



A permit trading scheme for facilitating energy transition: A case study of coal capacity control in China

Xunpeng Shi ^{a, b}, Ke Wang ^{c, d, e, *}, Yifan Shen ^f, Yu Sheng ^g, Yanfang Zhang ^h

^a Australia-China Relations Institute, University of Technology Sydney, Ultimo, NSW, 2007, Australia

^b Center of Hubei Cooperative Innovation for Emissions Trading System & School of Low Carbon Economics, Hubei University of Economics, Wuhan, Hubei, 430205, China

^c Center for Energy and Environmental Policy Research & School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China

^d Sustainable Development Research Institute for Economy and Society of Beijing, Beijing, 100081, China

^e Beijing Key Lab of Energy Economics and Environmental Management, Beijing, 100081, China

^f Institute of Politics and Economics, Nanjing Audit University, Nanjing, China

^g School of Advanced Agricultural Sciences, Peking University, Beijing, 100871, China

^h College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China

ARTICLE INFO

Article history:

Received 23 September 2019

Received in revised form

16 December 2019

Accepted 6 February 2020

Available online 8 February 2020

Handling Editor: Yutao Wang

Keywords:

Production capacity control

Cap and trade

Permit trading scheme

China

Coal

ABSTRACT

Restriction the production and consumption of fossil fuels is a necessary part in the energy transition. How to implement such restriction effectively is an issue that is of public interest to both academia and policy makers. Using production data of more than 1100 coal mines in China, we show that a capacity permit trading system originated from cap and trade practice could help the coal industry to save more than 30 percent of inputs and increase income by 26 percent. The results also demonstrate that the permit trading will lead to Pareto improvement for all participating provinces when compared with the capacity control administratively, and the accumulative welfare will increase as the trading zone is enlarged. The study suggests that adopting the permit trading schemes for capping policies is economically beneficial and politically feasible.

© 2020 Elsevier Ltd. All rights reserved.

1. Introduction

The energy transition involves a gradual process of shifting the fossil fuel production and consumption towards more cleaner energy products, in which capping the capacity of fossil fuel production and consumption is an essential part (Shi et al., 2018; Suwala and Labys, 2002). As the proportion of low carbon fuels in total energy consumption increases, the consumption and corresponding production of fossil fuels will decline, causing a premature retirement of trillions of assets and a loss of millions of jobs. The current practice of reducing capacity through administratively closing mines may not be efficient. Given the similarity between capacity cut and emission control, a permit trading scheme is

considered to be useful to achieve the capacity control goal with higher efficiency than the administrative measures (Shi et al., 2019). However, there is no empirical study to quantify the benefit of such a market instrument.

China coal industry provides a good example for studying the fossil fuel transition issue and its related policies, because coal production and consumption still dominate the primary energy production and consumption, thus symbolizing the urgency of the energy transition and cope with the overcapacity in the coal mining industry, Chinese government started to control coal production capacity a decade ago, soon after the global financial crisis in 2008 (Wang et al., 2019a; Wang et al., 2018b; Zhang et al., 2019). The subsequent “new normal” growth pattern, in addition to the global financial crisis, further strengthen the overcapacity concern. However, the policy did not achieve its goal as expected and incur a large amount of efficiency problems (Shi et al., 2018).

The capping policy implemented through the command and

* Corresponding author. Center for Energy and Environmental Policy Research & School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China.

E-mail address: wangkebit@bit.edu.cn (K. Wang).

control approach is not an economically efficient way and could be replaced with better instruments. Theoretically, market instruments (e.g. quota trading schemes) are better policy tools, since there are asymmetric information between government officials and firms and substantial time lags. However, they are not systematically introduced to cope with the capacity control issue in China. This is partly because that, there are little discussions in literature on the use of trading schemes to control production capacity, even though capacity control of coal industry has been discussed recently (Wang et al., 2019a; Wang et al., 2018a, 2018b). Shi et al. (2018) briefly mentioned the use of such a market instrument in their study of China's coal capacity cut policy in 2016.

Following the numerous cap and trade (CAT) theories and practices documented in the literature such as the emission trading scheme in the Europe (European Commission, 2012), recently, Shi et al. (2019) propose a capacity permit trading scheme, including tradable Individual Capacity Permits (ICPs), to minimize the loss of output and efficiency in capping China's coal production capacity. The proposal of the permanent cap is in line with the central government's direction on capping new coal production capacity and trading capacity quotas to facilitate capacity replacement and exchange (NDRC et al., 2016a, 2016b). For example, according to the Third Plenary Session of the 18th Communist Party of China (CPC) Central Committee in November 2013, the current economic system reform will strengthen the decisive role of the market in allocating resources (18th Central Committee of the Communist Party of China, 2013). As China accounts for more than half of global coal production and consumption (IEA, 2017), minimizing costs for the capacity control (including cap and cut) policies in China's coal mining industry will generate important policy implications.

This paper attempts to quantify potential benefits from applying the ICPs to control capacity using inputs, outputs and gazetted capacity of 1171 coal mining enterprises operating in 2013 in China. Based on a nonparametric frontier method, the potential benefits are measured as savings (reduction) in inputs and increases in income (output) in comparison with the traditional command and control practice, for the national-wide and provincial-wide ICP trading scenario, respectively. The nonparametric frontier method we applied is a data-driven technical for performance evaluation through estimating nonparametric production function as benchmarking. It does not require an assumption of a functional form relating coal industry's inputs to outputs in the production function, and the coal mines in our empirical test are directly compared against a combination of best performed mines, which provide an objective estimation of potential benefits of capacity trading scenario with the traditional command and control scenario. Moreover, assumptions on economic behaviours could be included in this method which makes it flexible for simulating various strategies of a coal mine on adjusting its production process when facing capacity control task.

Furthermore, this paper makes two contributions. First, we are the first to measure the economic benefit of applying a well-established market mechanism (cap and trade scheme) to deal with production capacity capping issues occurring during the "energy transmission" using firm level data. Currently, the majority of capacity control is still implemented through a command and control approach. While Shi et al. (2019) measure the theoretical benefits of such a capacity permit trading scheme, there is not quantification with real data.

Second, the paper proposes a simulation method to empirically quantify potential benefits from applying the market instrument to cope with capping issues, including capacity control. The methodology is based on a well-established nonparametric frontier method, for example, Xian et al. (2018) and Wang et al. (2014). The

unique firm-level dataset was constructed by matching rated mine capacity data with the firm census data. By applying the nonparametric frontier methodology to the firm-level data, we demonstrate that different permit trading scenarios will lead to different consequences. This method allows inputs and outputs having very different units which make it possible be applied to other areas that have similar capping issues in, for instance, backward steel industry and high emission coal power plants.

The rest of the paper is organized as follows. A brief introduction of the current capacity control policy in the Chinese coal industry and our proposed permit trading scheme are presented in Section 2. The loss of current practice and projected benefits from the trading scheme are also discussed. Section 3 explains the methodology and estimation strategy and data for quantify the benefits from such a permit trading scheme. Section 4 demonstrates the efficiency gains through comparative changes between the baseline and alternative scenarios. Two sensitivity analyses are also briefly conducted. Section 5 elaborates additional policy benefits of the scheme and its broader applicability. The final section concludes the paper with a discussion of the policy implications.

