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Original Research

Ready-to-implement low-carbon retrofit of coal-fired power plants in China: Optimal scenarios selection based on sludge and photovoltaic utilization

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ABSTRACT

Currently the flexible demand for high proportion penetration of renewable energy depends on coal-fired units (CFUs), and the large-scale phase-out of CFUs in a short time is not realistic in China. Due to urban expansion, approximately 458 Chinese coal-fired power plants (CFPPs) are now located in cities. Limited by space, urban CFUs face difficulty in becoming equipped with carbon capture and storage systems. This presents a sizeable challenge for the low-carbon transition of urban CFPPs and carbon neutral processes. Here, we present a ready-to-implement method to reduce the carbon emission of CFPPs in limited space: roof photovoltaic-assisted power generation combined with sludge co-combustion for coal-fired power generation systems (PVSCs). We also consider nonurban CFPPs with the method of roof photovoltaic-assisted power generation (PVs) only. Based on remaining life cycle analysis, we find that the PVSCs could save 28.47 Mt of coal, reduce CO_2 emissions by 69.76 Mt, treat 125.70 Mt of sludge, and also generate 12.08 billion RMB worth of electricity revenue per year. In addition, our scenario analysis shows that PVSCs are more profitable when choosing an urban CFU with a remaining life of more than 12 years and while the sludge treatment subsidy is set at 100 RMB t^{-1}. Under strict and lenient CFU decommissioning policies, CFUs with a remaining life of between 19 and 30 years and between 13 and 24 years should be selected for PVs, respectively. Thus, we conclude that PVSCs can not only generate economic benefits but also facilitate carbon reduction and solid waste treatment.

1. Introduction

By the end of 2019 there were nearly 1000 CFPPs in China, including 2734 CFUs with a total capacity of over 1200 GW. Over 450 of these are urban CFPPs comprising 1204 CFUs that often exacerbate the difficulty of retrofitting CFUs due to their corresponding urban space constraints. In addition, China's CO_2 emissions stem almost entirely from the power sector [1], and coal-fired power generation alone accounted for 37% of China's total CO_2 emissions in 2017 [2,3]. However, flexible and adjustable power sources such as hydropower and gas turbines only account for a small proportion of China's power grid. Therefore, the flexible requirements of high penetration of renewable energy remain dependent on CFUs before large-scale energy storage technology matures. China also has more CFPPs than any other country in the world [4], and the large coal power base and the need for stable power sources have caused double pressures on the breadth and depth of low-carbon transformation in China's power industry.

However, The Chinese government has announced to the international community in 2020 a timeline for achieving the double carbon goal, only 30 years have been reserved from "carbon peak"

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to “carbon-neutral”. Faced with both domestic and international pressure for emission reduction, low-carbon development in China's power sector is inevitable [5,6]. Decarbonization in existing CFUs involves two paths. The first is to reduce the power generation of CFUs at the input end, and the second is to control carbon emissions at the output end. Both of these paths are conducive to the advancement of the low-carbon process, but further technological innovation is needed at present. For example, carbon capture and storage (CCS) technology still needs to be more innovative in terms of cost and leakage prevention [7,8].

Before the large-scale application of CCS technology, a simple and feasible low-carbon transformation model of CFUs would seemingly be of great importance. However, there are few research papers in this field so far. Jiang et al. [9] proposed the idea of the photovoltaic-assisted single CFPP and proved that their method was feasible, and one other paper evaluated the technical potential of photovoltaic-assisted CFPPs and electricity parity by using nationwide data from CFUs in 2014 [10]. However, the remaining working life of CFUs and solar irradiation levels at their locations vary greatly, and China's CFU decommissioning policy will also have an impact on the systems' benefits. Therefore, based on the data from CFUs as of 2020, solar radiation intensity, and effective roof area availability, we estimate the expected cumulative benefits of all existing CFUs in China after PVs retrofit in the future. In addition, we construct a CFU decommissioning timeline and two scenarios for decommissioning policy in order to determine optimal target selection for CFPP rooftop photovoltaic construction.

However, sludge, which has a similar calorific value to lignite and most biomass fuels, can be used as a source of power generation in its own right [11–13]. Therefore, the coupling of sludge and CFUs is also an effective method to solve the problem of urban sludge treatment [14,15]. Ma et al. empirically analyzed the Kangshun Sewage Treatment Plant Project in Jiangxi, China and found that it can save 80% on drying costs and also reduce CO_2 emissions by using flue gas from a CFU to dry wet sludge [16]. In the existing literature, the sludge blending ratio is controlled within 10% of the coal power feed, the combustion effect is predicted not to be affected, and the emission of various pollutants can meet the desired emission standards [17]. The lower the sludge moisture content, the better the combustion effect [18], and sludge with water content less than 40% can be directly fed into the boiler for co-combustion with coal. Sludge-blended combustion for power generation has been shown to have benefits in terms of energy, economy, and the environment [19–22]. However, nationwide, there are few cases of large-scale sludge treatment in CFPPs. In addition, the sludge is generally only available in sludge sewage treatment plants in cities and its use is thus more conductive to the transformation of urban CFUs. However, there is no research on low-carbon transformation of urban CFUs on a large scale. Therefore, we estimate the sludge treatment capacity of each type of urban CFU based on available data and existing research on sludge-coal co-combustion. Finally, we determine the investment payback period for different types of urban CFUs in each province after transformation and the levelized cost of sludge treatment (LCOST), the optimal target selection of CFUs in sludge-coal co-combustion retrofit program, and the potential of sludge blending for power generation.

2. System description

Based on the existing technical scheme discussed above, we propose a simple and feasible transformation scheme for CFUs. All of the approximately 1000 CFPPs could be retrofitted with photovoltaic-assisted power generation (PVs), whether urban or nonurban. Due to the availability of sludge resources, 458 of these urban CFPPs have been additionally retrofitted with sludge co-combustion system (SCs), namely roof photovoltaic-assisted power generation combined with sludge co-combustion for coal-fired power generation systems (PVSCs). Both of these changes are expected in the short term to help achieve the low carbon emissions of thermal power as well as the effective treatment of urban solid waste.

Our technical transformation scheme is constructed as follows. The main engine, power transmission, water circulation, desulfurization, chemical treatment, coal transmission, ash removal, and office areas of the CFPP building are taken as the platform on which to carry and install the solar power generation device [10]. It is assumed that all PV arrays are installed at the optimal tilt position. The PVs use photovoltaic panels with specifications of 1956 mm $\times$ 992 mm (1.94 m^2), weight of 19.5 kg, and single power output of 291 W, whose photoelectric conversion efficiency decay rate does not exceed 20% for 25 years.

China's CFUs generally use pulverized coal direct current furnaces and fluidized bed boilers. Taking fluidized beds as an example, we design a two-stage sludge dryer to dry sludge. First, mechanical dehydrated sludge with a water content of 80% is transported to the urban CFPP, then flue gas with a temperature of about 200 $^\circ$C is extracted from the flue behind the economizer to dry dehydrated sludge to a water content of 40% [16,20]. Finally, the sludge is used as fuel to co-combust with coal in order to generate electricity [21,22]. Many countries in the world face the same problems as China, and PVSCs may therefore provide a reference for the low-carbon transformation of urban CFUs throughout the world. The system concept diagram is shown in Fig. 1. Importantly, we note that our work is focused on the technical transformation solution for PVSCs, where the upstream sludge supply is taken care of by the wastewater treatment plant but where the electricity relies on the existing power infrastructure of the power plant and where the photovoltaic power is inverted and supplied to the auxiliary equipment of the power plant.

3. Data and methods

3.1. The CFUs

For this study we extracted data on China's active CFUs in 2019 from the World Coal Combustion Map database (https://www.carbonbrief.org/mapped), including statistics on the installed capacity, geographic coordinates, and the start of operations of 2734 CFUs at all 1023 CFPPs. In addition, we screened all CFPPs by Google Earth as to whether they belong to urban CFPPs, and our plant-by-plant statistics show that urban CFPPs accounted for 45% of all plants, for a total of 1204 units. We explain our formal definition of urban CFPPs in the ***Supporting Information*** for this paper. As can be seen from Fig. 2, China's CFUs are primarily distributed in North and East China, concentrated in 11 provinces. The distribution of urban CFUs, however, is concentrated in Central and Eastern China; more than 50% of urban units are located in Shandong, Jiangsu, Henan, Hebei, and Nei Mongol. Although the total number of CFUs in Nei Mongol, Shanxi, and Xinjiang ranked at the top among all provinces, the proportion of urban CFUs in these provinces was not high.

