Energy Policy 151 (2021) 112165

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

Residential coal-switch policy in China: Development, achievement, and challenge

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A R T I C L E I N F O

Keywords:
Residential coal-switch policy (RCSP)
Policy review
Development characteristics
Achievement assessment
Future challenges
China

A B S T R A C T

Historically, coal has been a primary input driving China's economic growth. However, it has impacted air quality significantly and negatively in the past decades. Among all efforts and measures, the Residential Coal Switch Policy (RCSP), implemented in the 1990s, is considered the most fundamental but challenging pathway toward reducing pollution. This study offers a comprehensive policy panorama to policymakers and researchers, explaining the dynamic evolution of the RCSP under varying objectives and constraints. Based on 66 policy documents issued by the central government during the years 2012–2019, the study reviews the RCSP systematically and presents three development stages. We create an index to measure policy-enforcement intensity at each stage and find that policymakers have become more sophisticated in identifying specific target groups, increasing the use of target-management tools over time. Results indicate that most of the Beijing-Tianjin-Hebei and surrounding areas have achieved and exceeded established targets. Command and control, financial support, competitive funds, and residential willingness to pay for air quality are the primary factors related to achievement. Future challenges are also presented, including the unsustainability of subsidies, the absence of building-reconstruction investment, and the scarcity of clean energy.

1. Introduction

Coal is the dominant energy source fostering economic growth in China. Yet, it produces negative environmental impacts. The massive use of coal in recent years resulted in the severe air pollution that has swept across China, especially in the Beijing-Tianjin-Hebei (BTH) and surrounding areas, during the winter heating season from mid-November to mid- March (Yuan et al., 2018). To tackle coal-induced air pollution, the Chinese government has launched an ambitious and tough clean air action plan. During the past decade, dozens of policies have been released in an attempt to curb worsening air quality. In 2013, the State Council (SC) issued the *Air Pollution Prevention and Control Action Plan (APPCAP)*, which was considered to be the most stringent air pollution control policy in China. It promised to reduce coal consumption and improve air quality (Jiang et al., 2015; Zhang et al., 2018).

To support the implementation of *APPCAP*, the government also launched coal-switch policy, which aimed to strictly decrease coal consumption and increase the use of clean energy, such as natural gas. Specifically, small-scale coal-fired boilers would be superseded (Zhang et al., 2015) and household coal-based heating and cooking systems would be replaced by equipment fueled by natural gas and electricity (Chen et al., 2016b; Edwards et al., 2004). The policy covered not only centralized coal use in the power and industrial sector but also included scattered coal use in the residential sector.

This study focuses on the Residential Coal Switch Policy (RCSP) and evaluates its effectiveness for long-term development. The significance of the RCSP in practice is substantial large although its implementation is challenging. Controlling residential coal consumption is the most critical method of reducing coal-induced air pollution. Using the BTH region as an example, scattered coal in the residential sector contributes more than 50% of the major air pollutant emissions, due to its relatively poor fuel quality and low combustion efficiency (Chen and Chen, 2019). The challenge of implementing coal-switch policy varies across sectors. Considering all options for coal-reduction, targeting the centralized coal in the power and industrial sector, "low-hanging fruit," is a high priority (Liu et al., 2016; Shen et al., 2010; Zhao and Chen, 2015).

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https://doi.org/10.1016/j.enpol.2021.112165
Received 28 September 2020; Received in revised form 2 January 2021; Accepted 15 January 2021

Comparatively, controlling the scattered coal in the residential sector is the most difficult task, and has been a lower priority. The biggest concern in this area is that the retrofit costs are much higher than residents can afford, an obstacle that prevents programs from running smoothly (Carter et al., 2014). Another concern is that the RCSP is strongly connected to people's livelihood, and it is difficult to gain consensus among different populations, depending on their own personal heating preference (Kanagawa and Nakata, 2007; Romieu et al., 2002).

To our knowledge, the RCSP has had little systematic, quantified analysis; our study is among the first in this area. Previous studies have made substantial contributions to the cost-benefit simulation of regulatory policy (Guo et al., 2018; Peng et al., 2017; Sun et al., 2018; Yang and Teng, 2018; Zhang and Smith, 2007) and to the evaluation of temporary emission-control action (Brown et al., 2015; Kan et al., 2004; Liu et al., 2018). Research topics have ranged from the industrial sector to the residential sector and, geographically, from the city to the village (Chen et al., 2006; Sun et al., 2017; Wang et al., 2019b). However, many important questions remain and are worth investigating, including: how has the RCSP has developed over time, what factors determine the policy's performance, and what challenges the RCSP will confront in the future.