2. Controlling coal production capacity in China

2.1. The current capacity control practice

Despite significant progress in liberalizing the Chinese economy, the Chinese government often resorts to administrative interventions and capacity cut in the coal industry is a salient example. The coal industry in China has been frequently subjected to closing mines policy after 2000s (Shi, 2013). The capacity cut policy emerged after the global financial crisis in 2008 when coal production capacity becomes permanent excess due to the energy transition and China's low growth model (Shi et al., 2018) and was gradually tightening overtime when the situation has not been improved (Table 1). In 2009, the State Council backed the plan of National Development and Reform Commission (NDRC), China's national planning agency, to restrict overcapacity and redundant consutricion in some industries (State Council, 2009). In 2010, the State Council to moved from elimination of "excessive and less efficient capacity" to elimination of "backward production capacities" and issued specific targets for more than ten key industries, including coal (State Council, 2010). The Guiding Opinions issued by the State Council in 2013 and 2016 emphasized the need to rectify misallocation of resources. In order to prevent industry losses, non-performing loans, safety problems, unemployment and environmental degradation, the State Council continued to push capacity cut (State Council, 2016a, 2013). However, even in the early 2016, the financial loss of companies in the coal industry was still prevailing, which caused more dramatically policy interventions. In February 2016, the State Council announced its plan to cut up to 1000 million tons (MT) of coal production capacity in the next 3–5 years starting from 2016 and reduce the number of annual working days in coal mines from 330 to 276 (State Council, 2016a). Under this dramatic policy, the coal prices skyrocketed to level beyond the government's expectation in July 2016 and could not be eased by a gradually release of production capacity (Shi et al., 2018). The working-day limitation was suspended at the end of October 2016, and the capacity cut policy was also softened by allowing efficient coalmines to increase their capacity to prevent price hike (Shi et al., 2018).

Despite of evolving purposes, the production capacity control policy in China's coal industry is consistently implemented through a command and control approach under which the government decides how much production capacity is written off each year, that is, the capacity cut target. After the national capacity cut target is

Table 1
Key policies on capacity cut in the coal industry.

Year	Policies	Source
2009	State Council (2009). State Council forwarded notice by NDRC on restricting overcapacity and redundant construction in some Industries, Guofa [2009] No. 38.	State Council (2009)
2010	State Council (2010). Notice of the State Council on further Stengthening the Work of Eliminating Backward Production Capacities, Guofa [2010] No. 7.	State Council (2010)
2013	State Council (2013). Guiding Opinions of the State Council on Resolving Serious Production Overcapacity Conflicts. Guofa [2013] No. 41.	State Council (2013)
2016	State Council (2016a). Opinions of the State Council on Reducing Overcapacity in the Coal Industry to Achieve Development by Solving the Difficulties. Guofa [2016] No. 7. NDRC, NEA, SACMS, 2016a. Further Notice on Decremental Replacement of Coal Mines. Fagai Nenngyuan [2016] No. 1897.	State Council (2016a) NDRC et al. (2016a)
	NDRC, NEA, SACMS, 2016b. Notice on Decremental Replace to Control New Capacity of Coal Mines. Fagai Nenngyuan [2016] No. 1602.	NDRC et al. (2016b)

fixed, the central government allocates the capacity cut target, or quotas, to provincial governments. The quotas are further broken down to lower levels, along the hierarchy of governments. Ultimately, each firm will receive an instruction indicating whether it will be closed completely or allowed to produce in lower capacity.

To facilitate the implementation, all major coal mining enterprises are required to report and register the production capacities of each coal mine. These will be further verified and rated by the local administrative departments and the National Energy Administration (NEA). It is strictly prohibited for coal mines to produce coal beyond their registered capacity.

The National Development and Reform Commission requires that all new production capacity to be compensated by quotas that are generated from written-off existing capacity, a process called 'Chan Neng Zhi Huan' (capacity replacement) (NDRC et al., 2016b; State Council, 2016a). A closed mine may be assigned a 'capacity quota'. The typical practice for the replacement in a company is to trade off new capacity with old capacity. Such the replacement is regressive: for a unit of capacity that is written off, less than one unit of quota for replacement will be generated (NDRC et al., 2016b, 2016a).

While the central government agencies have allowed such capacity quotas to be traded among coal mines (NDRC et al., 2016a, 2016b), there are only a few cases of bilateral trading and therefore, effectively, most capacity control is still implemented through a command and control approach. In the limit cases of trading, the quotas are neither standardized, nor tradable in individual units. Such trading is ad hoc and thus the search-match costs are high for both parties. The buyers often have to purchase all the quotas in one transition. Therefore, it is not easy to match the buyers and sellers due to a lack of public information. It is also difficult and costly to match the number of quotas from both supply and demand sides.

The command and control approach, however, suffers from many problems that have been well documented in the literature (Wang et al., 2016a). For example, it generates high compliance costs or huge efficiency losses: allocation of capacity control targets along the hierarchy of governments leads to many high efficiency plants being closed in some regions while lower efficiency counterparts in other regions are preserved. Moreover, it is difficult to build new capacity with higher efficiencies. The command and control approach can also lead to unexpected price fluctuations that force governments to relax and even reverse their policies from time to time. For example, with the implementation of capacity cuts, the national coal benchmark price, i.e., the Bohai-rim port coal price, increased from RMB 370/ton in January 2016 to RMB 600/ton in January 2017 (CEIC, 2019). The skyrocketing prices forced the government to reverse its capacity cut policy. See Shi et al. (2018) for a complete account of the coal capacity policy in 2016.

2.2. A permit trading scheme for capacity control and its theoretical benefits

As an alternative to command-and-control method, CAT approaches are commonly used by governments and regulatory agencies to limit, or cap, the total level of specific items resulting from private business activity. For both air and marine resources, the CAT approach sets limits on resource exploitation (often annually, as quotas) and then allows trading of quotas, that is, individual transferable quotas (ITQs), between industry users (Chu, 2008). First proposed by (Dales, 1968), the use of tradable permits has a long history and become well-known over the past two decades due to the popularisation of emission trading systems.

The advantage of such a CAT scheme is that it increases the efficiency of the remaining production capacity, as carbon trading and other similar schemes do. In theory, compared to command-and-control mechanisms, a polluter's decision should lead to an economically efficient allocation of production among polluters, and lower compliance costs for individual firms as well as for the economy overall (Ma et al., 2018). When combining the two permit trading systems, the trading system becomes more preferable since it will often lead to relatively lower regulation compliance costs.

Based on the CAT concept, Shi et al. (2019) propose a capacity permit trading scheme to minimize the cost of capacity cut using the coal industry as a case study. According to their proposal, the total allowable production capacity (TAPC) is denominated in standardized individual capacity permits (ICPs). The ICPs can be traded among firms in unit as small as one ICP. A detailed discussion of how such a capacity permit trading system might operate is presented in Shi et al. (2019).

Compared to the command and control approach, the permit trading scheme can help minimize the compliance costs while assuring capping the total production capacity. Such trading schemes not only generate positive benefits and increase economic welfare for the society, but they can also compensate for the loss of the closed mines and thus buy more support from the public. Below are two benefits that are expected from economic theory but have not been empirically examined.

- 1) The first benefit is obtained through the saving of would-be closed mines. By applying a fixed cut to each mine, the marginal value of production capacity, which can be measured as marginal profit, will be different across mines and thus lead to welfare losses. When a permit trading scheme is introduced, some firms that should be closed in one region could survive by purchasing capacity permits from less efficient ones from other regions with lower efficiency benchmarks. The trading of permits from lower efficiency mines to higher efficiency mines will improve the efficiency of the total sector. In an equilibrium, the

marginal productivity of the last surviving firms will be equalized across the trading zone and thus a large trading zone is preferred. For example, in national emissions trading, the closed firms will be those ranked at the bottom nationally, rather than prefecture-wide.

- 2) The second benefit comes from relocation of capacity from low efficiency to high efficiency mines. With the presence of permit trading among the surviving mines, high efficiency mines can buy ICPs and expand their production capacity. On the other hand, less productive mines can earn revenues through selling their production permits temporarily or permanently for capacity cuts. Such revenue generation will encourage low efficiency mines to close down proactively and thus increase the overall efficiency of the whole sector. The efficiency could be either due to high technical efficiency or higher market value of the permits.

The benefits of capacity trading should not be worse off after the trading zone has been expanded. This is easy to understand because the scope of optimization in the larger trading zones is higher than that in smaller trading zones.