3.2. Installed photovoltaic capacity

Measuring the available roof area is a prerequisite for accounting for installed PV capacity. As CFUs are retired at different points in time, their supporting facilities and buildings may be used for other purposes, and the reduction of available roof area may become unconducive to PV installation. Therefore, we randomly

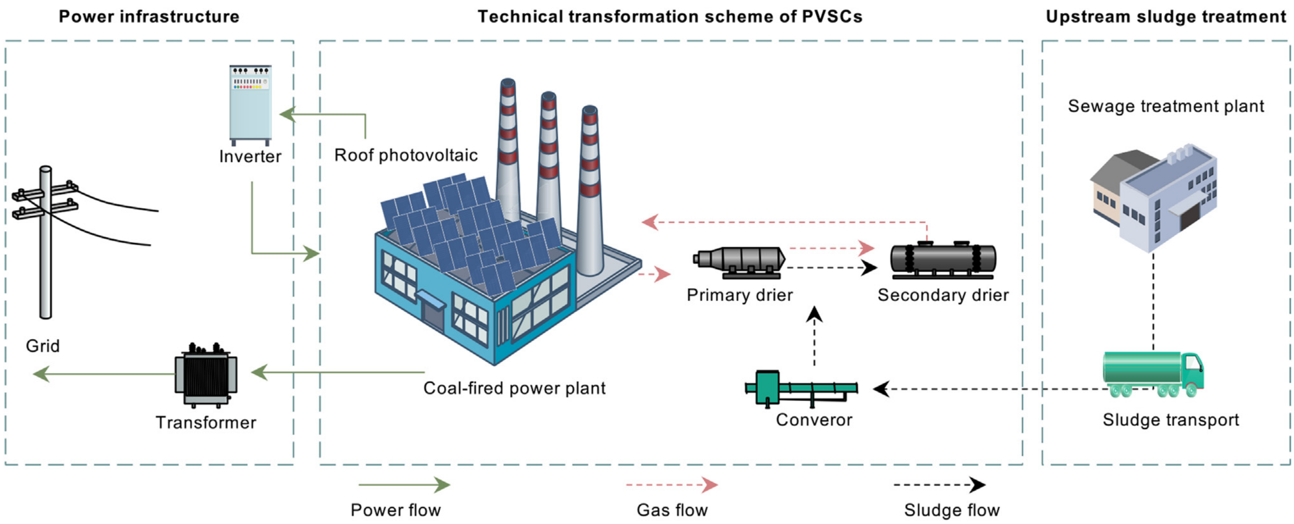


Fig. 1. The concept diagram of decarbonization transformation of urban CFUs (PVSCs).

selected CFPPs in order to measure their roof area, and the average share of available roof area for a CFU was estimated sample regression. The nationwide installed PV capacity is summarized in Table 1, and specific sampling procedures and detailed regression results are provided in the ***Supporting Information***.

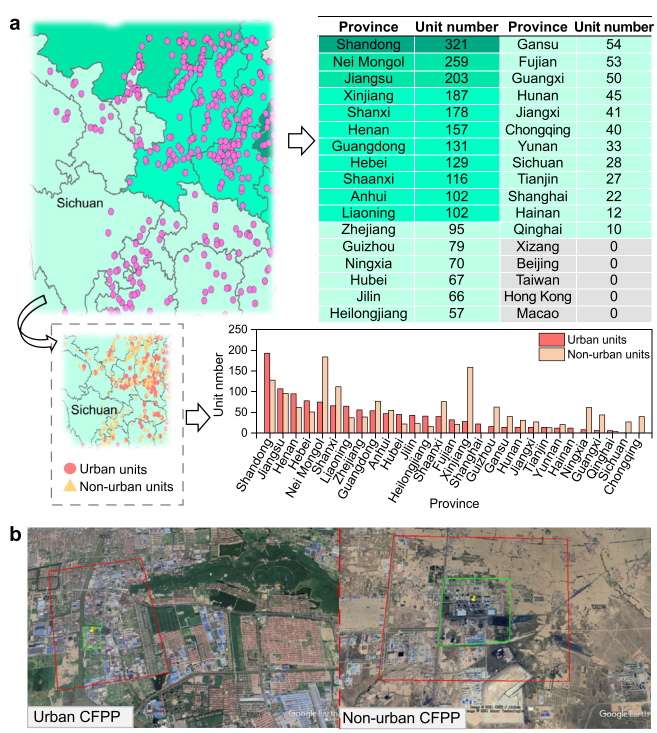
Installed PV capacity:

$$P_{ac} = \sum E_j \quad (1)$$

$$E_j = \sum \frac{S_{Xi}}{S_{PV}} \times P_{\text{single}} \times \delta \quad (2)$$

In Eqs (1) and (2), P_{ac} is the installed PV capacity in China after retrofitting, MW; E_j is the PV capacity in province j; S_{Xi} is the equalized roof area corresponding to different installed capacity CFUs, where Xi is the different CFU types (Table 1); S_{PV} is the area of one PV panel, taken as 1.94 m^2; P_{single} is the single power of PV panel, 291 W; The roofs of most CFPP buildings are close to the ideal condition for PV installations, and δ is the space utilization factor for PV installation, which is 0.9 [10]. The ***Supporting Information*** shows the detailed calculation process for photovoltaic power generation.

To minimize accounting errors, we estimated summary statistics of solar radiation intensity at the coordinate points of each CFU. Since the solar radiation data provided by the NASA database is high compared to the actual value [23], we selected the latest solar radiation intensity released in 2020 from the World Clim 2.1 database for this study, which counts the monthly average solar radiation levels for a total of 30 years from 1970 to 2000 for a total of 12 datasets with an accuracy of 1 km^2, see Figure S4. The solar radiation data at each coordinate point were extracted using the software of Geography Information System (Arc GIS), as shown in Fig. 3.



Province	Unit number	Province	Unit number
Shandong	321	Gansu	54
Nei Mongol	259	Fujian	53
Jiangsu	203	Guangxi	50
Xinjiang	187	Hunan	45
Shanxi	178	Jiangxi	41
Henan	157	Chongqing	40
Guangdong	131	Yunan	33
Hebei	129	Sichuan	28
Shaanxi	116	Tianjin	27
Anhui	102	Shanghai	22
Liaoning	102	Hainan	12
Zhejiang	95	Qinghai	10
Guizhou	79	Xizang	0
Ningxia	70	Beijing	0
Hubei	67	Taiwan	0
Jilin	66	Hong Kong	0
Heilongjiang	57	Macao	0

Fig. 2. Distribution characteristics of CFUs in China: (a) Distribution characteristics of the number of CFUs. (b) Geographical characteristics of urban and nonurban power plants.

3.3. Sludge blending

Assuming that CFUs of different installed capacities can be retrofitted without considering technical factors, we use the average annual coal consumption of a single CFU to derive its capacity for sludge treatment. However, since data on the coal consumption of a single CFU are not easily available, we estimate the average coal consumption rate, average operating hours, and average coal consumption based on available public data [24]. In addition, we do not distinguish between types of sludge, and the sludge selected for our study is from a typical municipal wastewater treatment plant.

Average annual sludge blending capacity of a single CFU:

$$C_{ij} = U_{ij} \times H_j \times E_i^R \times z \quad (3)$$

In Eq. (3), C_{ij} is the expected sludge blending volume of CFU i in province j; t; U_{ij} is the installed capacity of CFU i in province j, MW; H_j is the average annual operating hours of CFUs in province j, h; E_i^R

is the coal consumption coefficient corresponding to different installed capacities, g kWh^{-1}; R is the installed capacity of five types (Table 1); and z is the sludge blending ratio, taken as 4%. The ratio determination process is shown in detail in Section 4.1.1.

3.4. Benefit evaluation

The total benefits the PVSCs include two parts, one from PVs and the other from SCs, and the whole evaluation procedure is shown in Fig. 4. For the system of roof photovoltaic-assisted power generation (PVs), the economic benefits of PVs include three components. First is investment cost savings (C_1^{PV}); use of the original infrastructure of CFUs can save the transmission and distribution cost of PV power. Second is operation and maintenance cost savings (C_2^{PV}); due to the creation of new jobs, some employees can participate in the operation and maintenance of PVs after the CFU is decommissioned. Third is electricity revenue (I_{PV}); this is from PV power parity feed-in tariff revenue generated by PVs.

For the system of sludge co-combustion assisted power generation (SCs), the economic benefits include four components. First is the initial retrofit cost (C_1^{SS}); the system retrofit cost is about 150,000 RMB t^{-1} (80% wet sludge). Second are the operation and maintenance costs (C_2^{SS}); the unit cost of incinerating sludge using CFPPs is 100–120 RMB t^{-1} (80% wet sludge). Third is the sludge treatment subsidy (C_3^{SS}); this is received for each ton of wet sludge treated, and we take it as 200 RMB t^{-1} (80% wet sludge). Fourth is sludge blending for power generation revenue (I_{SS}); sludge blending for power generation replaces some of the coal power to generate revenue. For the investment payback period we consider the time value of money [9], and include the whole life cycle cost and benefits in our levelized cost of energy (LCOE) as they both are important economic indicators in judging the feasibility of a project. We take the internal rate of return (*IRR*) is 8% without considering the effect of bank interest, and the discount rate is taken as 5%.