To fill this research gap, we offer a comprehensive policy panorama by collecting policy documents amassed through online searches of various government agencies. More than sixty policies issued by the central government from 2012 to 2019 were used to conduct a systematic review of RCSP. We have carefully summarized policy in three development stages and generated a policy-enforcement intensity index at each stage. Results indicated that policymakers have become increasingly sophisticated identifying specific target groups using target-management tools more regularly over time. Achievement assessment indicated that most of the BTH and surrounding areas achieved and exceeded their targets. Importantly, our study identified the primary factors that affect RCSP fulfillment, ranging from command and control, financial support, and competitive funds to residential willingness to pay for air-pollution abatement. We have also detailed the challenges RCSP will confront in the future, including the unsustainability of subsidies, the absence of building-reconstruction investment, and the scarcity of clean energy options. Results of this study may be important to decision-makers and policymakers at all levels as well as to scholars, helping them better understand how and why China's public policy evolved under variable targets and constraints in different stages.

The remainder of this paper is organized as follows. In Section 2, we provide an overview and summarize policy development. Section 3 quantifies policy enforcement to date. Section 4 assesses achievement and discusses the driving forces behind policy performance. Section 5 presents future challenges. The last section offers conclusions and outlines policy implications.

2. Development of RCSP in China

This section reviews different policy documents obtained through online searches of government agencies. Themes cover residential clean heating, coal-to-gas transition, coal-to-electricity transition, among others. To summarize the historical timeline, 66 polices issued by the central government during the years 2012–2019 are employed (see Appendix for a complete document list). Acknowledging spatial-temporal change, we summarized the timeline as three development stages of the RCSP.

2.1. Local pilot stage (pre-2012)

China launched the RCSP as early as the 1990s. In October 1999, the Beijing Municipal Government issued *Environmental Pollution Prevention Targets and Countermeasures in Beijing* to reduce coal-heating pollution in winter and improve the energy mix. The "coal to clean energy" pilot program (including coal-to-electric and coal-to-gas for residential space heating) was implemented first. Primarily, it aimed to control coal-burning pollution and reduce building-fire risks. This program covered more than ten thousand households in core cultural-relics reserves during the years 2000–2003. To meet the promise of a "green Olympics" in 2008, the Beijing Municipal Government and the State Grid Corporation of China restarted the coal-to-electric program, addressing nearly 160,000 households during the years 2006–2009.

The pilot residential coal-switch program during this stage covered some of the key local protected urban districts (include the Xicheng District and the Dongcheng District) in Beijing.

2.2. Regional application stage (2012–2016)

The year 2012 featured a milestone: the residential coal-switch policy's transformation from a local pilot program to a large-scale regional application, motivated by the implementation of air-pollution-control policies nationwide. Compared with the previous stage, Stage 2 changes were as follows:

First, Stage 2 was large-scale and set quantitative goals for the first time. In September 2013, the SC issued the *APPCAP* and outlined the roadmap for national air-pollution control for the years 2013–2017. The established air-pollution-reduction goals covered the BTH area, the Yangtze River Delta, and the Pearl River Delta. The *APPCAP* also proposed a series of measures to move forward with the coal switch in industrial and residential sectors, including centralized coal heating, coal-to-electric heating programs, and coal-to-gas heating programs. The central government announced its first RCSP quantitative goals: gradually phasing out all coal-fired boilers with a capacity of 10 tonne/hour or less and forbidding construction of coal-fired boilers with a capacity of 20 tonne/hour in urban areas of prefecture-level cities by 2017. Although the goals of phasing out small coal-fired boilers with low efficiency were mainly implemented in the industrial sector, it also covered the residential sector such as coal-fired boilers using for urban central heating.

Second, Stage 2 set stricter goals for targeted areas. In September 2013, the Ministry of Environmental Protection (MOE, changed to the Ministry of Ecology and Environment after March 2018) and other ministries jointly issued *the Implementation Rules of the Action Plan for Air Pollution Prevention and Control in Beijing–Tianjin–Hebei and surrounding area*, which defined the Shandong, Shanxi, and Inner Mongolia as the surrounding areas of the BTH region. The BTH and surrounding areas were targeted for implementation of RCSP. In addition, the central government proposed a tighter RCSP quantitative goal for targeted areas: gradually phasing out all coal-fired boilers with a capacity of 10 tonne/hour or less in urban areas of prefecture-level cities by 2015.