3. Methodology for estimation of a capacity permit trading scheme

3.1. A nonparametric frontier approach to estimate the benefit of permit trading

Given that this is the first study to quantify this kind of permit trading scheme, we propose a methodology to quantify the two economic benefits. The nonparametric frontier models for estimating the impact of implementing the permit trading scheme in this study are derived from the method proposed by Brännlund et al. (1998) and Färe et al. (2014, 2013). This methodology has been utilized in Badau et al. (2016) and Wang et al. (2016a, 2016b, 2016c), which seeks to identify the potential gains or unrealized gains from emissions trading of environmental pollution and CO₂ in Sweden, the United States, and China. These models are linear programming optimization models with objective functions to maximize the output of each entity included in the emissions trading scheme. The theoretical support of the nonparametric frontier method are set theoretic representation of production technology, and efficiency and productivity measurements through a linear programming to construct a nonparametric piece-wise frontier over the observed input and output data in production economics. There are also many other applications of the nonparametric frontier methods, mainly in the case of performance evaluation, such as Wang et al. (2019b), Wang et al. (2019c), Zhang and Chen (2018) and (Zhang et al., 2018).

As the purpose of this study is to identify the potential benefits (income gains or cost savings) from capacity permit trading, we adjust the objective function to minimize the inputs of each entity while keeping the sum of the outputs of all entities unchanged within the rated capacity trading scheme.

For each coal mining enterprise, we assume that main business income comes from coal production (in Chinese yuan), and inputs include wages (Chinese yuan), total fixed assets (Chinese yuan), and intermediate inputs, i.e., main business costs excluding wages and depreciation (Chinese yuan). The government-rated capacity of coal production (originally in tons but converted into currency value through coal prices for convenient comparisons) in each enterprise is considered as a total tradable permit under the trading scheme. The rated capacity is treated as a boundary for adjusting the coal production of each enterprise in our modelling.

Each coal mining enterprise is denoted as a decision making

unit, i.e., DMU_{*j*} (or *l*) ($j = 1, \dots, n', \dots, n, l = 1, \dots, n', \dots, n$) with three inputs x_{ij} ($i = 1, 2, 3$, respectively representing intermediate input, wage, total fixed asset), one output y_j , and one capacity permit c_j , and the production technology is set as $P(x) = \{y: x \text{ can produce } y\}$. In $P(x)$, we assume the inputs and outputs are all freely disposable, and the assumption of variable returns to scale on output is applied. Then, the nonparametric frontier model (Färe et al., 2004) is used to estimate the minimum inputs x and adjusted production capacity c , as well as coal production y of each enterprise under different rated capacity trading schemes.

In this model, the efficiency of each enterprise θ could be estimated as in Model (1):

$$\begin{aligned} & \min \theta, \\ & \text{s.t. } \sum_{j=1}^n \lambda_j y_j \geq y_l, \\ & \sum_{j=1}^n \lambda_j x_{ij} \leq \theta x_{il}, i = 1, 2, 3, \\ & \sum_{j=1}^n \lambda_j = 1, \\ & \lambda_j \geq 0, j = 1, \dots, n', \dots, n. \end{aligned} \quad (1)$$

where $x_{ij}(x_{il})$ is a set of observed inputs: intermediate input, wage, total fix assets, and $y_j(y_l)$ denote the output represented by income from coal production. They are the parameters of the linear programming for each enterprise j (including benchmark DMU) or l (current under evaluation DMU). θ and λ_j are efficiency measures and intensity variables when minimization occurs. They are the decision variables of the linear programming of enterprise j or l . θx denotes the minimum inputs an enterprise could use, with the current output level unchanged when there is no capacity permit trading. Therefore, θ , the efficiency of each enterprise also can be defined as x^*/x , where $x^* = \theta x$, indicating the ratio of optimized inputs over the current observed inputs, given the current observed output unchanged. The optimized value of θ is in range $(0, 1]$ where larger value indicates higher efficiency and value 1 denotes full efficient of a DMU.

3.2. Estimation of benefits from permit trading using scenario studies

We use scenario studies to estimate the potential benefits from the proposed permit trading scheme. A baseline scenario is developed to estimate how the coal industry would be in 2016 under the current command and control capacity policy. In this scenario, coal production in each prefecture is limited to the rated capacity. We have formulated two policy scenarios in which rated capacity is allowed to be traded either within in the province or nation-wide. The estimated benefits are measured as savings (reductions) in inputs, which (at least partially) compensate the capacity cutting costs, and adjustments on output between the policy scenarios and the baseline scenario.

In the baseline scenario, enterprises in each prefecture are identified as being least efficient, in terms of efficiency scores, and will be eliminated to match the production capacity cap. Since we used coal industry data for 2013, we needed to remove over-capacity in the baseline scenario. The actual coal production in 2013 (our data) was approximately 37 percent higher than the rated capacity in 2016. Following the current command and control practice, the production capacities of the enterprises that ranked in the bottom 37% of each prefecture are eliminated. Specifically, we first gradually eliminated the low efficiency enterprises (denoted by DMU_{*j*}, $j = n'+1, \dots, n$) in each prefecture until the sum of actual output from the remaining high efficiency enterprises (denoted by DMU_{*j*}, $j = 1, \dots, n'$) reached the total rated capacity in the respective

prefecture. This process assumes that the total rated coal production capacities for all remaining n enterprises would not be broken through. The above scheme is considered as a constraint from the command and control regulation scheme and is taken as the baseline scenario.

This capacity cutting process will lead to shut down costs derived from the income losses in each of the $j = n'+1, \dots, n$ eliminated enterprises and we define this cost as direct capacity cutting cost (DC): $DC = \sum_{j=1}^n y_j - \sum_{j=n'+1}^n y_j$. In addition, the shutting down of the low efficiency enterprises will also lead to redundancies in intermediate inputs, labour, and assets. The reduction of intermediate inputs could be considered as a cost saving from production capacity control in the short term, and we define the sum of direct capacity cutting cost (+) and intermediate input saving (IS) (-), $IS = \sum_{j=1}^n x_{1j} - \sum_{j=n'+1}^n x_{1j}$, as the net capacity cutting cost in the short term: $NCS = DC - IS$. Furthermore, in the mid- and long-term, the redundant labour, i.e., measured as employee wage saving (ES): $ES = \sum_{j=1}^n x_{2j} - \sum_{j=n'+1}^n x_{2j}$, and the reduction of total fixed asset (AS): $AS = \sum_{j=1}^n x_{3j} - \sum_{j=n'+1}^n x_{3j}$, could be relocated to other productive sectors and thus also be considered as cost savings from capacity control. Thus, we could additionally define the sum of direct capacity cutting cost (+), employee wage saving (-), and total fixed asset saving (-) as the net capacity cutting cost in the mid and long term: $NCM = DC - IS - ES$ and $NCL = DC - IS - ES - AS$. These three types of net capacity cutting costs will be further utilized for comparing the total cost savings from alternative capacity trading scenarios.

In the presence of capacity trading (i.e., capacity permit is tradable) among enterprises, we use this tradable scheme to search the adjusted output for each remaining enterprise \tilde{y}_l ($l = 1, \dots, n$). This could be estimated as in Model (2):

$$\begin{aligned} & \min \sum_{l=1}^n \theta_l, \\ & s.t. \sum_{j=1}^n \lambda_{jl} y_j \geq \tilde{y}_l, l = 1, \dots, n, \\ & \sum_{j=1}^n \lambda_{ji} x_{ij} \leq \theta_l x_{il}, i = 1, 2, 3, l = 1, \dots, n, \\ & \sum_{j=1}^n \lambda_{jl} = 1, l = 1, \dots, n, \\ & \lambda_{jl} \geq 0, j = 1, \dots, n, l = 1, \dots, n, \\ & \sum_{l=1}^n \tilde{y}_l = \sum_{j=1}^n c_j. \end{aligned} \tag{2}$$

where x_{ij} (x_{il}) and y_j are observed inputs and output parameters of the enterprises participating in the capacity permit trading scheme, while \tilde{y}_l and λ_j are output and intensity variables when minimization occurs. In addition, \tilde{y}_l is also utilized as the rated or tradable capacity permit variable, represented by income from coal production with reallocated production capacity permits. Note that the last constraint in Model (2) indicates the sum of the optimized tradable capacities or that reallocated tradable capacities should equal the sum of the rated tradable capacities c_j of all participating enterprises. θ denotes the efficiency measure of each participating enterprise when rated capacities can be exchanged among enterprises. The definition and range of θ are the same as in Model (1).

