

Distributed energy system (DES) integrates middle/small-scale on-site power generations with thermal energy production and/or storage devices to provide electricity, cooling and heating to end-users nearby [1]. It is regarded as an efficient, clean and reliable energy supply alternative and is attracting increasing attentions in recent decades[2, 3]. In China, the government has launched ten measures to address the pollution problem, one of which is to replace coal with natural gas for clean thermal energy supply [4]. The government plans to increase the energy consumption fraction of natural gas from 5.9% to 10% by 2020 [5]. In addition, the electrical and thermal demands keep rising due to the urbanization development [6]. Under this context, the DES based on natural gas can be an effective alternative to meet the electrical and thermal demands and improve the atmospheric environment by reducing pollution emissions[7].

DES using natural gas can generate cooling, heating and power on site and close to users. Without long distance transmission, which exists in central grid, and recover energy from exhaust gas or steam, the energy efficiency of DES is regarded to be high. The economic performance of DESs plays a significant role in the promotion of DESs. The short payback period and high benefits would attract more investment opportunities. However, large uncertainties exist in the energy markets and local policies, which would affect the economic performance of DESs. For instance, the natural gas price was fluctuated largely in 2017 due to the shortage of natural gas [8]. Even the domestic use of natural gas is limited and the local government has to implement rationing (less than i.e. 150 Nm^3/household per month) for users [9]. Without considering these uncertainties in the economic performance, the investment can be risky and the promotion of DES can be challenging.

Energy policies determine the economic performance of DESs. Currently in China, energy policies associated to DES can be categorized into two types.

i. *Compensation for the first cost based on the installation capacity of the DES.* During the installation of DESs, the local government will give financial support for investors of DESs and the value is calculated based on the capacity of the DES. For instance, the local government in Changsha announces that 2000 CNY/kW will be supported for the installation of DESs [10]. The incentive can be different in different cities (i.e. 3000 CNY/kW in Shanghai, 2000 CNY/kW in Beijing) [11].

ii. *High feed in tariff for the surplus electricity sent to the grid.* The surplus electricity generated by DESs in some cities is permitted to be sent to the grid with a higher price than that for electricity generated from the coal fired plants. The difference is usually compensated by the government to the local utilities.

Another factor that affects the application of DES is the carbon tax, which is a fee imposed on the burning of carbon-based fuels (coal, oil, gas) [12]. It is regarded as the core policy aiming to reduce and eventually eliminate the use of fossil fuels. Many countries have been implemented carbon tax, such as Denmark, Finland [13], Australia [14], South Africa [15], New Zealand [16], etc. In China, the carbon tax is still controversial and not in use yet. However, it is proved that the carbon tax is an effective policy tool because it can reduce carbon emissions with a little negative impact on economic growth [17]. The impact of carbon tax on DESs should be considered because the DES using natural gas is regarded as a clean energy supply system.

It is therefore necessary to involve all these uncertainties in energy markets and policies during the development and promotion of DESs. This study quantifies the impacts of these uncertainties on the economic performance of the DESs, aiming to provide suggestions for the promotion of DESs in China. A DES integrated with district cooling systems (DES&DCS) serving a building cluster in cooling dominated areas of China is selected. By quantifying the payback period of DES&DCS under various uncertainties, recommendations are summarized concerning the energy market and policies.

2. Method to evaluate impacts of energy market uncertainties

The methodology of this study is illustrated in Fig. 1. A DES&DCS serving a campus is selected to investigate the impacts of uncertainties in the energy markets and policies, based on historical cooling and electricity loads. The conventional system, which adopts the DCS for cooling supply and the grid is the only energy source (CES), is taken for comparison. Detailed steps are explained as follows.