Third, Stage 2 began supplementing supporting policies in unexpected cases. RCSP was expanded rapidly and on a large scale; the BTH and surrounding areas were prioritized high. However, the intensive installation and application of the coal-to-gas program in some regions unexpectedly resulted in a severe natural gas shortage in the winter of 2013. To ease the supply-demand gap, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the *Emergency Notice on Effectively Committing Gas Sources and Gas Supply Contracts to Ensure the Orderly Implementation of Coal-to-gas* in November 2013. The notice proposed that coal-to-gas projects only be pursued once access to natural gas supplies had been secured. In terms of gas supply, the central government supplemented with two supporting targets. The first was to establish a clean-coal network covering all town and villages in the BTH area; the utilization rate of clean-coal was to be above 90% by the end of 2017 (National Development and Reform Commission, 2014). The second target was to prepare an action program to meet the 112 bcm/y of natural gas demand expected to be generated from coal-to-gas projects by 2020 (Office of the State Council, 2014).

2.3. Overall adoption stage (post-2016)

The year 2016 marked a new era, with the overall and uniform adoption of RCSP in Northern China. Compared with previous stages, this stage differed in the following ways:

First, Stage 3 provided wider coverage. The $PM_{2.5}$ targets committed to by *APPCAP* had not been met, especially in the northern cities. Therefore, all northern provinces, instead of just the ten provinces (including Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia, Shanghai, Jiangsu, Zhejiang and Guangdong) of Stage 2, became covered areas. More importantly, coverage spread from urban to sub-urban areas (especially urban village and urban-rural junctions) as well as to rural areas. In July 2016, the MOE and the governments of Beijing, Tianjin, and Hebei announced *the Intensive Air Pollution Prevention and Control Measures for Beijing–Tianjin–Hebei (2016–2017)*. The measure first required local government to promote the coal-to-gas or coal-to-electricity switch in the residential sector in rural areas of the BTH region by October 2017.

Second, Stage 3 established specific high-priority target cities. In February 2017, the MOE issued the *Work plan for air pollution prevention and control in Beijing-Tianjin-Hebei and surrounding areas in 2017*. As shown in Fig. 1, the targeted BTH and surrounding areas had a new boundary that included the "2 + 26" cities, which contains Beijing, Tianjin and 26 other cities in the smog-prone provinces of Hebei, Henan, Shandong and Shanxi. It also required each city to complete the replacement of 50,000–10,0000 coal-fired home heaters by gas or electricity home heaters by October 2017.

Third, more quantitative goals were set. In August 2017, the MOE, together with other ministries, promulgated a further *Action and Inspection Plan for Tackling and Comprehensive Management of Air Pollution in Beijing–Tianjin–Hebei and Surrounding Areas during 2017–2018 Autumn/Winter*. This plan set up a detailed list of coal-to-gas and coal-to-electricity targets, aiming to complete the replacement of coal by gas or electricity in three million households (including 300,000 in Beijing, 290,000 in Tianjin, and 1,800,000 in Hebei) by October 2017. During the same period, the NDRC and other ministries collaborated to issue *Clean winter heating planning for northern areas (2017–2021)*. It set a target to save 150 million tonnes of scattered coal by 2021 in the residential sector. It is equal to the total energy consumption in Poland in 2017 and will complete coal the transition for more than 26 million households. This would be the largest-scale residential energy transition in the world.

Fourth, Stage 3 was more flexible and adaptable. For example, in 2017 the idea of supplying gas to approximately 180,000 households was disrupted due to a natural gas supply shortage in Hebei (Miyamoto and Ishiguro, 2018). To respond to this urgent social problem, in December 2017 the NDRC, the NEA, the Ministry of Housing and Urban-Rural Development (MHURD), and the MOE issued four documents with emergency measures to address the heating problem. The central government urgently adjusted coal-switch policies and relaxed the coal-to-gas quantitative targets. Instead of a "one-size-fits-all" outlook, they promoted clean heating in accordance with local conditions; in fact, smokeless coal was accepted in some areas.