PV power generation can replace part of the self-consumption of electricity, flue gas from CFUs can be used to dry sludge, and semi-dried sludge can be used as a fuel to help generate electricity. All of these processes save coal, which can generate environmental benefits. Using emission factors and environmental cost factors, we calculate the environmental benefits of reductions in four emissions: CO_2, SO_2, NO_x, and dust. To evaluate the amount of sludge that can be treated by CFUs and whether this meets the actual demand for sludge treatment, we introduce a new evaluation index, sludge treatment potential (STP):

$$STP = \frac{Q_j^{CFPPs}}{V_j \times l \times 365}. \tag{4}$$

In Eq. (4), V_j is the average daily wastewater treatment capacity of province j, 10,000 m^3, as shown in Table S6; l is the content of sludge in general municipal wastewater, where the extraction ratio is taken as 0.1%; and Q_j^{CFPPs} is the total amount of sludge that can be treated by CFPPs in province j, t. See the ***Supporting Information*** for the specific benefit calculation process.

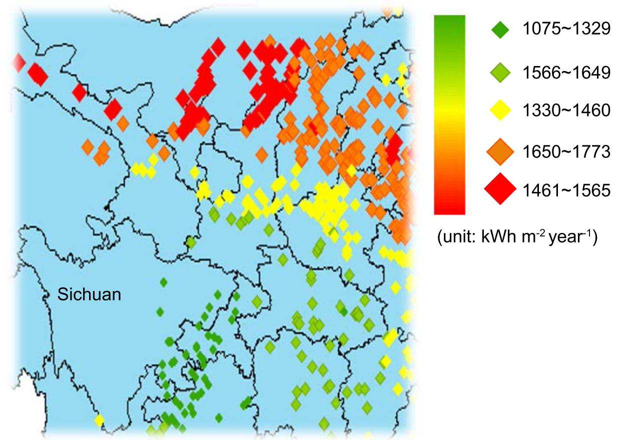


Fig. 3. Average annual solar radiation from coordinate points of CFPPs in China (kWh m^{-2} $year^{-1}$).

3.5. Scenario analysis

China is currently implementing a policy to phase out CFUs with an installed capacity of less than 300 MW, which creates uncertainty in PV installed capacity estimates. To deal with this, we have identified two scenarios. Scenario 1 is a slow policy implementation; CFUs with a capacity less than 300 MW can achieve slow retirement, and we estimate PV power generation according to the normal retirement cycle. Scenario 2 is a fast policy implementation; CFUs with a capacity less than 300 MW will be completely retired soon, and we therefore do not consider the renovation of CFUs with an installed capacity less than 300 MW in the estimation.

There is no uniform subsidy standard for sludge blending, and the existing literature sets sludge subsidies at 200 RMB t^{-1} in general. To evaluate the response of the economic benefits of sludge blending to the subsidy stimulus, we set five subsidy scenarios: 0 RMB t^{-1}, 50 RMB t^{-1}, 100 RMB t^{-1}, 150 RMB t^{-1}, and 200 RMB t^{-1} [25,26]. The effect of different sludge subsidies on the levelized cost of electricity (LCOE) of SCs and the levelized cost of sludge treatment (LCOST) was also investigated. All of the calculation processes are shown in ***Supporting Information.***

4. Results

4.1. The spatial distribution of system benefits

4.1.1. Economic and environmental benefits

As of 2019, there were a total of 1204 urban CFUs in China, 39% of which were units with an installed capacity of less than 300 MW. All existing urban CFUs are to be retrofitted with SC systems, with an aim not to affect the normal operation of CFUs. In addition, the

Table 1
The installable PV capacity of different grades of CFUs and their average coal consumption rates.

CFU type	Installed capacity of single CFU (MW)	Average roof area (m^2)	Installed capacity of PV (MW)	Average coal consumption rate (g kWh^{-1})
X1	(100) < 150	3338	0.45	617 (47–1289)
X2	(200) 150–300	4876	0.66	605 (427–861)
X3	(300) 300–500	5392	0.73	558 (322–715)
X4	(600) 500–800	9430	1.27	542 (473–851)
X5	(1000) ≥ 800	13230	1.79	328 (292–440)

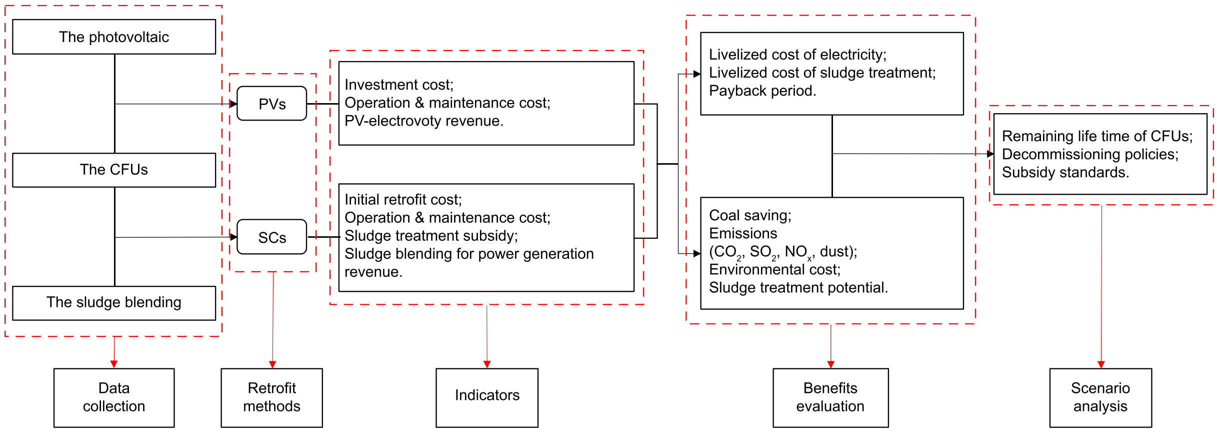


Fig. 4. Benefit calculation roadmap of PVSCs.

retrofit framework must also determine the appropriate blending ratio to meet realistic power demands and analyze the optimal scenario from the perspective of supply and demand balance for sludge volume itself. Fig. 5 visualizes the magnitude of STP in different provinces at different blending ratios. The sludge blending ratio for individual CFUs in existing studies is almost always chosen to be lower than 10%, but on a national scale, the demand capacity of urban CFUs at a 6% sludge blending ratio is much higher than the sludge supply capacity in most provinces. Therefore, different provinces need to determine their own blending ratios for themselves. In our work, a range of STP between 1 and 2 is considered reasonable in that it can balance supply and demand with fault-tolerant capacity set aside.

Using the sludge production (80% water content) of each province in 2019 as a benchmark, we have that the higher the potential capacity of CFUs to treat sludge, the lower the optimal blending ratio for that province. For example, a blending ratio of 1% in Shandong can meet the actual demand for sludge treatment, and when the blending ratio in Ningxia is 2%, the STP is exactly equal to 1. Nationally, the sludge blending ratio is concentrated in the range of 1%–4%. Therefore, considering fault tolerance capacity, we use a 4% sludge blending ratio as the optimal scenario our analysis below.

All CFUs were assumed to have a 30-year service life, and we also assume that the PV panels are retired simultaneously with the CFUs while taking into account the year-by-year decay rate. The initial investment cost of retrofitting urban CFUs nationwide with both forms of solutions is estimated at 90.81 billion RMB, with PVs and SCs accounting for 7% and 93%, respectively. After the decommissioning of a CFPP, the treatment plan is uncertain, so we ignore the residual value of the whole system. The whole system generates electricity up to 34.35 TWh per year, and upgraded plant electricity parity can lead to a gain of 12.56 billion RMB, with PVs and SCs contributing 8% and 92%, respectively. If power generation from PVs and SCs and heat required for sludge drying are converted into coal consumption, 38.59 Mt of coal can be saved annually, which is equivalent to 1.14% of the coal consumption for thermal power in 2018. The annual CO_2 emission reduction in this case would be 71.03 Mt, and the environmental benefit due to emission avoidance would be 517.96 billion RMB. Over 2200 MW of PV capacity is slated to be installed nationwide, and the cumulative PV power provided by PVs will be 47.20 TWh. We estimate that15.20 Mt of coal will be saved during the whole service period and that the PVs will generate a total of 24.42 billion RMB in benefits. Of these benefits the power revenue contribution could be as high as 67.84%, followed by investment cost savings and personnel placement costs, accounting for 30.75% and 1.41%, respectively. Furthermore, we estimate that the uniform installation of SCs in urban CFUs in service nationwide will be able to treat 125.70 Mt of sewage sludge (80% water content) per year. Without considering subsidies, the revenue generated from sludge power generation in that year could cover 13% of the investment cost of SC retrofits.