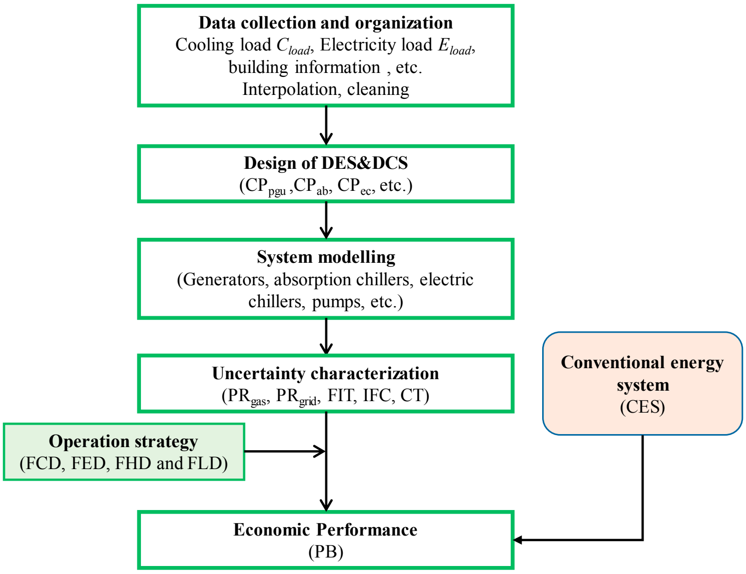


Fig. 1. The method to quantify the impacts of uncertainties in energy market and policy

(1) Data collection and organization

The annual hourly loads of buildings in a campus are collected. The electricity loads of each building are recorded by the meters of power utility. The cooling loads of each building are obtained from the building management systems (BMSs). The collected data are re-organized to keep consistent. The raw data from different BMSs have different resolutions. Some data are recorded every 15 minutes while others may be collected every 30 minutes. All these data are normalized into the same timescale, which is one hour in this study. For some BMSs, data during several hours or days may be lost or abnormal in certain periods due to various uncertainties and accidents in operation. The data therefore are carefully processed by interpolation and cleaning to ensure the consistence and completeness.

(2) DES&DCS design

The DES&DCS can be designed based on the collected electricity demand, cooling demands and the location of buildings. Absorption chillers meet partial cooling loads while the electric chillers complement to meet the excess cooling load. Based on the cooling and electricity demands, the numbers and capacities of power generator unit (PGU), absorption chillers, electric chillers, pumps and cooling towers can be designed. The hydraulic head of chilled water pumps in the DCS is calculated based on the loads of each building and the layout of the district/campus.

(3) System modelling

The performance of the DES&DCS is evaluated by modelling primary components including PGUs, absorption chillers, electric chillers, pumps, etc. The energy balance is expressed as Eq.1. Where, Q_{gas} is energy from the primary energy (natural gas), Q_e is the energy used for power generation, Q_{tml} is the energy used for cooling, and Q_{waste} is the waste energy. The electrical efficiency η_{ele} and thermal efficiency η_{tml} is expressed in Eq. 2 and Eq. 3. The electrical efficiency η_{ele} depends on the partial loads (PL_{ele}) as shown in Eq. 4. Where, $\eta_{ele.full}$ is the electrical efficiency of generators at full loads and PL_e is the part electricity load ratio of generators. When the PL_{ele} is less than 30%, the generator will shut down to avoid operating with too low efficiency. The COP_{ec} (coefficient of performance) of electric chillers also follows a curve under different partial loads [18]. The cooling water and primary chilled water pumps work at a constant speed and efficiency. Variable-speed pumps are adopted in the secondary chilled water network and the required pressure varies with the cooling loads.

$$Q_{gas}=Q_{ele} + Q_{tml} + Q_{loss} \tag{1}$$

$$\eta_{ele} = Q_{ele} / Q_{gas} \tag{2}$$

$$\eta_{tml} = Q_{tml} / Q_{gas} \tag{3}$$

$$\eta_{ele} = \eta_{ele.full} \times (a_1 \times PL_{ele}^3 + a_2 \times PL_{ele}^2 + a_3 \times PL_{ele} + a_4) \tag{4}$$

(4) Control strategy

Four commonly-used strategies are selected and tested:

- *Following the electricity demand method (FED)[19-21]:* The generators operate to meet the electricity loads. If the cooling load exceeds the capacity of absorption chillers, electric chillers start.
- *Following the cooling demand method (FCD)[19-21]:* The generators operate to meet the cooling loads. If all the generators work at full loads but still cannot meet the cooling load, electric chillers start. The lacking/surplus electricity may be imported/exported from/to the grid.
- *Following the electricity or cooling demand which requires generators to consume higher primary energy (FHD)[19]:* The operation of generators switches between the FED and FCD, which meets the cooling or electricity demand always requiring higher primary energy. This strategy would make full use of the DES. When the generators operate to meet the cooling demand, surplus electricity arises. When the generators operate to meet the electricity demand, excessive heat would be wasted.
- *Following one of the electricity or cooling demand which requires generators to consume lower primary energy (FLD):* The operation of generators switches between the FED and FCD, which meets the cooling or electricity demand requiring less primary energy. This strategy will lead to neither cooling waste nor surplus electricity. It would always need to import electricity from the grid to meet the cooling and electricity demands.