Fifth, policy was evolving over time. When winter ended and the heating problem was alleviated, the central government revised the residential coal-switch policy, proposing that clean heating should be promoted according to local conditions. Local governments were encouraged to explore options for clean heating, such as smokeless coal heating, geothermal heating, and solar heating. The coal-to-gas and coal-to-electricity projects would proceed effectively in key regions. The central government emphasized that measures that supported these projects must be ensured. For example, coal-to-gas switch projects should only be pursued once access to natural gas supplies was secured and the steps to upgrade supporting power grids completed well in

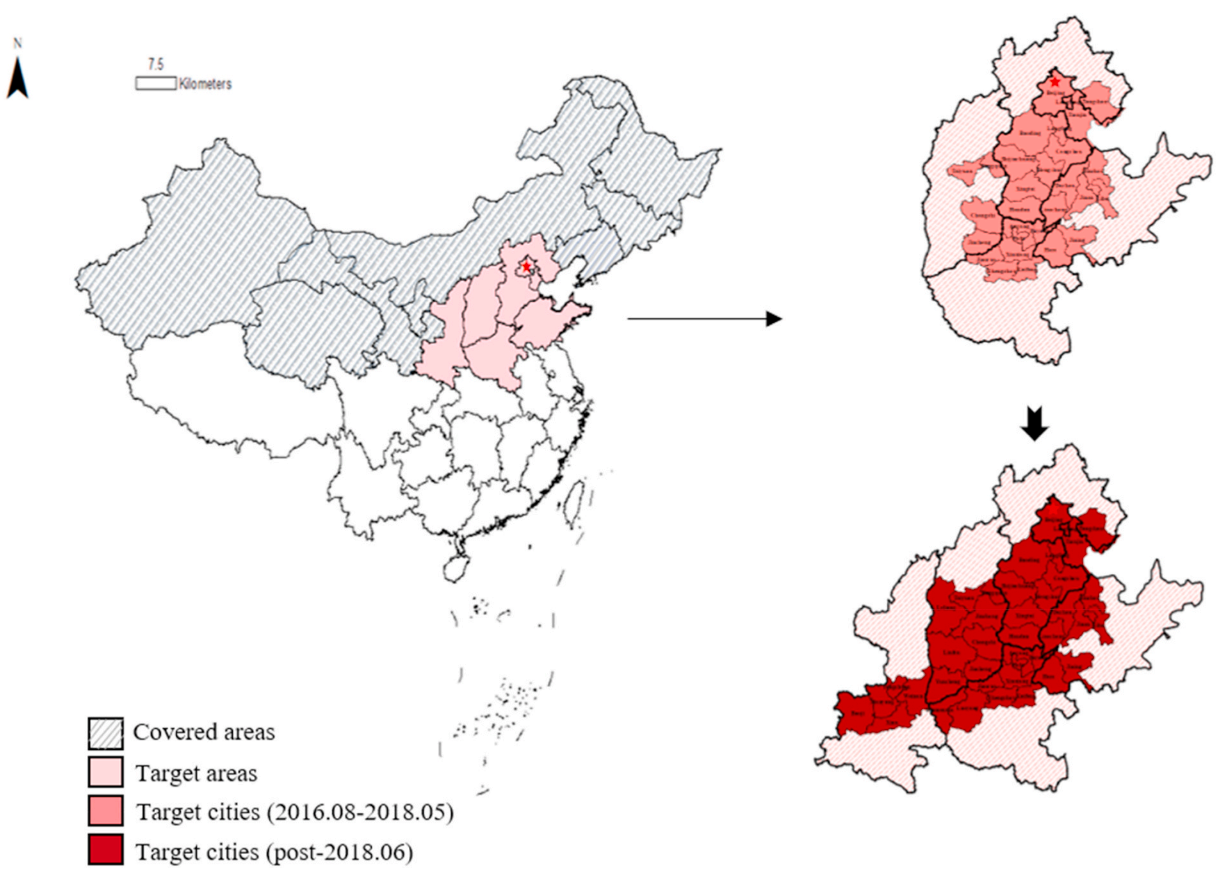

Fig. 1. The covered and target areas of RCSP in Stage 3.

advance.