Before ending the instruction of our modelling, we would like to identify the possible limitations of the method which analyst should keep in mind when choosing to use it for simulating tests in other cap issues: 1) noise on input and output data (e.g. measurement error) can cause biased evaluation; 2) it just provides “relative” efficiency measure (compared to peers) other than “absolute” efficiency measure (compared to theoretical maximum); and 3) it could be computationally intensive for large (simulation) problems.

The differences between the net capacity cutting cost in the

command and control regulation scheme (baseline scenario) and the net capacity cutting cost in the rated capacity trading scheme is defined as the total cost savings (CS) from rated capacity trading. The calculation of cost savings helps to identify the possible recovery from income losses that occur from eliminating the regulatory rigidity of the capacity cutting policy through allowing the trade of rated capacity between enterprises.

Our key interests are the benefits from permit trading schemes. Therefore, the difference between the trading and baseline scenarios is the key finding here.

3.3. Data and variables

We estimate the benefits using firm level data in China’s main coal producing provinces. The firm-level data for the coal industry in terms of inputs and outputs are from the survey of China’s National Bureau of Statistics (NBS) in 2014. The surveyed mining enterprises included two types: all independent accounting coal firms in the state sector; and coal enterprises in the non-state sector but having a gross output of more than 5 million yuan. The aggregation of these data is reported as the “industrial” sector in the *China Statistical Yearbooks* (Jefferson et al., 2008).

Next, we match the surveyed firms with the capacity data gazetted by the NEA. To support the efforts to cut capacity, the NEA started to gazette capacity data for coal mines in October 2014 (NEA, 2017). By the end of September 2017, the NEA had gazetted 12 times and some coal mines had been gazetted twice with their capacity reduced the second time.

There were 1171 coal mining enterprises operating in 2013 that were included in our study.¹ They were located in China’s 10 major coal producing regions (see Fig. 1): Shanxi (221), Liaoning (34), Henan (47), Sichuan (180), Heilongjiang (39), Shandong (71), Guizhou (198), Shaanxi (112), Inner Mongolia (118) and Yunnan (151). The total annual main business income from coal production in each province in our sample was over 7.5 billion yuan. The key variables of each coal mining enterprise included rated capacity, income from coal production, wages, total fixed assets, and intermediate inputs. The rated capacity was converted into monetary terms, i.e., output from rated capacity associated through multiplication of the rated capacity with prices in each prefecture, sourced from the China Coal Industry Association.

Table 2 reports the values of inputs and outputs. It can be seen that there are significant differences in input and production scales among coal mining enterprises, and that the actual total income of coal production of these 1171 coal mining enterprises (568.7 billion yuan) exceeded the 2016 rated capacity associated income (360.8 billion yuan) by approximately 37%.

4. Simulation results

To estimate the impact of imposing a capacity trade scheme, we compared the results from different scenarios to reach the total rate capacity. The baseline scenario is the current practice of capping the capacity to the rated capacity using the command and control approach. In this administrative cut scenario, lowest efficient coal mines from each prefectural jurisdiction will be eliminated to bring down the total production capacity in the sample to the rated capacity.² The total output and inputs of the remained coal mines are

¹ Due to confidentiality requirement, we cannot share the data publicly. However, we are willing to share the data in Excel format for those wish to replicate the results.

² Note that our baseline scenario refers to the command and control approach with the highest welfare loss.

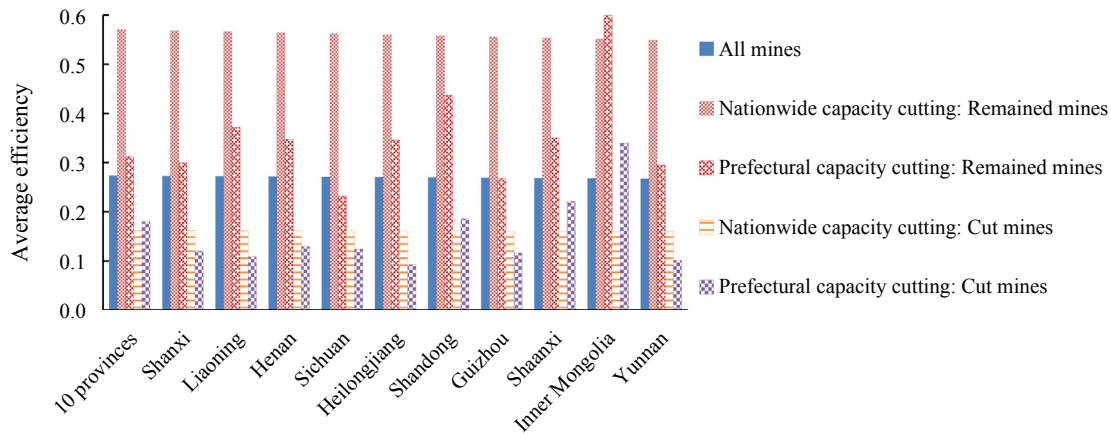


Fig. 1. Average efficiency scores of coal enterprises by province and under various scenarios.

Table 2

Summary statistics.

Inputs and outputs	Total	Maximum	Minimum	Mean
Intermediate inputs (billion yuan)	262.3	104.9	3.6	26.2
Employee wages (billion yuan)	86.5	43.1	1.4	8.6
Total fixed assets (billion yuan)	428.4	197.4	5.4	42.8
Income from mining (billion yuan)	568.7	229.8	7.5	56.9
Income from rated capacity (billion yuan)	360.8	136.5	4.2	36.1

calculated as the reference. Then, the capacity trading scheme represented by Model (2) is utilized for estimating the efficiency scores and the adjusted inputs and outputs when rated capacities are allowed to be traded among them. We modelling the impact of the nation-wide trading scheme by removing the least efficient coalmines nationally until the total capacity is below the target. Similarly, in the province-wide trading, we eliminated the least efficient mines in each province until the total capacity control target is met.

4.1. The current administrative cut policy scenario: the baseline

Under the existing command and control approach, the capacity cut is implemented by each prefecture. That is, each prefecture is required to limit its capacity at a certain level and there is no capacity permit trading among enterprises.

To simulate this impact, we first estimated the efficiencies of all 1171 enterprises according to Model (1), whose average efficiency value is 0.273, indicating there would be theoretically 72.7% input saving potentials on average coal mining enterprise if the technical inefficiency is all removed. Then we gradually eliminated the enterprises with relatively lower technical efficiency scores in each prefecture until the sum of actual income from the remaining enterprises was closer to the total rated capacity of each prefecture. Since the total national capacity needed to be cut by 37%, we tried to set 37% as the target of each province. However, due to the large number of marginally efficient mining enterprises, closing some may lead to too large or too small capacity cuts. In practice, we would not cut a marginal mining enterprise if its closure could lead to a more than 60% capacity cut in the prefecture. However, if a marginal enterprise was kept and the remaining capacity was above the rated capacity, the capacity shortage can be made up in other prefectures which are not necessarily within the same province.

By the end of this process, 852 enterprises with relatively low efficiency scores would be eliminated and there would remain 319

enterprises whose total income from coal production is 361 billion yuan, a 37% cut (Table 3). This volume is the same as the total rated capacity announced by the NEA for all 1171 enterprises and is thus used as the baseline scenario for further comparison. The outputs and inputs in the baseline scenario will be used to measure the impact of different alternative scenarios.

The 10–12th columns of Table 3 show the volumes and percentages of overcapacities that would be cut off through shutting down the 852 enterprises with low efficiency, indicating that a total of 208 billion yuan in coal production capacity associated income from 10 Chinese regions would be eliminated. This accounts for about 37% of the current total income from coal production in these regions. The size of the capacity cuts, however, show significant diversity: the average cut ranged from 18% in Guizhou and Shaanxi to 62% in Liaoning (Column 12 of Table 3). The change in inputs show different patterns compared to the change of income, which are due to the heterogeneity in technical efficiencies.

As expected, there is a significant variability in efficiency scores in the remaining coal enterprises. The efficiency scores range from 23.2% in Sichuan to 59.9% in Inner Mongolia (Fig. 1). The significant variation in technical efficiency creates room to improve efficiency through trading schemes that can equalize efficiencies across a large trading area.