(5) Evaluation criterion

To assess the economic performance of DES compared with the system that depending on the grid (CES), the payback period (PB) is calculated as shown in Eq. 5. It represents the time required for the DES to recover the additional first cost compared with CES. Where, ΔC_{cap} and ΔC_{opr} are the capital cost difference and annual operation cost difference between DES and CES, as shown in Eq. 6~7. Where, m and n is the number of equipment in CES and DES, PR_{gas} is the price of natural gas (CNY/Nm^3), PR_{ele} and FIT are the prices of electricity and feed-in tariff (yuan/kWh), and E_{PGU} is the electricity generated by PGU (kWh), and CM_{PGU} is the maintenance cost coefficient (CNY/kWh). The equipment capital costs and other economic parameters are summarized in Table 1 [22-26].

$$PB=\frac{\Delta C_{cap}}{\Delta C_{opr}} \tag{5}$$

$$\Delta C_{cap}=\sum CAP_m \cdot C_{cap,m} - \sum CAP_n \cdot C_{cap,n} \tag{6}$$

$$\Delta C_{opr}=C_{opr,CES}-C_{opr,DES}$$

$$=(E_e+E_c)\cdot PR_{ele}-(F_{gas}\cdot PR_{gas}+E_{grid}\cdot PR_{ele}-E_{sell}\cdot FIT+E_{PGU}\cdot CM_{pgu}) \tag{7}$$

Table 1. Parameters associated with the economic performance of DES&DCSs

Item	Parameter	value
Equipment capital cost (yuan/kW)	PGU	4800
	Absorption chiller	1200
	Electric chiller	970
Maintenance cost (yuan/kWh)	PGU and others	0.0394-0.0031ln(CAPPGU)
Carbon emission factor (kg/kWh) [26]	Natural gas	0.2
	electricity	0.997

(6) Uncertainty characterization

Uncertainties that affect the economic performance of the DES can be classified into three categories as follows.

Uncertainty in the energy markets: The source includes the natural gas price, the electricity price, and the price for surplus electricity sold to the grid. The benefits of the DES are determined by these three factors simultaneously instead of one factor. Therefore, the PBs under the uncertainties of these three factors are quantified.

Uncertainty in the incentives from the government: The incentives from the government are different from region to region and even from time to time. Therefore, the PBs under different incentives for the first cost are evaluated.

Uncertainty in the carbon tax. Currently the carbon tax varies in different countries. The uncertainty in the carbon tax is considered and its impact on the PB of DES is evaluated.

It is hard to get the probability function of the above uncertainty factors but it is possible to get the intervals. Therefore, the uncertainty quantification is conducted by sensitivity analysis.

3. A DES&DCS for a campus

The campus in the Hong Kong Polytechnic University is selected to investigate the performance of DESs considering uncertainties. Information for these buildings is shown in Table 2. The electricity load and cooling loads of the campus in 2015 are collected, as shown in Fig. 2. It shows that the campus needs cooling all the year because of the subtropical climate and the cooling loads in summer are much higher. The electricity loads have no apparent fluctuations in different months. The DES&DCS can be designed based on the peak cooling and electricity loads. In this study, the capacity of generators is designed to meet the peak electricity load and the demand resulting from the pumps serving the absorption chillers. The capacity of absorption chillers accordingly can be determined based on the exhaust gas from the generator. Electric chillers are selected to complement the absorption chillers to meet the left cooling loads. The schematic diagram of the DES&DCS is shown in Fig. 3.

Table 2. Buildings and gross floor areas

Phase	**Area (m^2)**	**Phase**	**Area (m^2)**
Phase 1	47270	Phase 6	12310
Phase 2	7980	Phase 7	25000
Phase 2A/B	24420	Phase 8	44000

Phase 3A	16780	PCD	10200
Phase 3B	23400	JCA	4800
Phase 4	19330	JCIT	15320
Phase 5	10080		