The severe gas-shortage problem prompted policymakers to prepare new and more rational quantitative targets. In June 2018, the SC issued the *Three-Year Action Plan for Winning the Blue-Sky Defense Battle* that presented a three-year comprehensive action plan to tackle air pollution. It delivered two measures related to RCSP. The first extended the geographical scope of coal-fired boiler management to county-level. By 2020, local governments in targeted areas should gradually phase out all coal-fired boilers with a capacity of 10 tonne/hour or less in the urban areas of each county. The second measure expanded the number of targeted cities (as shown in Fig. 1). Under this plan, three new areas (Xiong'an New District, Fenhe river plain, and Weihe river plain) were added to the targeted areas.

2.4. Summary of the three stages

We compared the three development stages of the RCSP by policy coverage, technical options, and quantitative targets. The results are summarized in Table 1, which presents the policy-change trends discussed here.

First, RCSP coverage expanded from a local pilot program to northern areas of China, with more attention paid to the BTH and surrounding areas. Within that zone, the RCSP coverage spread from urban areas to suburban and rural areas.

Second, more technical alternatives and options were allowed, considering the economic cost and feasibility of coal-switch programs. In Stage 1, the residential coal switch in Beijing was primarily a coal-to-electric heating model. Since 2012, coal-to-gas heating and coal-to-electric heating have both been common pathways. Note that there were significantly different costs for these two options. The cost of the coal-to-gas transition was relatively lower than the cost of the coal-to-electricity transition (Wu et al., 2020). Correspondingly, the number of coal-to-gas programs was larger than that of coal-to-electricity programs during Stage 2. In Stage 3, expanded technical options, including coal-to-clean-coal and coal-to-biomass, were introduced and made available in different areas.

Third, additional quantitative goals were proposed. The goals of RCSP were qualitative in Stage 1 but quantitative in Stages 2 and 3. Quantitative goals included phasing out coal-fired boilers in Stage 2 and completing coal-to-gas/electric programs in Stage 3. In addition, the decision-makers has carried more and more supporting measurements for the coal switch since Stage 2, such as financial support for pilot areas. As RCSP advanced through time, the policymakers learned and improved. It shows that, along with putting the programs into practice and getting feedback, the policymakers are more sophisticated to identify the specific target groups for transition programs with increased use of target management tools.

3. Assessing policy intensity

To illustrate the RCSP's dynamic changes over the years, we quantified policy-enforcement intensity during the years 2012–2019. The time period before 2012 was excluded due to the fact that very few policy documents were issued during that time. More than sixty policy documents related to residential coal-switch policy that were issued by the central government and relevant ministries were selected for text analysis. We divided all of the documents into three categories: special policy, supporting policy, and comprehensive policy. Special policy directly addressed the issue of the coal switch and included documents such as *Plan on Air Pollution Prevention and Control in Key Regions, Winter Clean Heating Plan in Northern Area During 2017–2021.* Supporting policies involved supporting measurements for the coal switch, such as *Emergency Notice on Effectively Committing Gas Sources and Gas, Implementation of the Central* Financial Support *for Winter Clean Heating in Pilot Areas in Northern Regions.* Finally, comprehensive policy included plans or notices issued by the central government that mentioned residential coal switch just briefly, such as *Energy Development Strategy Action Plan (2014–2020).*

Extracting a set of keywords that characterize the policy documents, we established the policy enforcement intensity index (PEII) based on two criteria: the authority level and the target guidance. Table 2 lists the five indicators of these two criteria and their definitions.

Authority level was a three-part criterion. First was the document type. A policy with a title that included "Notice" or "Announce" was awarded a score of 1, while a document with key words such as "Opinions" or "Measurement" in its title was scored as 2. The words "Planning" or "Deployment" in a title produced the highest score of 3. The second indicator of authority level was the leading body. The

Table 2
The hierarchical structure of policy enforcement intensity index.

Index	Indicator definition		Value
Policy enforcement intensity	Authority level	Document type	1 = Notice or Announce 2 = Opinions or Measurement 3 = Planning or Deployment
		Leading body	1 = Ministry 2 = NPC or SC
		Number of involved agencies	1 = one agency 2 = some agencies (2–5) 3 = more agencies (≥5)
	Target guidance	Target type	1 = qualitative target 2 = a few of quantitative targets 3 = detailed quantitative targets
		Implementation duration	1 = less than one year 2 = between 1 and 5 years 3 = more than 5 years

Table 1
The characteristic of RCSP in different stage.