4.2. Benefit of the capacity trading scheme

In this section, we report the benefits of a nation-wide trading scheme by comparing the savings (reduction) in inputs and possible increases in income (output). We use the case of nation-wide trading as the case for elaboration and use province-wide trading for sensitivity testing. We also compare the result between nation-wide trading and a national single cut line. In the national single cut line, the least efficient mine will be closed but there is no relocation of capacity and thus the benefits of such a national single cut are expected to be less than those of the national trading scheme.

Table 3

Inputs and outputs in previous and baseline scenarios.

Inputs and Outputs Column	Intermediate (billion yuan)			Wages (billion yuan/%)			Fixed Assets (billion yuan/%)			Income (billion yuan/%)		
	(1) Previous	(2) Baseline	(3) Change	(4) Previous	(5) Baseline	(6) Change	(7) Previous	(8) Baseline	(9) Change	(10) Previous	(11) Baseline	(12) Change
Regions/Scenarios	Previous	Baseline	Change	Previous	Baseline	Change	Previous	Baseline	Change	Previous	Baseline	Change
10 provinces	262.32	155.15	-41%	86.50	53.43	-38%	428.42	261.05	-39%	568.65	360.77	-37%
Shanxi	104.87	57.21	-45%	43.09	25.79	-40%	197.42	117.54	-40%	229.81	136.99	-40%
Liaoning	3.55	2.40	-32%	3.47	0.71	-79%	10.25	3.69	-64%	11.02	4.23	-62%
Henan	7.82	4.06	-48%	2.90	2.00	-31%	13.94	10.24	-27%	16.75	10.76	-36%
Sichuan	10.58	8.08	-24%	4.29	3.21	-25%	14.26	8.66	-39%	20.29	15.38	-24%
Heilongjiang	3.98	2.27	-43%	1.42	0.63	-56%	5.41	3.34	-38%	7.52	4.58	-39%
Shandong	23.33	15.33	-34%	9.57	5.61	-41%	35.28	20.17	-43%	51.84	33.73	-35%
Guizhou	12.83	10.00	-22%	4.04	3.16	-22%	11.37	9.22	-19%	28.06	22.87	-18%
Shaanxi	34.07	24.95	-27%	7.91	6.68	-16%	59.25	50.99	-14%	83.34	68.27	-18%
Inner Mongolia	54.26	26.31	-52%	7.32	4.19	-43%	74.34	33.83	-54%	105.05	54.55	-48%
Yunnan	7.02	4.55	-35%	2.49	1.44	-42%	6.90	3.38	-51%	14.98	9.42	-37%

In the national trading scheme, the savings from inputs cut and increases in output are significant. The largest savings are from increases in income due to the relocation of capacity from low value regions to higher value regions (94.79 billion yuan) and savings from reductions in fixed assets (93.58 billion yuan). Savings from cuts in intermediate inputs (49.58 billion yuan) are half the scale of the largest two while the savings from reduced wages are the lowest (15.82 billion). The total savings from the 10 provinces in the study sample can reach 253.87 billion yuan, equivalent to 45% of the sample's total income and 70% of the total income after capacity cuts by prefecture (baseline) (Table 4).

The most significant benefit is the increased income, followed by fixed asset savings. As shown in Table 4, the percentage of inputs saving is more than 30% for all inputs and the increase in income is 26%. The lowest benefits from wage cuts may make the provincial governments comfortable as job creation is a key concern, in addition to economic benefits.

The benefit of a national trading scheme can also be demonstrated in comparison to a national single cut line. In this national single cutting scenario, according to the technical efficiency scores, we gradually eliminate 852 enterprises with relatively low efficiency scores until the sum of actual coal production from the remaining enterprises with relatively high efficiency scores (approximately) reaches the total rated capacity announced by the NEA. Compared to the baseline scenario where the cutting scores for each prefecture are different, in this alternative command and control scenario, the efficiency score of the last cut mining enterprise is the national single cutting line.

Though the production capacity cut is the same as in the baseline scenario, this national cutting line allows those enterprises which were closed in the baseline scenario, but which have higher efficiency than the national single cutting line, to be rescued. Instead, those enterprises with efficiency scores below the national cutting and which survived in the prefectural franchises, will be closed. Overall, the national average score has been increased from 0.312 to 0.570, while the efficiency score change is different across

provinces. Provinces that see declines in their average efficiency scores are better off by saving more lower efficiency (but higher than the national single cutting line) enterprises. The total benefits from such an alternative command and control policy amount to 38.28 billion yuan, which is much less than what a nation trading scheme (Table 4) would generate. The reason is that permits cannot be relocated to regions with higher efficiency and market value.

According to the economic theories presented in Section 4.1, a large trading zone will result in better benefits. To demonstrate the impact of different scopes within the trading zone, we also simulate the impact of trading by province, that is, inter-provincial trading. As shown in Table 4, the total benefits are reduced to 114.25 billion yuan, less than half of what the national trading scheme would render. The low benefits from provincial-wide trading are a result of the fact that the technical efficiency heterogeneity among enterprises within each province is relatively lower than what it is nation-wide. This finding suggests that nation-wide trading is strongly preferred.

4.3. Cross province impact of national emissions trading

Under the national trading scheme, the nation-wide trading of ICPs will lead to some provinces reducing production capacity while others possibly increasing it. Fig. 2 reports the production capacity before the capacity cut (previous), in the current administrative cut (baseline scenario) and after national trading. While the total production capacity in the national trading scenario remains the same as in the baseline scenario, and equal to the rated capacity, there is significant change across provinces. Shanxi, Liaoning, Heilongjiang, Sichuan and Yunnan will expand their production capacity, while others will reduce it.

By visualizing the change between the baseline and national capacity trading scenarios, the pattern is more obvious. The production permits relocate from east to west and northeast, or more generally inland (Fig. 3). This is consistent with a recent finding on regional heterogeneity in China's coal capacity cut policy (Shi et al., 2018).

Table 4

Inputs and outputs under various cases, billion yuan.

Scenarios/Inputs and outputs	Intermediate	Wages (L)	Fixed assets (K)	Income (Y)	Total
Full sample/Previous (A)	262.32	86.50	428.42	568.65	—
Prefectural cut (Current policy/Baseline) (B)	155.15	53.43	261.05	360.77	—
National single cut (C)	162.51	50.86	217.99	360.77	—
National trading (D)	105.58	37.61	167.37	455.56	—
Provincial trading (E)	153.30	50.72	232.94	442.35	—
Benefits of national trading (D vs. B)	49.58	15.82	93.68	94.79	253.87
Benefits of national single cut (C vs. B)	-7.36	2.57	43.06	0.00	38.28
Benefits of provincial trading (E vs. B)	1.85	2.70	28.11	81.58	114.25

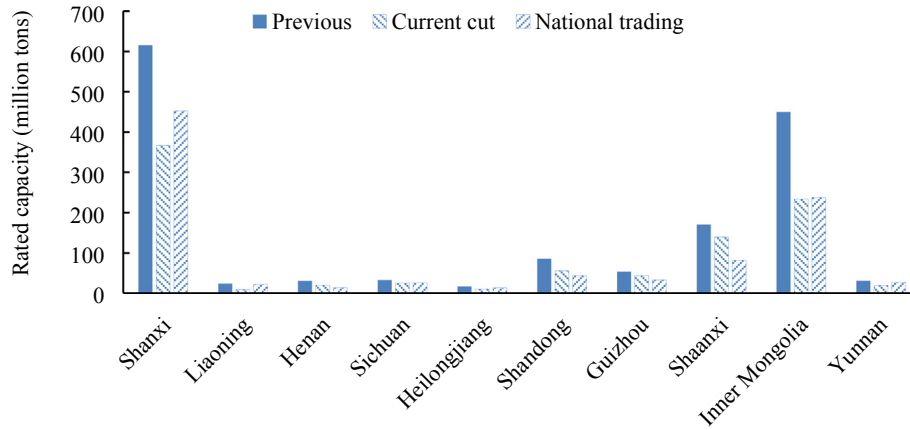


Fig. 2. Production capacity by province in Baseline and Nation Trading.