4.1.2. Provincial distribution of system benefits

The difference between the economic and environmental benefits of the PVs in each province over their entire service lives is shown in Fig. 6a. The economic benefits include the PV power benefits as well as the investment cost and operational cost savings, where we include avoided pollutant emissions as an environmental benefit. The trends of economic and environmental benefits are the same across provinces. In our analysis we weigh the implementation of retrofitting strategies in different provinces from two different perspectives, environmental and economic benefits. For example, Guangdong ranks third in terms of economic benefits but seventh in terms of potential emission reductions. The fluctuations in initial investment costs are small and do not vary greatly, but the fluctuations in PVs benefits are divided into three stages, with Shandong, Nei Mongol, and Jiangsu having high and fluctuating

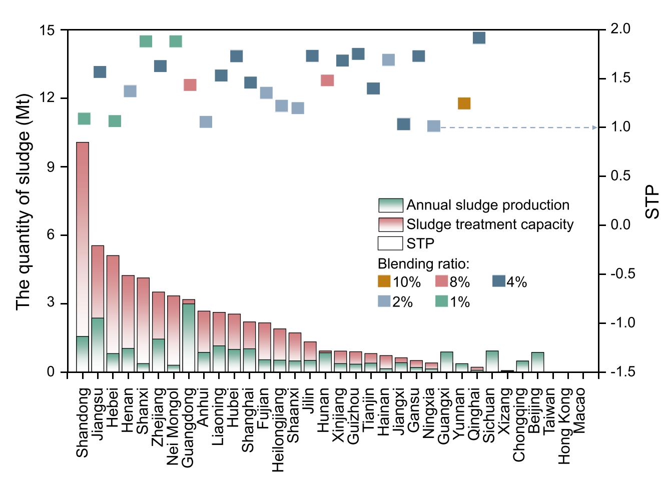


Fig. 5. A comparison of China's average sludge production in 2019 with the sludge treatment capacity of urban CFUs at a 6% sludge blending ratio and the STP in different provinces at different sludge blending ratios.

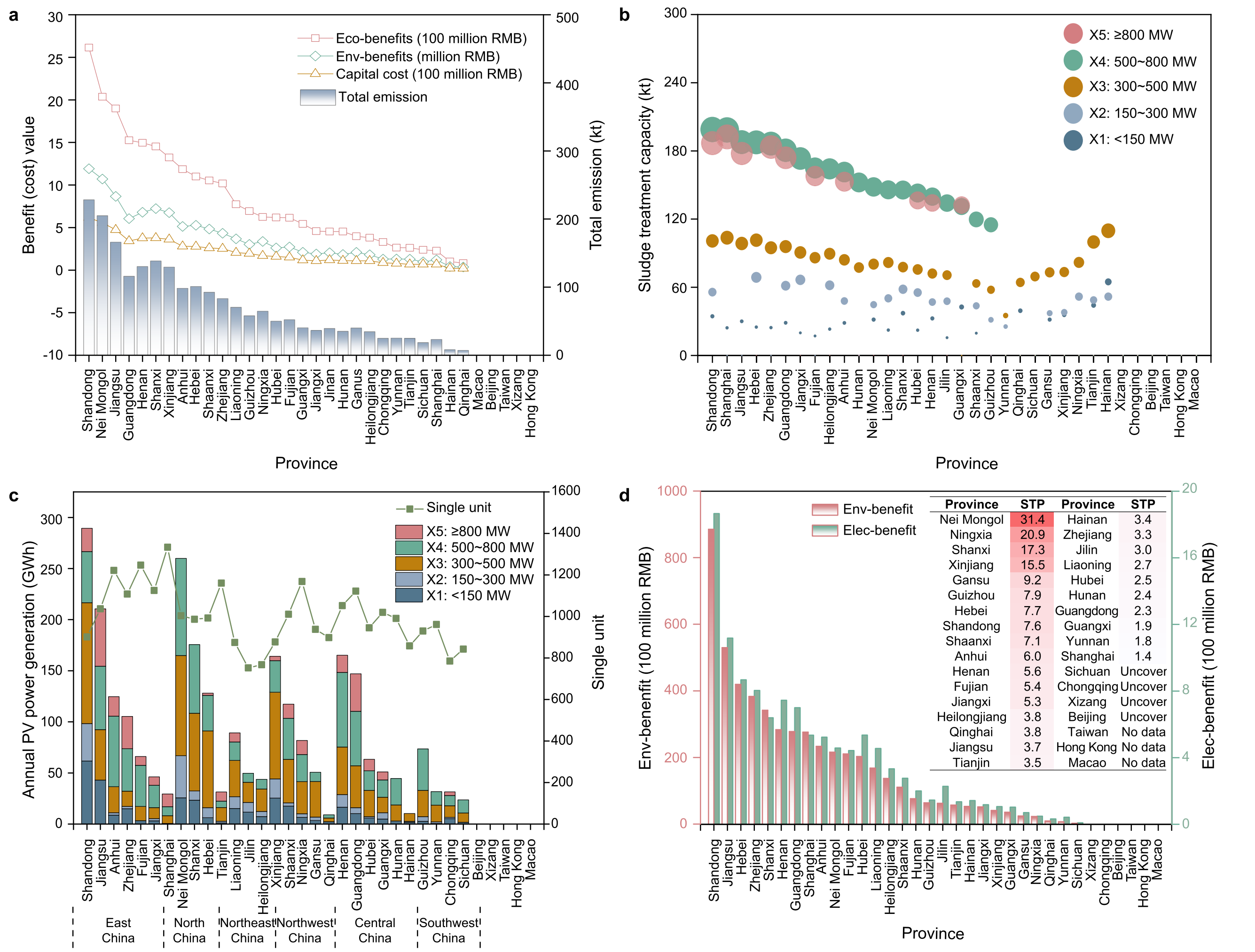


Fig. 6. Provincial distribution of system benefits. (a) Benefit evaluation of PVs in each province (differences in economic benefits, environmental benefits, initial capital cost, and total emission of CO_2, SO_2, NO_x, and dust. (b) The sludge treatment capacity of different types of urban CFUs in each province. (c) Average annual PV power generation (MWh) and total annual PV power generation (GWh) of 5 types of CFUs in different provinces after PV retrofits. (d) Differences of sludge treatment benefits and sludge treatment potential in different provinces with the sludge blending ratio of 4%.

overall benefits, and the other eight provinces being able to maintain high and less fluctuating benefits in the second stage of retrofitting. Provinces in the third stage having relatively low benefits and a steadily downward trend.

The economic and environmental benefits of SCs are closely linked to the sludge treatment capacity of single urban CFUs. Differences in the benefits of single urban CFUs in different provinces are often caused by structural differences in unit capacity, so we compared the magnitude of the sludge treatment capacity of five types of urban CFUs in different provinces as shown in Fig. 6b. The larger the installed capacity of a single urban CFU, the greater the amount of sludge that can be treated. However, nationwide, the fourth type of unit (X4: 500–800 MW) has a higher average sludge treatment capacity per unit and is more suitable to be used as a retrofit. Judging from the sludge treatment potential of each province, units of type X3, X4, and X5 are the main contributors in most provinces, so they are the first choice for PV retrofits. However, there are special cases. For example, the installed capacity of a single urban CFU in Hainan Province is generally small, while both X1 and X3 sludge treatment potentials are relatively large. Therefore, the CFUs with rank X3 are the optimal objects for some provinces that have no urban CUFs with installed capacity above 500 MW.

Fig. 6c shows the PV power generation obtained from the average of single units in each province and the annual PV power generation by region. From a single-unit perspective, the top three provinces in terms of annual average PV power generation are Shanghai (1333.46 MWh), Fujian (1247.24 MWh), and Anhui (1221.99 MWh). This difference is driven by the difference in available rooftop area among provinces, with Shanghai having the largest average available rooftop area. However, on a one-year time scale, the PV generation capacity of single units in different provinces does not follow the same trend as PV generation potential. For example, Shandong, Nei Mongol, and Jiangsu, which rank in the top three in terms of total generation potential, have an annual average generation capacity of single units that is only located at a medium level. This is because of the large number of small capacity units, involving less roof area available for PV installation and resulting in dilution of the power generation capacity of a single unit. The northwest region (Gansu and Qinghai), which is rich in solar energy resources, does not show a significant PV power generation advantage after the conversion of CFUs. However, we do find one in the eastern and northern regions, where the provinces of Shandong and Nei Mongol with a larger number of units have a greater PV power generation advantage. Most of the PVs' contribution comes from units of 300–500 MW (X3) and 500–800 MW (X4) in individual capacity as units of this size are the main contributors to China's electricity supply and have both large numbers and large roof areas available.

Fig. 6d visualizes the annual wet sludge treatment capacity of urban CFUs in each province. Under the scenario of 4% sludge blending ratio, Shandong province occupies first place with an annual wet sludge capacity of 6.71 Mt, followed by Jiangsu (3.69 Mt) and Hebei (3.40 Mt). Henan, Shanxi, Zhejiang, Nei Mongol, and Guangdong each have an annual sludge treatment capacity of more than 2 Mt. Overall, the provincial variations in sludge treatment capacity and the number of urban CFUs remain largely consistent. Sludge treatment capacity is positively correlated with electricity revenue, but the different local desulfurization benchmark feed-in tariffs lead to a mismatch in the trend of electricity revenue and sludge treatment capacity in some provinces. For example, Nei Mongol has the highest potential sludge treatment capacity in China, but the tenth highest electricity revenue. Sludge treatment potential (STP) evaluates the ratio of the amount of sludge that can be treated by an urban CFU relative to the current sludge production. A larger value of STP indicates that the sludge treatment capacity of the urban CFU in that province is high. The comparison shows that Nei Mongol has the largest STP at 31.4. Although Jiangsu, Henan, and Zhejiang have high sludge treatment capacities, their ranking of STP is in the middle to lower range because the sludge blending ratio needs to be adjusted to cope with the pressure from the gradual decommissioning of urban CFUs. However, alternative methods can be sought for sludge treatment in Xizang, Chongqing, and Beijing as there are no available urban CFUs for the retrofit of SCs. A similar situation exists in Sichuan as existing urban CFUs are still unable to cover the sludge production at a 10% blending ratio.