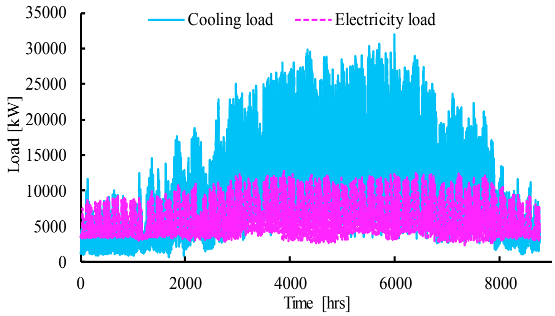


Fig. 2 Annual hourly electricity load and cooling load in 2015

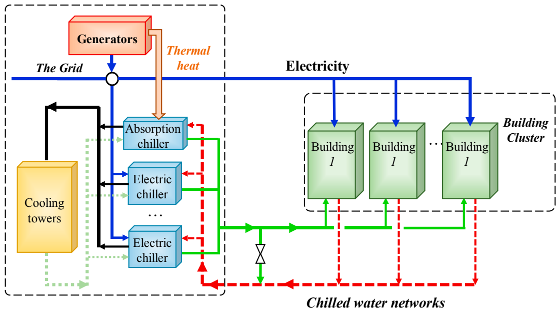


Fig. 3 Schematic diagram of the DES&DCS

4. Results and analysis

4.1. Impacts of uncertainty in the energy market

The uncertainty in the energy market includes the natural gas price, the electricity price and the feed-in tariff. These factors affect the economic performance simultaneously. The electricity price in different regions of China does not have very significant differences. However, the price of natural gas price can be very different, as shown in Table 3. It can be seen that the natural gas price ranges from 2.19 to 4.51 in different cities of China. Therefore, the ratio of the natural gas price to the electricity price (PRR) is used to quantify the uncertainty in energy market, which varies between 1 and 4. For the surplus electricity sent to the grid, the price also varies in different cities, even for different projects in one city. Therefore, the ratio of electricity price sold to the grid to that purchased from the grid (FR) is used to quantify the uncertainty.

Table 3 Natural gas prices in several cities of China

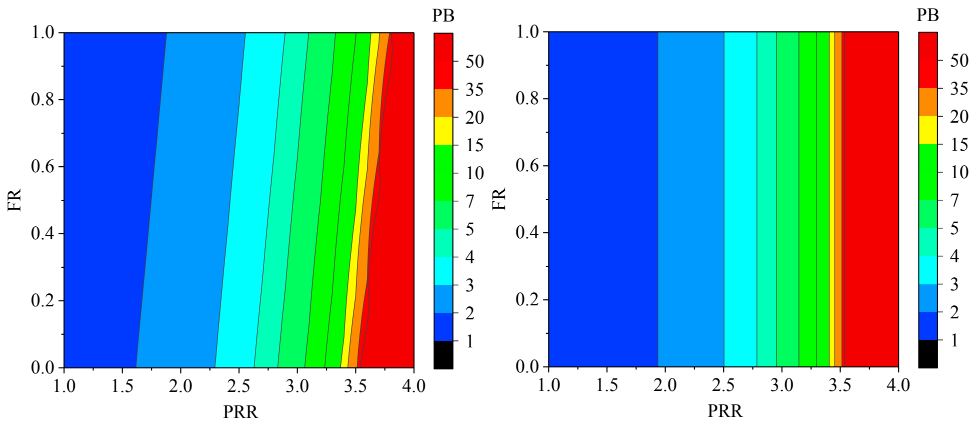
City	Residential	Industrial	Commercial	City	Residential	Industrial	Commercial
Urumqi	1.37	2.28	2.28	Shanghai	3.01	3.57	3.57
Xining	1.48	1.82	2.19	Hangzhou	3.11	3.28	3.28
Nanjing	2.51	2.99	2.99	Nanning	3.23	4.19	4.19
Wuhan	2.54	3.50	3.50	Guangzhou	3.46	4.26	4.26
Changchun	2.81	3.16	3.16	Shenzhen	3.51	4.51	4.51
Harbin	2.81	4.58	4.58	Beijing	2.29	3.23	3.23
Jinan	3.01	3.13	3.13	Tianjin	2.41	2.67	2.67

The PB of the DES&DCS controlled by FCD is shown in Table 4, considering the uncertainty in PRR and FR. It can be seen that the PB increases with the PRR and FR. When the PRR is less than 3, the investment can be paid back in 7 years. A higher FR results in a lower PB. Currently the utility company purchases the power from the coal-fired plants at a price of 0.35CNY/kWh, which corresponds to 0.35 for FR. The commonly-used FR for DESs in China is 0.8. It can be seen that if the FR is reduced from 0.8 to 0.3, the PB under different PRRs would be increased by 5% to 8%. It means that if the energy market is open and the DES has to compete with existing power plants to sell the surplus electricity to the utility company, 5%~8% more time is required to get the investment paid back. Table 4 also shows that the PRR is more significant to the PB than the FR. When the PRR is over 3.4, the PB is not satisfactory and the DES is economically infeasible.