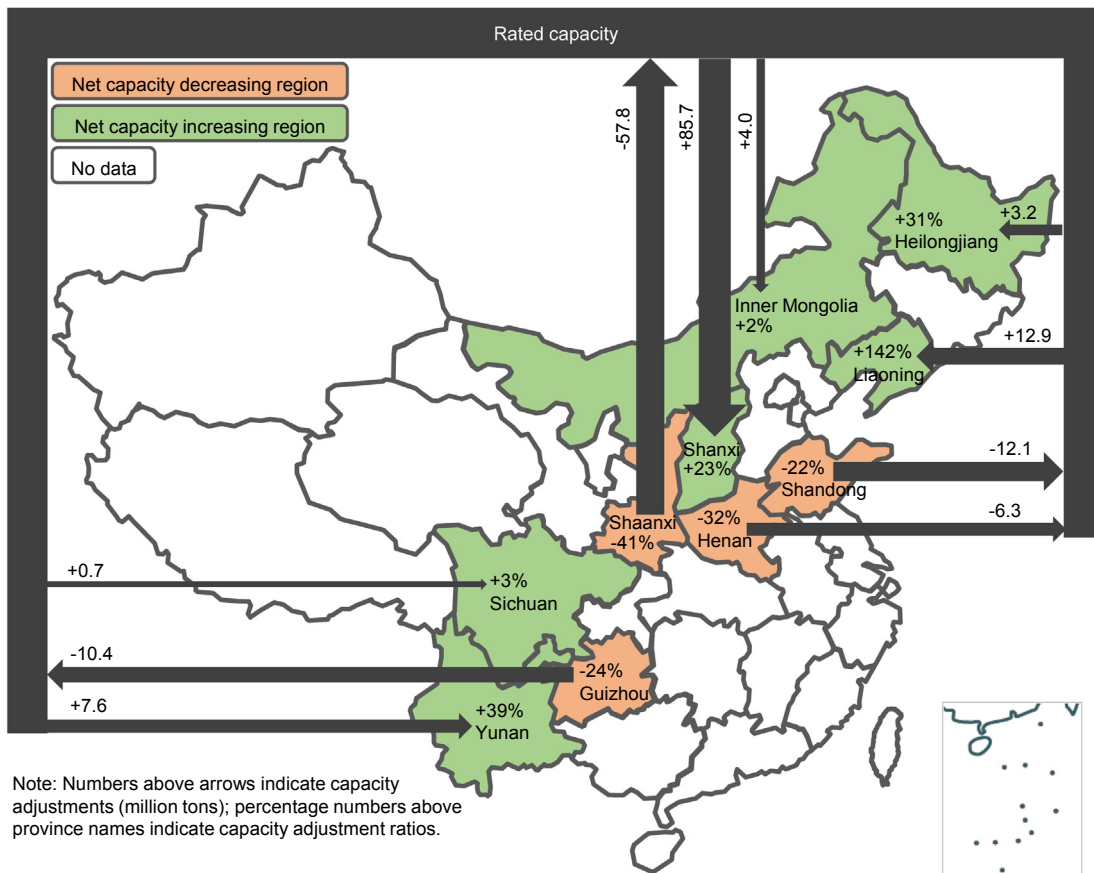


Fig. 3. Change of production capacity, national trading vs. baseline scenarios, million tons.

In term of benefits, the two key coal producing provinces, Shanxi and Inner Mongolia, which increased their production capacity, reap the highest benefits from national capacity trading. As shown in the sum of the direct cost savings and income boost in Column 13 of Table 5, Shanxi and Inner Mongolia gain 99 and 47 billion yuan, respectively. Interestingly, the other key coal producing province, Shaanxi, gains 32 billion yuan by reducing its production capacity and selling capacity permits. As in the aggregate, the income boost and savings from fixed assets are the key sources of benefits arising from national trading. Despite some provinces reducing income, or increasing inputs, all provinces gain from

national trading. More importantly, even though some provinces will expand their production capacity, none will increase capital investment, labour, or intermediate inputs.

5. Discussion

The most important finding of this analysis is that all provinces will gain from participating in national capacity trading, a typical result of Pareto optimality. This suggests the capacity trading policies are economically beneficial and politically acceptable.

The employment saving is desirable for sustaining China's

Table 5

Saved inputs and income gains from national trading by province, billion yuan.

Inputs and outputs	Intermediate			Wage			Fixed asset			Income			Total benefits (3 + 6+9 + 12)
	Scenarios	Baseline	National trading	Saving	Baseline	National trading	Saving	Baseline	National trading	Saving	Baseline	National trading	
Regions/Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
10 provinces	155.15	105.58	49.58	53.43	37.61	15.82	261.05	167.37	93.68	360.77	455.56	94.79	253.87
Shanxi	57.21	64.93	-7.72	25.79	26.29	-0.49	117.54	90.44	27.11	136.99	217.13	80.14	99.03
Liaoning	2.40	1.51	0.89	0.71	2.81	-2.10	3.69	6.80	-3.12	4.23	10.51	6.29	1.96
Henan	4.06	1.07	2.98	2.00	0.17	1.83	10.24	0.80	9.44	10.76	6.45	-4.30	9.96
Sichuan	8.08	1.32	6.76	3.21	0.43	2.78	8.66	1.07	7.59	15.38	12.25	-3.13	14.00
Heilongjiang	2.27	0.66	1.61	0.63	0.22	0.41	3.34	0.61	2.73	4.58	6.39	1.82	6.56
Shandong	15.33	3.68	11.66	5.61	1.17	4.44	20.17	4.42	15.75	33.73	20.85	-12.87	18.97
Guizhou	10.00	1.60	8.40	3.16	0.43	2.73	9.22	0.83	8.39	22.87	15.82	-7.05	12.47
Shaanxi	24.95	5.83	19.11	6.68	1.65	5.04	50.99	13.28	37.71	68.27	39.26	-29.02	32.84
Inner Mongolia	26.31	24.03	2.28	4.19	4.11	0.08	33.83	48.43	-14.60	54.55	113.91	59.36	47.12
Yunnan	4.55	0.94	3.61	1.44	0.33	1.11	3.38	0.70	2.67	9.42	12.98	3.56	10.95

Note: Savings here denotes the difference between those in National Trading and the Baseline.

economy growth. As China has reached the Lewis turning point (Zhang et al., 2011); labour is increasingly scarce and expensive. Any labour released from the coal sector will boost labour productivity in the coal industry and also in the national economy. This is desirable for the sustainable development of the sector as well as the whole national economy. However, in the short run, such a high percentage of unemployment in the coal mining sector will likely create dire social issues. For example, many provinces will have a potential reduction of more than 70% in employment. As the people involved will need assistance in relocating to other sectors, proper mitigation policies and measures will be needed. However, with the income from selling ICPs, the enterprises will have some financial resources to manage the labour relocation.

Similar to the case of employment, significant amounts of fixed assets will also be saved. While such savings are desirable in the long run, the short run impacts on economic growth must also be mitigated. Additionally, many mining specific fixed assets may not be productive outside the coal mining industry and will therefore need to be written off. This will have permanent impact when everything else is equal. However, given the positive savings and boost in income, the benefits will still be positive even if fixed asset savings are excluded. Furthermore, revenues that are generated from selling capacity permits could offset some of the negative impacts of capacity being written off.