Table 2
Average payback period of PVs and SCs under different scenarios.

Administrative division	Province	Investment payback period (year)						
		SCs-the installed capacity of single urban CFU					PVs-the policy scenario	
		X1	X2	X3	X4	X5	Slow	Fast
North China	Tianjin	7	8	7	–	–	6	6
	Hebei	5	7	7	7	–	6	6
	Shanxi	8	9	8	9	–	7	7
	Nei Mongol	8	7	8	8	–	7	7
Northeast China	Liaoning	7	8	8	8	–	6	6
	Jilin	8	9	9	9	–	7	6
	Heilongjiang	6	8	7	7	–	7	7
East China	Shanghai	7	–	6	7	6	6	6
	Jiangsu	6	–	7	7	6	6	6
	Zhejiang	6	–	7	7	6	6	6
	Anhui	7	8	7	8	7	6	5
	Fujian	7	–	8	8	7	6	6
	Jiangxi	7	6	8	7	–	6	6
	Shandong	7	7	7	7	6	6	6
South Central China	Hunan	–	–	7	7	–	7	6
	Hubei	6	6	8	8	7	7	6
	Henan	8	9	9	9	7	7	6
	Guangdong	6	7	7	7	6	5	5
	Guangxi	10	–	–	9	7	6	6
	Hainan	7	7	7	–	–	5	5
Southwest China	Sichuan	–	–	9	–	–	7	7
	Guizhou	–	9	10	10	–	8	8
	Yunnan	–	14	20	–	–	7	7
Northwest China	Xinjiang	9	9	9	–	–	9	8
	Gansu	9	8	10	–	–	7	7
	Ningxia	–	8	9	–	–	8	8
	Qinghai	7	–	10	–	–	7	7
	Shaanxi	9	8	9	10	–	7	7

4.2. Optimal CFUs selection for PVs and SCs retrofit

4.2.1. The payback periods of PVs and SCs

All CFUs in service in China are set to be retired in the next 30 years. If we take 6 years as a basic unit of time, all CFUs can be divided into 5-unit categories (Y1: ≤6 years; Y2: 7–12 years; Y3: 13–18 years; Y4: 19–24 years; and Y5: 25–30 years) according to their remaining operation time, where CFUs in different categories will be retired during different time intervals. According to the PV capacity and sludge treatment potential of urban CFUs at different intervals in each province, the optimal units suitable for PV and SC retrofits are determined by comparing payback period and the remaining life of CFUs. As shown in Table 2, for PVs Xinjiang and Ningxia are affected by the low feed-in tariff, and their payback period is thus longer, generally taking 8–9 years. The payback period of PVs in East China is generally shorter at 6 years, and overall, the nationwide payback period is 6 years as well. Hence, we find it to be better to choose units with a remaining life of more than 6 years for PVs retrofit. For SCs, the capital payback period for investment in the fifth type of urban CFU is the shortest, generally 6–7 years. Therefore, without considering the difficulty of technical transformation, prioritizing the retrofit of large urban CFUs will result in faster payback. We see through China's administrative partition that the payback period after the transformation of urban CFUs in west China is generally longer, which is 9–10 years. The rich hydro resources in Yunnan Province lead to less coal consumption for thermal power and less sludge treatment capacity, which in turn lead to a long payback period that is not as suitable for retrofitting. The payback period in East China is generally shorter, especially in Shanghai, Jiangsu, Zhejiang, and Shandong, and all types of units here are therefore suitable for retrofitting, even suitable for use as a pilot for the national SCs retrofitting roll out. In general, all types of units in East China can be targeted for retrofitting, while the remaining areas are suitable for selecting units with larger single-installed capacity as retrofitting targets.

The CFU classifications described above are shown in Table 1, X1: <150 MW, X2: 150–300 MW, X3: 300–500 MW, X4: 500–800 MW, and X5: ≥800 MW.

4.2.2. Optimal CFUs selection for SCs retrofit

The average payback period of all provinces is 6–10 years, so we do not recommend the urban CFUs in the 1st and 2nd gradients for retrofitting. We compare the sludge treatment capacity of urban CFUs with different remaining years between different administrative subdivisions, as shown in Fig. 7, with the size of the sludge treatment potential of different provinces from top to bottom on the left and the size of the sludge treatment capacity of urban CFUs in different gradients from top to bottom on the right. The urban CFU retrofitting pilot in different regions can be selected from provinces with high sludge treatment capacity. For example, we select Liaoning in Northeast China and Hebei in North China. The focus of urban CFU selection also differs within the same administrative sub-region. For example, from the perspective of sludge treatment capacity of different capacity CFUs, CFUs in the 3rd gradients are better selected in the northeast region, while units in the 4th gradients are selected in other regions. In addition, the selection of the most suitable transformation target for different provinces can be judged according to the sludge treatment capacity of urban CFUs in different gradients. Taking Liaoning province in Fig. 7b as an example in the northeast region, Liaoning province ranks first in terms of sludge treatment capacity, and most of this sludge treatment capacity is contributed by urban CFUs with

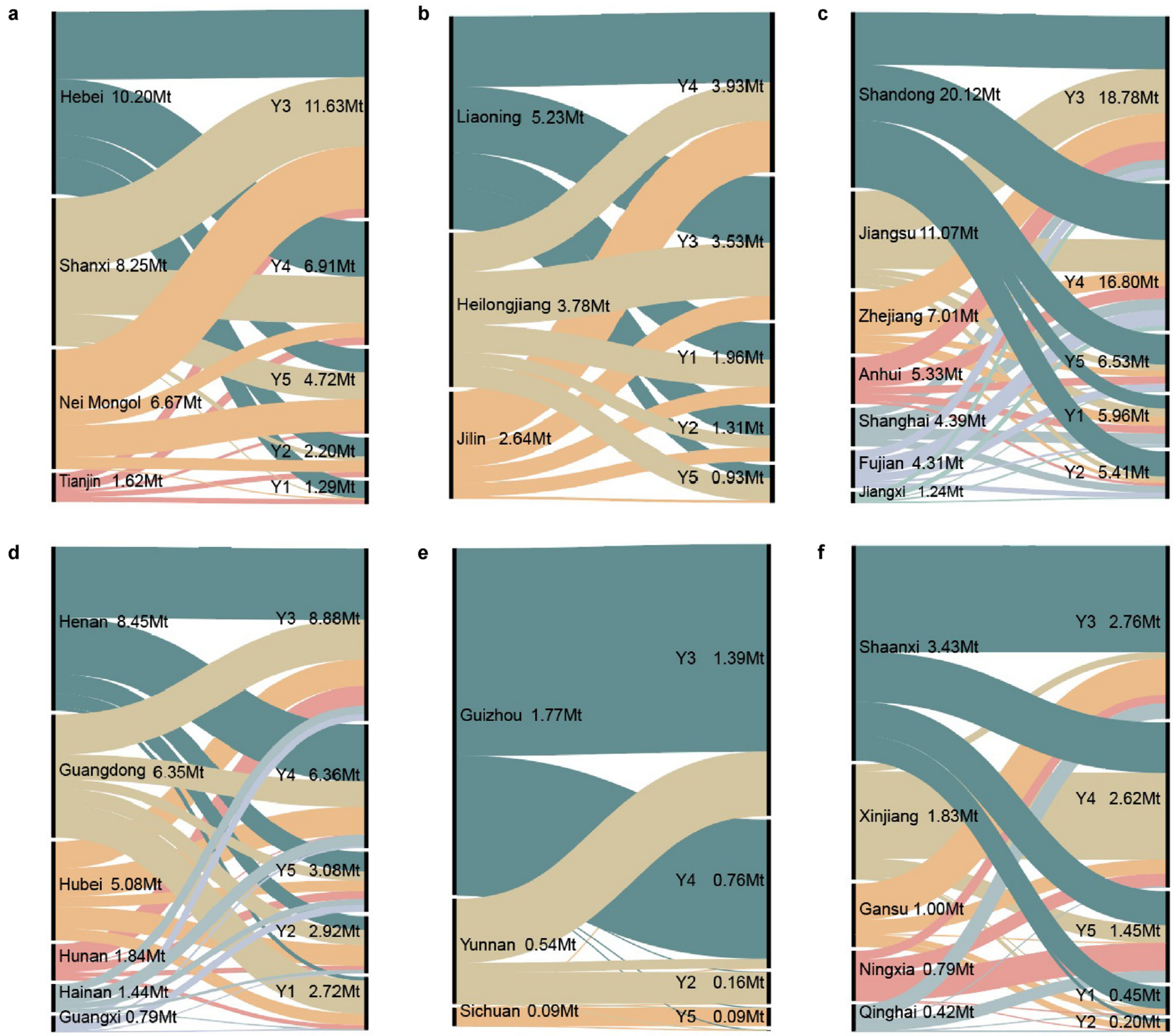


Fig. 7. The sludge treatment capacity of different gradient units (Y1, Y2, Y3, Y4, and Y5 respectively represent the service life of the unit ≤6 years, 7–12 years, 13–18 years, 19–24 years, and 25–30 years. a, b, c, d, e, and f represent the administrative divisions in China: North China, Northeast China, East China, Central China, Southeast China, and Northwest China, respectively.).

remaining lives of 13–18 and 19–24 years and contribution values of 30% and 34%, respectively. However, the payback period of the units in both gradients is 8 years, so we find it to be more optimal to give priority to choosing the units in the Y4 gradient.