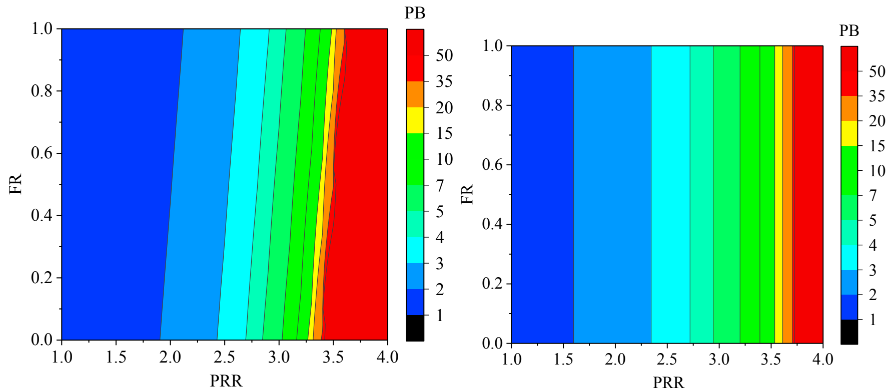
Table 4 PBs of the DES&DCS controlled by FCD considering the uncertainty in PRR and FR

PRR	FR 0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	1.53	1.52	1.50	1.49	1.48	1.46	1.45	1.43	1.42	1.41	1.40
1.2	1.66	1.64	1.62	1.61	1.59	1.57	1.56	1.54	1.53	1.51	1.50
1.4	1.81	1.79	1.77	1.75	1.73	1.71	1.69	1.67	1.65	1.63	1.62
1.6	1.98	1.96	1.93	1.91	1.89	1.86	1.84	1.82	1.80	1.78	1.76
1.8	2.20	2.17	2.14	2.11	2.08	2.05	2.03	2.00	1.97	1.95	1.92
2	2.47	2.43	2.39	2.35	2.32	2.28	2.25	2.22	2.19	2.16	2.13
2.2	2.81	2.76	2.71	2.66	2.62	2.57	2.53	2.49	2.45	2.41	2.37
2.4	3.26	3.19	3.13	3.06	3.00	2.95	2.89	2.84	2.79	2.74	2.69
2.6	3.88	3.78	3.69	3.61	3.52	3.45	3.37	3.30	3.23	3.16	3.10
2.8	4.80	4.65	4.52	4.39	4.26	4.15	4.04	3.94	3.84	3.75	3.66
3	6.28	6.03	5.81	5.59	5.40	5.22	5.04	4.88	4.73	4.59	4.46
3.2	9.09	8.59	8.13	7.72	7.35	7.02	6.71	6.43	6.17	5.93	5.71
3.4	16.47	14.87	13.56	12.46	11.53	10.72	10.02	9.41	8.87	8.38	7.95
3.6	87.05	55.58	40.82	32.25	26.66	22.72	19.79	17.54	15.74	14.28	13.06
3.8	-26.49	-32.00	-40.41	-54.83	-85.24	-191.34	781.54	128.45	69.97	48.08	36.63
4	-11.49	-12.42	-13.52	-14.82	-16.40	-18.36	-20.85	-24.12	-28.61	-35.15	-45.58

The PBs of DES&DCS under different control strategies are shown in Fig. 4. The red colour represents that the DES is not applicable where the PB is either too long (more than 50 years) or negative. It can be seen that when the PRR is low (i.e., less than 2.5), the DES controlled under the FED and FHD has shorter PBs, which should be preferred. When the PRR is higher (i.e., more than 3), the FCD and FLD should be preferred. According to the results in Fig. 4, the feasibility of the DES and the optimal control strategy can be determined. When the PRR is over 3.5, the DES is not applicable under all the control methods.