While the fixed asset savings may overestimate the benefits of capacity trading, there are many other benefits that have not been quantified in this study. For example, the benefits of relocation could also be obtained through temporarily closure of production capacity. Some low efficiency enterprises could trade out their ICPs for processing to upgrading, and temporarily suspend their operations leaving the market open for more efficient plants. This scenario can avoid permanent writing-off of fixed investments which could be of use in the future. Temporary closures can also avoid efficiency losses in national policies such as the “276 working day limit” that was applied in the coal industry in 2016. This limitation brutally restricted the capacity factors of all coalmines, causing significant efficiency losses (Shi et al., 2018).³

Our findings suggest that the permit trading scheme can

facilitate China's pursuit of its capacity cut policy in at least three ways:

- 1) The permit trading scheme can create a market price for production capacity and provide additional signals and flexibility for policy-makers to manage the capacity control process. With the presence of price signals, higher permit prices likely indicate too radical progress in the capacity cut, as occurred in China's coal industry in the second half of 2016 (Shi et al., 2018). If the price of permits is beyond the tolerance level set by the government, the government may intervene by selling more ICPs. On the contrary, the government can buy back ICPs to prevent failure of the permit trading scheme as happened in the European Union's ETS.
- 2) Implementing a permit trading scheme can facilitate the implementation of capacity cuts through providing financial incentives and mitigating regional shocks. Compensation for the closure of mines, either through direct subsidies, or market instruments, could facilitate the closure of undesirable capacity. Various compensation schemes have been introduced to facilitate the retirement of capacity, such as those in Australia and Germany (Jotzo and Mazouz, 2015). However, a market approach is better than compensation as the latter may defer retirement in bids for future subsidies (Riesz et al., 2013). Firstly, the permit trading scheme will incentivize regions to implement the cap more seriously and may facilitate regional economic restructuring. In the current regulatory model, regions that follow superior government commands will have no benefits from cutting capacity and thus lack incentive to implement the policy strictly. In the permit trading scheme, regions that cut capacity can benefit by selling their permits and get compensation. Furthermore, those regions that have plans to cut capacity in certain industries can now get revenues from selling permits and thus use the additional financial resources to develop alternatives. Secondly, the current ad hoc allocated capacity cap targets will cause shocks to some regions and undermine the enforcement of the targets. In the command and control policy, capacity-cutting targets are allocated along the hierarchy of the governments and may not be reasonable across all regions. The provinces which face caps that are too harsh will have to comprise their compliance with the targets. For example, in the aftermath of dramatic coal price shocks in 2016, Guizhou and Heilongjiang provinces changed their capacity cut policy (Shi et al., 2018). Such regional price shocks could be mitigated through cross-province permit trade.

³ In the current command and control approach, there is no possibility of trading the capacity permits. In our proposed permit trading scheme, the ICPs could be exchanged between mining enterprises under different local jurisdictions. While economic efficiency will demand as large a scope of trading as possible, political realities may create boundaries, as evidenced by the debates surrounding the linking of ETS schemes.

3) The permit trading scheme provides efficient instruments for policy-makers. The government can adjust the capacity control process without frequently changing the rules and regulations. Currently, the government cannot determine the optimal quota volume in advance, and thus must rely on feedback to make adjustments later on. The result can only be observed through realized production, and it is often too late to adjust the policy. Moreover, the government often adjusts its regulations, such as safety and environmental standards, to achieve its capacity control targets. This practice will undermine the creditability of policies and thus create uncertainty and speculation. In contrast, by adjusting the cap through selling or buying back permits, the government can adjust the policy in a subtle way instead of in a big bang manner that causes huge volatilities.

The permit trading schemes can be applied to other areas that have similar capping rules both in China and abroad. Though the case study focuses on the coal industry, the scheme is applicable to capacity control in other sectors, such as the steel industry, and other cap issues such as the capping of fossil fuel consumption, or retirement of high emission coal power plants. In China's context, it can be applied to the control of total energy consumption and be used as a key instrument for the "energy transition" (State Council, 2016b, 2014). In addition, considering that some overcapacity issues exist in other countries, for example the global steel production (Lu and Lucy, 2016), such a permit trading program could also be applied to other countries. It has been shown that a permit trading scheme can be applied to expedite the retirement of thermal power plants and promote lower emission generation, for example, in Australia (Jotzo and Mazouz, 2015).

Our estimated benefits are comprehensive but conservative. The nonparametric frontier method makes it possible to estimate the benefits from efficiency improvement, a key benefit of ICP trading. While our estimation of results are significant, many benefits still have not been quantified. For example, in a permit trading scheme, the standardization of quotas and the centralization of information can save search and match costs between buyers and sellers, and each side can trade with more counterparts at a time.

6. Conclusions and policy implications

In order to facilitate energy transition, China needs to cap the production and consumption of coal. Although the government have attempted to use the command and control approach to manage the production capacities of coal mines, the consequence is not favourable. Such a *de facto* cap policy does not achieve the capacity cutting goal, and it causes a significant efficiency and welfare losses. In this paper, we propose a permit trading scheme to minimize the costs related to controlling production capacity and apply it to China's coal industry for an empirical test.

Based on theoretical analysis, we show that the benefits that result from implementing a permit trading scheme compared to those that result from the traditional command and control approach, come from two aspects: the saving of high efficiency mines from being closed at the capacity cutting stage and the relocation of capacity from low efficiency to high efficiency enterprises. Once applying this framework to analyse the capping of coal production in China, we show that: Under a national permit trading scheme, there would be a positive income effects and help to save intermediate input equivalent to about 254 billion yuan, which is 70% of the total income in the baseline scenario and thus economically significant. In this sense, limiting the scope of trading within the provinces will significantly reduce the benefits. Although some provinces will increase their production by buying permits while others will reduce it, all provinces will benefit from

national permit trading. Such a Pareto optimality suggests that the permit trading scheme is economically attractive and politically feasible for controlling China's total coal production capacity.

As an important policy implication, we show that in order to minimize the compliance costs, China should establish permit trading schemes for capping policies such as capacity cuts in the coal and steel industries, capping of energy consumption and accelerating energy transitions from thermal power to renewable power generation. Moreover, a large scope in trading is preferred to a smaller scope and a national-wide permit trading scheme is the most desirable. Such Chinese experience can also be learnt by other developing countries which aim to facilitate the energy transition by using the market instrument.

Future extension of this study could be done in at least three frontiers. On the one hand, the study could be extended to other sectors that also subject to capacity control, such as cement and steel industries in China and thermal power plants across the world. Second, the study could be extended to multiple periods whether dynamic behaviour of firms can be observed. Third, additional benefits, such as saving of transaction costs for the market instrument can be estimated.

Authors' contributions

Shi: Overall design; discussion and policy implications; fundraise; project administration; and writing – original draft, review and editing.

Wang: Collection of gazetted capacity data and data match; model design and empirical analysis; drafting; fundraise; and writing – methodology, review and editing.

Shen: Suggestion on theoretical benefits; writing – review and editing.

Zhang: Collection of capacity cut policies; writing – review and editing.

Sheng: Provide and clean of the firm level data; writing – review and editing.

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.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (Grant Nos. 71871022, 71828401, 71471018, 71521002), the Fok Ying Tung Education Foundation (Grant No. 161076), the National Key R&D Program (Grant No. 2016YFA0602603), the Training and Practice Base for Innovative Energy Talents, the Joint Development Program of Beijing Municipal Commission of Education, and the National Program for Support of Top-notch Young Professionals.

References

- 18th Central Committee of the Communist Party of China, 2013. Decision of the Central Committee of the Communist Party of China on Some Major Issues Concerning Comprehensively Deepening the Reform (china.org.cn).
- Badau, F., Färe, R., Gopinath, M., 2016. Global resilience to climate change: examining global economic and environmental performance resulting from a global carbon dioxide market. *Resour. Energy Econ.* 45, 46–64. <https://doi.org/10.1016/j.reseneeco.2016.05.002>.
- Brännlund, R., Chung, Y., Färe, R., Grosskopf, S., 1998. Emissions trading and profitability: the Swedish pulp and paper industry. *Environ. Resour. Econ.* 12, 345–356.
- CEIC, 2019. CEIC Database.