4.2.3. Optimal CFUs selection for PVs retrofit

In Scenario 1, Fig. 8a presents the national ranking of PV power generation capacity by province (including all CFUs). Comparing the data characteristics of different provinces, we see that more than 66.69% of the cumulative PV power generation potential nationwide comes from the top ten provinces, namely Shandong (11.70%), Nei Mongol (10.52%), Xinjiang (8.47%), Shanxi (7.05%), Jiangsu (6.42%), Henan (5.70%), Hebei (4.95%), Shaanxi (4.55%), Guangdong (4.38%), and Anhui (4.05%), while the remaining 22 provinces and cities contribute only 32.22%. Comparing the characteristics of different gradient units, the national PV power generation is concentrated on the CFUs of the Y3, Y4, and Y5 gradient, accounting for 30.73%, 35.91%, and 27.13% of the total, respectively. The advantage of PV power generation potential in Xinjiang derives from the CFUs of the Y4 and Y5 gradients, while the advantage of PV power generation potential in Shandong and Nei Mongol stems from the CFUs of the Y3, Y4, and Y5 gradients. The other provinces have higher potential for PV power generation on the Y3 and Y4 gradient CFUs, accounting for 33.56% and 34.31% of the total power, respectively. In addition, Nei Mongol and Shandong also show high potential on the Y3 gradient with 963.81 GWh and 822.81 GWh of PV power generation, respectively. Therefore, combining our investment payback period analysis and the accumulated PV power in scenario 1, we find that Shandong and Nei Mongol should choose CFUs of the Y3, Y4, and Y5 gradient, Xinjiang should choose CFUs of the Y4 and Y5 gradient, and the remaining provinces should give priority to the renovation of CFUs of the Y3 and Y4 gradient for their optimal renovation target.

In Scenario 2, Fig. 8b compares the PV generation capacity of CFUs (excluding 300 MW units) in different provinces. Nationwide, Nei Mongol (9.94%) has the highest PV generation potential. The PV potential of the CFUs of the Y3 gradient in Shandong varies widely across policy environments, which is the result of stricter phase-out policies that leave fewer CFUs available for retrofitting. As shown in

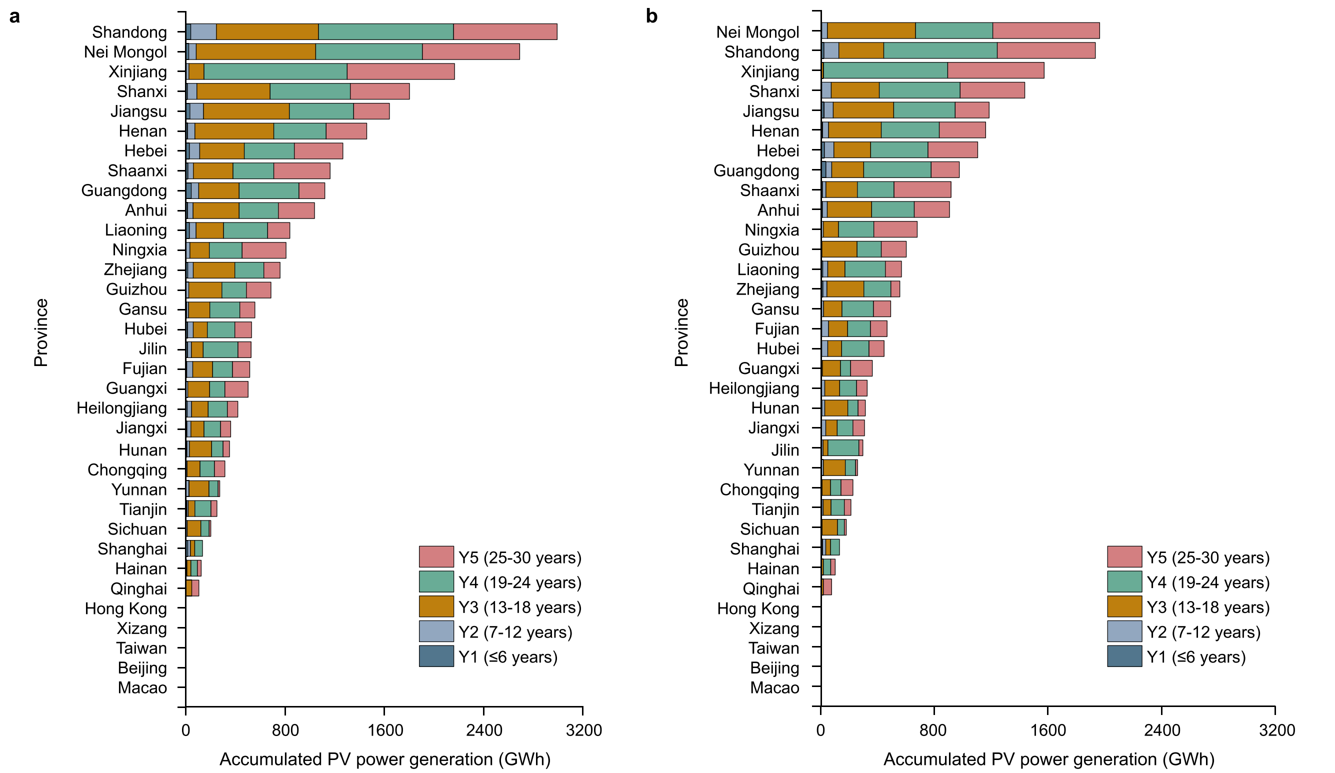


Fig. 8. Cumulative PV power generation during different time intervals. (a) Statistics for the cumulative PV power generation. (b) Statistics for the cumulative PV power generation of China's provinces (including only units with a single-unit capacity of 300 MW or more).

Fig. 8b, the maximum PV power generation potential of most provinces is in the Y4 gradient, and the top three PV power generation CFUs on this gradient are Xinjiang (873.90 GWh), Shandong (799.01 GWh), and Shanxi (569.66 GWh). In addition, Nei Mongol (753.21 GWh) and Shandong (691.20 GWh) also have large PV power generation potential on theirY5 gradient CFUs. Therefore, the target CFUs that should be selected in Nei Mongol and Shandong are first the Y5 gradient followed by the Y4 gradient, while all other provinces should give priority to retrofitting CFUs in the Y4 gradient.

4.3. LCOE for decarbonization of CFPPs

Without considering the PV power feed-in-tariff subsidy and sludge treatment subsidy, the LCOE for PVs, SCs, and PVSCs retrofits of urban CFUs range from 0.050 to 2.443 RMB kWh^{-1}, 0.339 to 4.559 RMB kWh^{-1}, and 0.044 to 4.436 RMB kWh^{-1}, respectively. After the retrofit of PVs, we expect 91.53% of the urban CFUs to have LCOEs better than the national average tariff (0.3642 RMB kWh^{-1}). However, the LCOEs of SCs are mostly higher than the national average tariff without considering the sludge treatment subsidy, which is only 2.16% better than the national average, and all of these units have a single installed capacity of 800 MW or more. Obviously, SC retrofits of only urban CFUs does not bestow a universal benefit. However, after retrofit of PVSCs, we expect that 62.96% of the urban CFUs will have PVSC LCOEs better than the national average tariff. Comparing Fig. 9a, b, and 9c, we see that the sludge blending component has a greater impact on the total LCOE of the PVSCs and that the addition of PVs reduces the peak LCOE of the whole PVSCs.

There is no doubt that PV will achieve grid parity in the long term, so here we do not consider the subsidy of PV power generation. However, the economic benefit of sludge blending relies heavily on government subsidy, so we design LCOST parameters for sludge blending and discuss the difference between the LCOE of sludge blending power generation and the national average electricity price under five different subsidy scenarios. The five scenarios correspond to five kinds of sludge treatment subsidies. Scenario 1 has zero subsidies and is therefore the reference scenario. Scenarios 2, 3, 4, and 5 are subsidies of 50 RMB, 100 RMB, 150 RMB, and 200 RMB per ton of wet sludge treated, respectively. As shown in Fig. 9d, LCOST gradually decreases as subsidies grow, with LCOST close to 200 RMB t^{-1} in scenario 1, and LCOST is negative in scenario 5. Additionally, with an increase in subsidies, the proportion of the LCOE for sludge blending over the national average tariff grows rapidly. From scenario 1 to scenario 5, the proportions are 2.16%, 3.65%, 79.32%, 90.95%, and 95.02%, respectively. Clearly, the cost of SCs depends greatly the amount of subsidy. In addition, the compensating effect of subsidized sludge blending economics is not always present as it has a threshold of around 100 RMB t^{-1}. When the subsidy is less than 100 RMB t^{-1}, the proportion of units that meet the economics of the subsidy increase grows rapidly. However, when it is greater than 100 RMB t^{-1}, the stimulating effect of the increase in subsidy is far less.