(a) FCD (b) FED



(c) FHD (d) FLD

Fig. 4 PBs of the DES&DCS under four control strategies considering uncertainty in PRR and FR

4.2. Uncertainty in the incentives

The PB of the DES&DCS considering the incentives from the government is shown in Fig. 5. The PB of the base case without any incentive is evaluated based on a PRR of 3.5 and FR of 0.8, which currently are used in many projects. It shows that the PB is 11.3, 13.1, 20.1 and 25 years under FCD, FLD, FHD and FED. It means that FCD is recommended considering the economic performance of the DES&DCS. The PB under the FHD and FED is more than 20 years, which is not acceptable. The FCD and FLD can be used with a much smaller PB. With the incentives from the government, the PB is decreased significantly. When the incentive is 1300 CNY/kW, the PB can fall in 10 years under the FCD and FLD. When the incentive is 2500 CNY/kW (used in some areas of China), the PB under FCD, FLD, FHD and FED is 5.86, 6.78, 10.4 and 12.94 years, which is acceptable. It indicates that at least 1300 CNY/kW should be supported by the government to promote the DES if the natural gas price is not decreased.

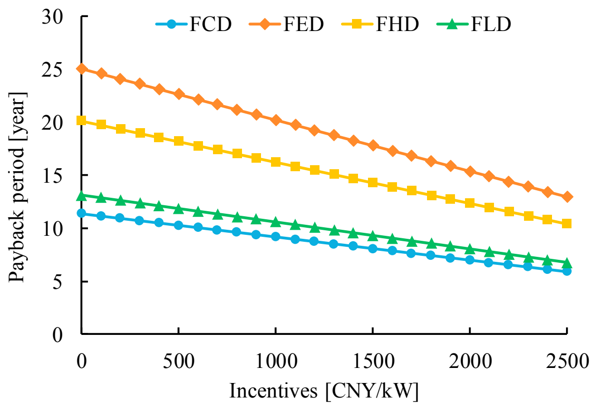


Fig. 5. PBs of the DES&DCS under different incentives

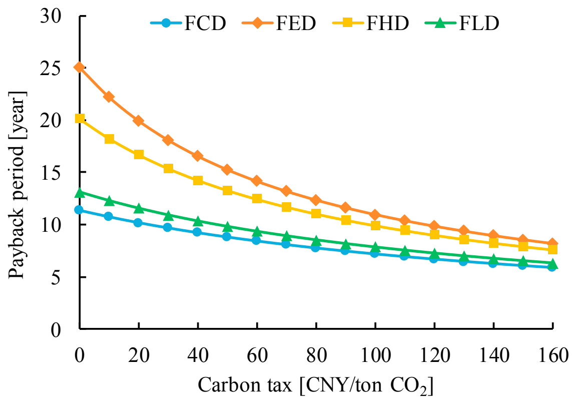


Fig. 6. PB of the DES&DCS under different carbon taxes

4.3. Uncertainty in the carbon tax

The effect of different carbon taxes on the PB of DESs is shown in Fig. 6. The range is determined by referring to existing carbon tax in other countries [13-15]. It shows that with the increase of carbon tax, the PB under the four control strategies decreases. It is because that the carbon emission of DESs using natural gas is lower than the CES depending on the grid primarily powered by coal in China. Additionally, the high efficiency of DESs will reduce the primary energy consumption. Fig. 6 shows that the PB can be less than 10 years for the DESs operated under FCD and FLD when the carbon tax is charged as 50 CNY/ton. When the carbon tax is over 120 CNY/ton, all the PBs of the DESs under four control methods fall in 10 years. It means that when the government attempts to promote the DESs via carbon tax, the minimum charge should be not less than 50 CNY/ton.

5. Conclusions

The economic performance plays a significant role in the promotion of DESs and is concerned by both investors and users. However, large uncertainties exist in the energy market and policy, which would affect the economic performance and promotion of DESs. In this paper, uncertainty in the energy market and policy and their impacts on the promotion of DES are quantified. The conclusions are obtained as follows.

1) The natural gas price has a significant effect on the economic performance of DESs. When the PRR is more than 3, the investment of DES is hard to be beneficial. The feed-in tariff also affects the PB of DESs but not as important as the PRR. If the energy market is open and the price for the surplus electricity sent to the grid is the same as that utility company pays for other plants, the PB would increase by 5%~8%.

2) The optimal control strategy varies under different PRRs and FRs. FHD is recommended when the PRR is lower than 2.5. Otherwise, the FCD should be preferred.

3) The incentives from the government can help decrease the PB of DESs dramatically. If the investment needs to be paid back in 10 years, the incentive should be not less than 1300 CNY/kW.

4) If the government attempts to promote the DESs via carbon tax, the charge should be not less than 50 CNY/(ton CO_2)

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