- Chu, C., 2008. Thirty years later: the global growth of ITQs and their influence on stock status in marine fisheries. *Fish Fish.* 10, 217–230.
- Dales, J., 1968. *Pollution, Property and Prices*. University of Toronto Press, Toronto.
- European Commission, 2012. EU emission trading scheme handbook. *Eur. Community* 138. <https://doi.org/10.2834/55480>.
- Färe, R., Grosskopf, S., Hernandez-Sancho, F., 2004. Environmental performance: an index number approach. *Resour. Energy Econ.* 26, 343–352. <https://doi.org/10.1016/j.reseneeco.2003.10.003>.
- Färe, R., Grosskopf, S., Pasurka, C.A., 2013. Tradable permits and unrealized gains from trade. *Energy Econ.* 40, 416–424. <https://doi.org/10.1016/j.eneco.2013.07.015>.
- Färe, R., Grosskopf, S., Pasurka, C.A., 2014. Potential gains from trading bad outputs: the case of U.S. electric power plants. *Resour. Energy Econ.* 36, 99–112. <https://doi.org/10.1016/j.reseneeco.2013.11.004>.
- IEA, 2017. *World Energy Outlook 2017*. OECD Publishing, Paris.
- Jefferson, G.H., Rawski, T.G., Zhang, Y., 2008. Productivity growth and convergence across China's industrial economy. *J. Chin. Econ. Bus. Stud.* 6, 121–140. <https://doi.org/10.1080/14765280802028237>.
- Jotzo, F., Mazouz, S., 2015. Brown coal exit: a market mechanism for regulated closure of highly emissions intensive power stations. *Econ. Anal. Pol.* 48, 71–81. <https://doi.org/10.1016/j.eap.2015.11.003>.
- Lu, Z., Lucy, 2016. State of play in the Chinese steel industry [WWW document]. Peterson inst. Int. Econ. https://piie.com/blogs/china-economic-watch/state-play-chinese-steel-industry#_ftn6.
- Ma, C.Q., Ren, Y.S., Zhang, Y.J., Sharp, B., 2018. The allocation of carbon emission quotas to five major power generation corporations in China. *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2018.04.006>.
- NDRC, NEA, SACMS, 2016a. Further Notice on Decremental Replacement of Coal Mines. Fagai Nenggyuan, Beijing [2016] No.1897 (关于做好建设煤矿产能减量置换有关工作的补充通知).
- NDRC, NEA, SACMS, 2016b. Notice on Decremental Replace to Control New Capacity of Coal Mines. Fagai Nenggyuan, Beijing [2016] No. 1602 (关于实施减量置换严控煤矿新增产能有关事项的通知).
- NEA, 2017. Gazette of Capacity for Coal Mines (全国煤矿生产能力公告). <http://www.nea.gov.cn/ztlz/mtscnlgg/index.htm> (accessed 4.5.18).
- Riesz, J., Noone, B., MacGill, I., 2013. Payments for Closure - Should Direct Action Include Payments for Closure of High Emission Coal-Fired Power Plants? Centre for Energy and Environmental Markets Working Paper 2013. Sydney.
- Shi, X., 2013. China's small coal mine policy in the 2000s: a case study of trusteeship and consolidation. *Resour. Pol.* 38, 598–604. <https://doi.org/10.1016/j.resourpol.2013.09.009>.
- Shi, X., Rioux, B., Galkin, P., 2018. Unintended consequences of China's coal capacity cut policy. *Energy Pol.* 113, 478–486. <https://doi.org/10.1016/j.enpol.2017.11.034>.
- Shi, X., Shen, Y., Wang, K., Zhang, Y., 2019. Capacity permit trading scheme, economic welfare and energy insecurity: case study of coal industry in China. *Singapore Econ. Rev.*
- State Council, 2009. State Council Forwarded Notice by NDRC on Restricting Overcapacity and Redundant Construction in Some Industries (国务院批转发展改革委等部门关于抑制部分行业产能过剩和重复建设引导产业健康发展若干意见的通知). Beijing.
- State Council, 2010. Notice of the State Council on Further Stengthening the Work of Eliminating Backward Production Capacities. Guofa [2010] No. 7 (国务院关于进一步加强淘汰落后产能工作的通知). Beijing.
- State Council, 2013. Guiding Opinions of the State Council on Resolving Serious Production Overcapacity Conflicts. Guofa [2013] No. 41 (国务院关于化解产能严重过剩矛盾的指导意见). Beijing.
- State Council, 2014. Energy Development Strategy Action Plan (2014–2020) (能源发展战略行动计划(2014–2020年)). Beijing.
- State Council, 2016a. Opinions of the State Council on Reducing Overcapacity in the Coal Industry to Achieve Development by Solving the Difficulties. Guofa [2016] No. 7 (国务院关于煤炭行业化解过剩产能实现脱困发展的意见). Beijing.
- State Council, 2016b. Comprehensive Work Program of Energy Conservation and Emission Reduction in the 13th Five-Year Plan (国务院关于印发“十三五”节能减排综合工作方案的通知). Beijing.
- Suwala, W., Labys, W.C., 2002. Market transition and regional adjustments in the polish coal industry. *Energy Econ.* 24, 285–303.
- Wang, Q., Zhou, P., Zhao, Z., Shen, N., 2014. Energy efficiency and energy saving potential in China: a directional meta-frontier dea approach. *Sustain. Times* 6, 5476–5492. <https://doi.org/10.3390/su6085476>.
- Wang, K., Wei, Y.M., Huang, Z., 2016a. Potential gains from carbon emissions trading in China: a DEA based estimation on abatement cost savings. *Omega* 63, 48–59. <https://doi.org/10.1016/j.omega.2015.09.011>.
- Wang, K., Xian, Y., Zhang, J., Li, Y., Che, L., 2016b. Potential carbon emission abatement cost recovery from carbon emission trading in China: an estimation of industry sector. *J. Model. Manag.* 11, 842–854. <https://doi.org/10.1108/JM2-03-2016-0027>.
- Wang, D., Wan, K., Song, X., 2018a. Quota allocation of coal overcapacity reduction among provinces in China. *Energy Pol.* <https://doi.org/10.1016/j.enpol.2018.02.003>.
- Wang, D., Wang, Y., Song, X., Liu, Y., 2018b. Coal overcapacity in China: multiscale analysis and prediction. *Energy Econ.* <https://doi.org/10.1016/j.eneco.2018.01.004>.
- Wang, D., Wan, K., Song, X., Liu, Y., 2019a. Provincial allocation of coal de-capacity targets in China in terms of cost, efficiency, and fairness. *Energy Econ.* <https://doi.org/10.1016/j.eneco.2018.11.004>.
- Wang, J., Wang, K., Shi, X., Wei, Y.M., 2019b. Spatial heterogeneity and driving forces of environmental productivity growth in China: would it help to switch pollutant discharge fees to environmental taxes? *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2019.03.045>.
- Wang, K., Wu, M., Sun, Y., Shi, X., Sun, A., Zhang, P., 2019c. Resource abundance, industrial structure, and regional carbon emissions efficiency in China. *Resour. Pol.* 60, 203–214. <https://doi.org/10.1016/j.resourpol.2019.01.001>.
- Wang, K., Zhang, X., Yu, X., Wei, Y.M., Wang, B., 2016c. Emissions trading and abatement cost savings: An estimation of China's thermal power industry. *Renewable and Sustainable Energy Reviews* 65, 1005–1017.
- Xian, Y., Wang, K., Shi, X., Zhang, C., Wei, Y., Huang, Z., 2018. Carbon emissions intensity reduction target for China's power industry: an efficiency and productivity perspective. *J. Clean. Prod.* 197, 1022–1034.
- Zhang, Y.-J., Chen, M.-Y., 2018. Evaluating the dynamic performance of energy portfolios: empirical evidence from the DEA directional distance function. *Eur. J. Oper. Res.* 269, 64–78. <https://doi.org/10.1016/j.ejor.2017.08.008>.
- Zhang, X., Yang, J., Wang, S., 2011. China has reached the Lewis turning point. *China Econ. Rev.* 22, 542–554. <https://doi.org/10.1016/j.chieco.2011.07.002>.
- Zhang, Y.J., Jin, Y.L., Shen, B., 2018. Measuring the energy saving and CO2 emissions reduction potential under China's belt and road initiative. *Comput. Econ.* <https://doi.org/10.1007/s10614-018-9839-0>.
- Zhang, Y., Rui, N., Shi, X., Wang, K., Qian, X., 2019. Can energy-price regulations smooth price fluctuations? Evidence from China's coal sector. *Energy Pol.* 128, 125–135. <https://doi.org/10.1016/j.enpol.2018.12.051>.