5. Discussion

5.1. Uncertainty analysis

The assessment of a system's effectiveness will be influenced by the type of sludge it uses. However, selecting the right type of sludge for all units is not practical here. Since the type of sludge can be reflected by different calorific values, we can effectively estimate the interval of specific benefits by setting the maximum and

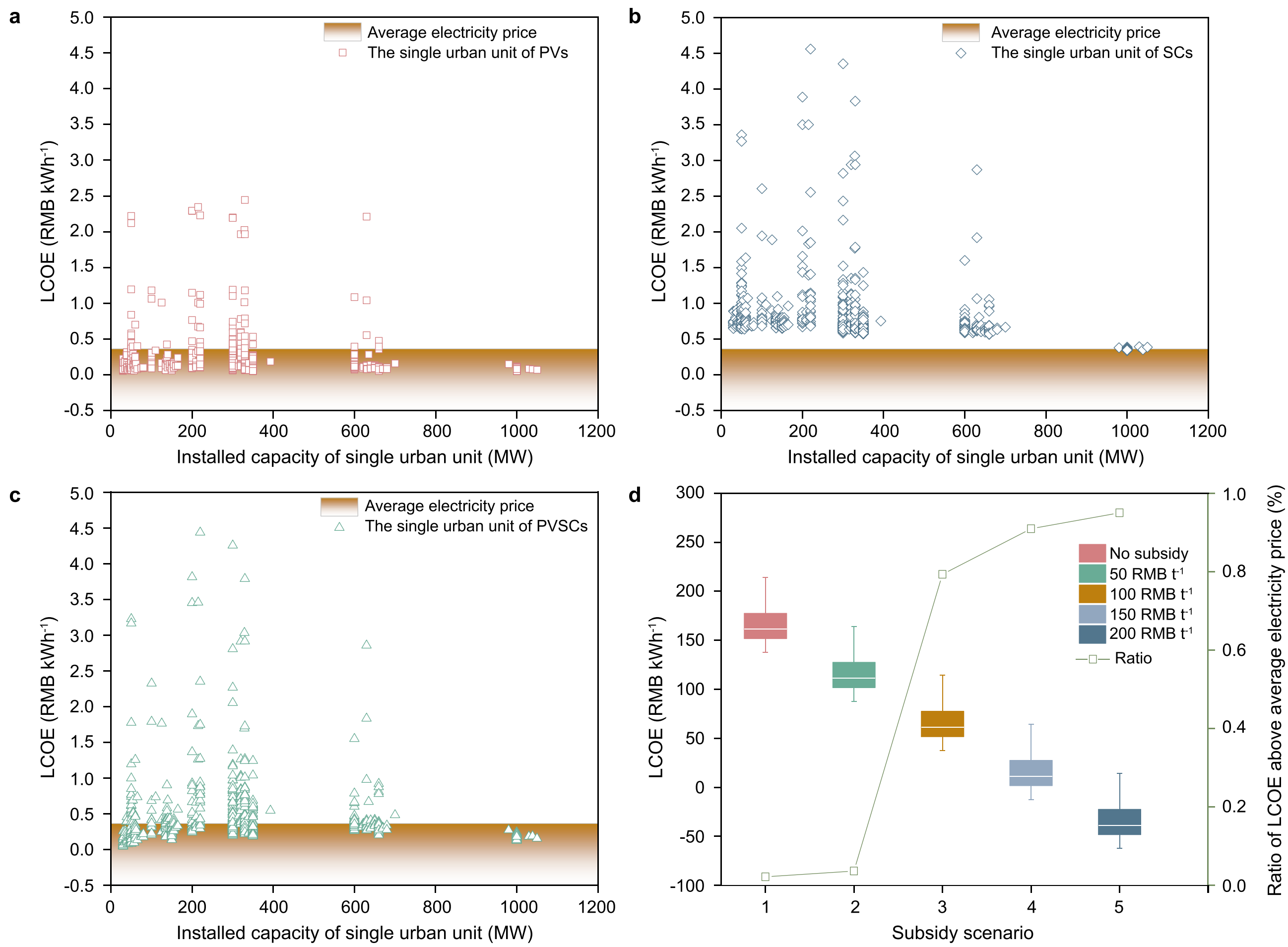


Fig. 9. LCOE for decarbonization retrofitting of urban CFUs and LCOST for SCs. (a) LCOE for a single unit of PVs. (b) LCOE for a single unit of SCs. (c) LCOE for a single unit of PVSCs. (d) LCOST of SCs in 5 different subsidy policies.

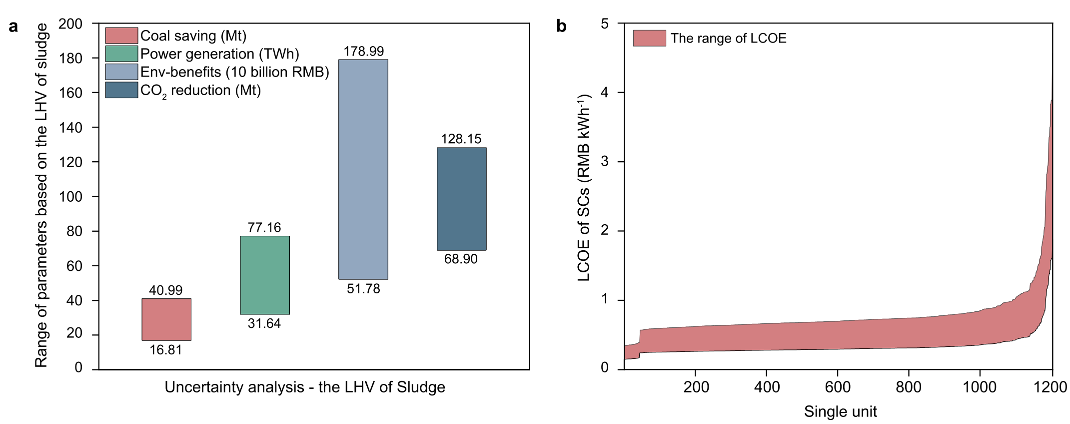


Fig. 10. The uncertainty analysis caused by the LHV of sludge. (a) The range of four basic indicators in the highest and lowest calorific value scenarios, namely 9062 to 22,100 kJ kg^{-1}. (b) The fluctuation range of the LCOE of a single CFU caused by the LHV of sludge after the retrofitting of SCs.

minimum values. Fig. 10 shows the variation of specific indicators for the highest and lowest sludge calorific value scenarios. When the calorific value is set to a maximum of 22,100 kJ kg^{-1}, the fuel properties of the sludge are closer to those of fuel coal and more coal can thus be saved. A unit's coal consumption rate is also an influencing factor. As shown in Table 1, we have selected the average value for estimation among the coal consumption rate data obtained statistically for each type of unit.

5.2. The scale effect and subsidy

The implementation and large-scale use of PVs and PVSCs can help reduce the use of carbon-based energy and ease the pressure of emission reduction through the nationwide decarbonization of CFUs, facilitating the gradual integration of the thermal power industry with renewable energy sources. With SC-only retrofits alone, only 2.16% of urban CFUs have an LCOE above the national average tariff, but the coupling of SCs and PVs for urban CFUs raises that percentage to 62.96%. Moreover, we expect this percentage to keep increasing as it becomes stimulated by subsidies for sludge treatment. In order to make more urban CFUs profitable in decarbonization, a high priority therefore needs to be set for the role of PV assistance and subsidized incentives. Although our analysis shows that our new program design looks profitable overall, multiple leaders may not be agree to a unified pace of transformation due to the scattered locations of urban CFUs and their affiliation with different enterprises. Therefore, we also recommend that the Chinese government should encourage the thermal power companies in the region to negotiate a joint installation program by means of public bidding that we expect to from a scale effect that can help reduce costs.

5.3. Selection of pilot provinces

The provinces with high PV power potential and low STP should be prioritized for CFU retrofitting. Nearly 50% of PV power potential is concentrated in six provinces: Shandong, Nei Mongol, Xinjiang, Jiangsu, Shanxi, and Henan. Therefore, more PV power can be obtained by retrofitting in these areas. In addition, the focus should be on the provinces where the economic and environmental benefits are expected to be high, especially in Shandong and Nei Mongol. We therefore recommend that provinces with PV power generation capacity be used as construction pilots for the photovoltaic-assisted power system. Shanghai (133.46 MWh), Fujian (1247.24 MWh), and Anhui (1221.99 MWh) are among the top three provinces in terms of single CFU PV power generation, and the construction of demonstration bases in these provinces may help to realize the transformation results more quickly. The purpose orientation of SCs is different from the PV system, and to solve the disposal problem of urban sludge the provinces with high sludge production, Guangdong (2.98 Mt), Jiangsu (2.36 Mt) and Shandong (1.56 Mt), should be enlisted first to help meet the actual demand. To consider the appropriate blending ratio is also of great importance. For example, Nei Mongol can treat all its sludge by choosing a 1% blending ratio. Furthermore, with a highest, 10% blending ratio, the sludge treatment capacity of urban CFUs in some provinces still does not cover all sludge production and the focus in these areas should therefore be on other sludge treatment location options, such as Chongqing, Sichuan, and Guangxi.

5.4. Selection of optimal CFUs

Since the cumulative power generation potential of PVs is affected by remaining operating time and since the implementation effect of the decommissioning policy varies widely among different CFUs, in order to promote the retrofit of CFUs sustainably and scientifically, provincial policymakers should plan a reasonable transition path based on the decommission policy of CFUs and the remaining life of their CFUs. When the policy environment is relaxed, except for Shandong and Nei Mongol, which should focus on CFUs of the Y3, Y4, and Y5 gradients, and Xinjiang, which should focus on CFUs of the Y4 and Y5 gradients, the remaining provinces should give priority to CFUs of the Y3 and Y4 gradients as the optimal transformation target. However, when the policy environment is tight, all provinces should focus on CFUs of the Y4 gradient as the optimal target, except for Nei Mongol and Shandong where the target CFUs should be chosen first from the Y5 gradient.

The selection of optimal targets for SCs should consider the payback period and sludge treatment capacity. First, the average payback period for all types of urban CFUs is over 5 years, and we exclude Y1 CFUs from selection. From a national perspective, the CFUs of Y3 and Y4 are the main contributors for sludge treatment. Second, the payback period of CFUs with different installed capacity varies greatly across administrative divisions; all types of urban CFUs (X1, X2, X3, X4, and X5) are targets for retrofitting of SCs in East China and South Central China. In conclusion, in the case of taking into account the payback period, the CFUs with largest capacity should be preferentially selected as much as possible.

6. Conclusions

This paper evaluates the potential benefits of PVSCs for urban CFUs and PVs for nonurban CFUs, respectively. We find that the cumulative annual emission reduction of CO_2 from the PVs will reach 2.13 Mt and that the fixed asset investment will be reduced by 7.51 billion RMB by using the existing power infrastructure of CFUs for transmission, distribution, and substation of PV power. Furthermore, retrofitting can solve the problem of transferring at least 1821 employees and directly save 341 million RMB in salary expenses. In addition, if all the PV power generated is uploaded to the grid, the total revenue of PV power generation can reach 16.57 billion RMB. Without considering the difficulty of technical transformation, the existing urban CFUs are set to be transformed and SCs to be added. As we find that the drying and blending process saves 28.12 Mt of coal, the annual emission reduction of CO_2 is estimated to be 68.90 Mt. The heat provided by sludge blending alone can provide 11.68 billion RMB of revenue when converted to electricity. Therefore, we expect the decarbonization retrofit method for CFUs to generate both economic and environmental benefits not only for China but possibly for other countries as well.

Without considering subsidies, we estimate the LCOE of PVSCs to be 0.044 to 4.436 RMB kWh^{-1}, which is mostly influenced by the cost of the SCs. When the subsidy is about 100 RMB per ton of wet sludge treatment, we find that more than 80% of CFUs have good economic benefits after retrofitting. The results of our scenario analysis show that under the slow policy, more than 30% of the PV power potential originates from Shandong, Nei Mongol, and Xinjiang and that CFUs with Y3, Y4 and Y5 are optimal targets for retrofitting of PVs. Under the fast policy, the national PV power potential contributed by Shandong, Nei Mongol, and Xinjiang decreases to 27.68%, and the CFUs with Y4 and Y5 become the optimal targets for retrofitting PVs. In addition, when we consider the payback period, we find that the urban CFUs with installed capacity with X3, X4, and X5 and remaining lives in the Y3 and Y4 gradients are more suitable as the optimal target for SCs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2022.100147.

References

[1] L. Du, J. Mao, Estimating the environmental efficiency and marginal CO 2 abatement cost of coal-fired power plants in China, Energy Pol. 85 (2015) 347–356.

[2] J. Fan, S. Wei, S. Shen, M. Xu, X. Zhang, Geological storage potential of CO2 emissions for China's coal-fired power plants: a city-level analysis, Int. J. Greenh Gas Con. 106 (2021) 103278.
[3] NBS, China Energy Statistical Yearbook, 2019.
[4] G. He, J. Lin, F. Sifuentes, X. Liu, N. Abhyankar, A. Phadke, Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system, Nat. Commun. 11 (2020).
[5] Y. Yu, Z. Jin, J. Li, L. Jia, Low-carbon development path research on China's power industry based on synergistic emission reduction between CO2 and air pollutants, J. Clean. Prod. 275 (2020) 123097.
[6] X. Ma, Y. Wang, C. Wang, Low-carbon development of China's thermal power industry based on an international comparison: review, analysis and forecast, Renew. Sustain. Energy Rev. 80 (2017) 942–970.
[7] X. Zhang, X. Ma, Y. Wu, Q. Gao, Y. Li, A plant tolerance index to select soil leaking CO2 bio-indicators for carbon capture and storage, J. Clean. Prod. 170 (2018) 735–741.
[8] Y. Tan, W. Nookuea, H. Li, E. Thorin, J. Yan, Property impacts on carbon capture and storage (CCS) processes: a review, Energ. Convers. Manage. 118 (2016) 204–222.
[9] M. Jiang, Y. Lv, T. Wang, Z. Sun, J. Liu, X. Yu, J. Yan, Performance analysis of a photovoltaics aided coal-fired power plant, Energy Proc. 158 (2019) 1348–1353.
[10] M. Jiang, J. Li, W. Wei, J. Miao, P. Zhang, H. Qian, J. Liu, J. Yan, Using existing infrastructure to realize low-cost and flexible photovoltaic power generation in areas with high-power demand in China 101867: 2589-0042, iScience 12 (2020) 101867.
[11] M.B. Folgueras, M. Alonso, J.R. Folgueras, Effect of sludge addition to coal on Na, K and S volatilisation in ashing process and ash fusibility, Fuel Process. Technol. 138 (2015) 714–723.
[12] D. Vamvuka, S. Sfakiotakis, S. Saxioni, Evaluation of urban wastes as promising co-fuels for energy production – a TG-MS study, Fuel 147 (2015) 170–183.
[13] G. García, J. Arauzo, A. Gonzalo, J.L. Sánchez, J. Ábrego, Influence of feedstock composition in fluidised bed co-gasification of mixtures of lignite, bituminous coal and sewage sludge, Chem. Eng. J. 222 (2013) 345–352.
[14] C. Xu, W. Chen, J. Hong, Life-cycle environmental and economic assessment of sewage sludge treatment in China, J. Clean. Prod. 67 (2014) 79–87.
[15] J. Hong, C. Xu, J. Hong, X. Tan, W. Chen, Life cycle assessment of sewage sludge co-incineration in a coal-based power station, Waste Manag. 33 (2013) 1843–1852.
[16] X. Ma, H. Weng, M. Su, L. Pan, Drying sewage sludge using flue gas from power plants in China, Environ. Earth Sci. 65 (2012) 1841–1846.
[17] Q. Zhang, Q. Zhou, J. Liang, Research and practice of coal burning coupled sludge combustion technology, Ind. water Treat. 39 (2019) 7–11.
[18] A. Abuşoğlu, E. Özahi, A. İhsan Kutlar, H. Al-jaf, Life cycle assessment (LCA) of digested sewage sludge incineration for heat and power production, J. Clean. Prod. 142 (2017) 1684–1692.
[19] L. Chen, Y. Liao, X. Ma, Economic analysis on sewage sludge drying and its co-combustion in municipal solid waste power plant, Waste Manag. 121 (2021) 11–22.
[20] J. Chen, Y. Sun, Z. Zhang, Evolution of trace elements and polluting gases toward clean co-combustion of coal and sewage sludge, Fuel 280 (2020) 118685.
[21] K. Lei, R. Zhang, B. Ye, J. Cao, D. Liu, Combustion of single particles from sewage sludge-pine sawdust and sewage sludge-bituminous coal under oxy-fuel conditions with steam addition, Waste Manag. 101 (2020) 1–8.
[22] B. Fu, G. Liu, M.M. Mian, C. Zhou, M. Sun, D. Wu, Y. Liu, Co-combustion of industrial coal slurry and sewage sludge: thermochemical and emission behavior of heavy metals, Chemosphere 233 (2019) 440–451.
[23] Q. Yang, T. Huang, S. Wang, J. Li, S. Dai, S. Wright, Y. Wang, H. Peng, A GIS-based high spatial resolution assessment of large-scale PV generation potential in China, Appl. Energ. 247 (2019) 254–269.
[24] S. Zhou, W. Wei, L. Chen, Z. Zhang, Z. Liu, Y. Wang, J. Kong, J. Li, Impact of a coal-fired power plant shutdown campaign on heavy metal emissions in China, Environ. Sci. Technol. 53 (2019) 14063–14069.
[25] L. Chen, Y. Liao, X. Ma, Economic analysis on sewage sludge drying and its co-combustion in municipal solid waste power plant, Waste Manag. 121 (2021) 11–22.
[26] P. Tan, L. Ma, J. Xia, Q. Fang, C. Zhang, G. Chen, Co-firing sludge in a pulverized coal-fired utility boiler: combustion characteristics and economic impacts, Energy 119 (2017) 392–399.