Stage	Year	Coverage			Technical options			Quantitative goal		
		geographic position	Urban	Rural	Coal-to-gas	Coal-to-electric	Others	Phasing out coal-fired boilers	Completing coal-to-gas or coal-to-electric	Carrying supporting measures
Stage1	Pre-2012	Beijing	★		★	★★				
Stage2	2012–2016	B-T-H, Pearl River deltas, Yangtze River deltas	★★★		★★★	★★	★	★★		★
Stage3	Post-2016	Northern China	★★	★★★	★★★	★★★	★★	★★★	★★★	★★★

Note: The number of stars qualitatively describes the degree for each characteristic. 1 star represents "few, minority or weak", 2 stars implies "some, moderate or middle" and 3 stars means "many, majority or strong".

National People's Congress (NPC) and SC represent the highest administrative and legislature organizations, respectively. Accordingly, policy issued by NPC or SC were scored 2, while documents from ministries were scored 1. The third indicator of authority level was the number of involved agencies. A document issued jointly by multiple government agencies would be expected to generate a wider scope and greater impact. Counting the number of involved agencies, documents were scored accordingly on a 1–3 scale.

The target-guidance criterion had two components. The first component was target type, with the score dependent on whether the proposed target was qualitative or quantitative. Goals that were "measurable, reportable, and verifiable" fulfilled the quantitative definition. Documents with vague qualitative targets were scored lowest with a score of 1, while detailed quantitative goals within documents earned the highest score of 3. The second component was policy duration. In general, a short-run policy was associated with a temporary task while a long-term policy was designed to solve strategically challenging tasks. This component was scored on a 1–3 scale as well, with an established duration of 5+ years scoring highest at 3.

The PEII was estimated by multiplying the five indicators' scores. The mean ranged from 1 to 81, depending on policy type. Fig. 2 illustrates the PEII of RCSP in China during the year 2012–2019 by the three policy types. Color is used to depict different policy types, while the bubble size represents the PEII score. A larger bubble implies a stronger policy-enforcement intensity.

We can summarize the policy-enforcement trends shown in Fig. 2. First, the RCSP was strengthened during the years 2017–2018 in terms of both the number of policies and policy-enforcement intensity. These results indicate that the residential coal-switch policy received more attention and focus, and saw more improvement, as a result of enforcement by the central government in Stage 3. Second, supporting policies seemed to follow special policies in Stage 2, with certain lags. This trend may reflect the fact that policymakers did not respond completely or adequately in some cases and supporting policies were issued to supplement or close loopholes of existing special policy. However, supporting policies in Stage 3 (i.e., financial support and natural gas supply policies) were pre-designed and synchronized with the special policies. These results offer evidence that the coordination and synergy among policies greatly improved in the latest stage of RCSP. Third, the RCSP was more frequently mentioned in comprehensive policies in stage 3, indicating that this issue was given high priority and incorporated into various policies.

4. Assessing the driving forces and achievements of RCSP

4.1. Assessing achievement

With policy implementation, the most important factor is whether it can achieve the committed target. During the years 1999–2018, the RCSP have replaced coal with clean energy (particularly, with gas and electricity) in approximately 13 million households, reducing coal use by approximately 40 million tonnes in the BTH and surrounding areas. Beijing has been implementing RCSP since the 1990s; more than 200,000 households completed the coal-substitution process in Stage 1 (Wang, 2013). During Stage 2, the goal of phasing out all coal-fired boilers with a capacity of 10 tonne/hour or less was achieved in urban sections of prefecture-level cities in the targeted area.

We compared the target to the achievement of RCSP in targeted areas in Stage 3 using detailed data from the period. For the BTH and surrounding areas, the central government established a coal-substitution goal in more than 3 million households in 2017. The goal was more than realized, with nearly 6 million households completing a coal-substitution process and 18 million tonnes of coal reduced. These results contributed 21% to the decline of the average concentration of $PM_{2.5}$ in 2017 (Natural Resources Defense Council, 2018). Fig. 3 presents the goals and final achievements for the BTH and surrounding areas in 2017.

Most of the BTH and surrounding areas achieved and exceeded the target goals. The completion rates for replacing coal with gas or electricity in households in Beijing and Tianjin were 78% and 62% more than planned, respectively. The completion rate in Hebei was the lowest, but it still exceeded the goal by 18%. The rate of achievement in Henan was substantial compared to its goal, 2.9 times more than the policy's goal. With coal substitution completed for nearly 6.15 million households and a total coal reduction of 16.08 million tonnes, the RCSP achievements in 2018 exceeded target goals (Natural Resources Defense Council, 2019).

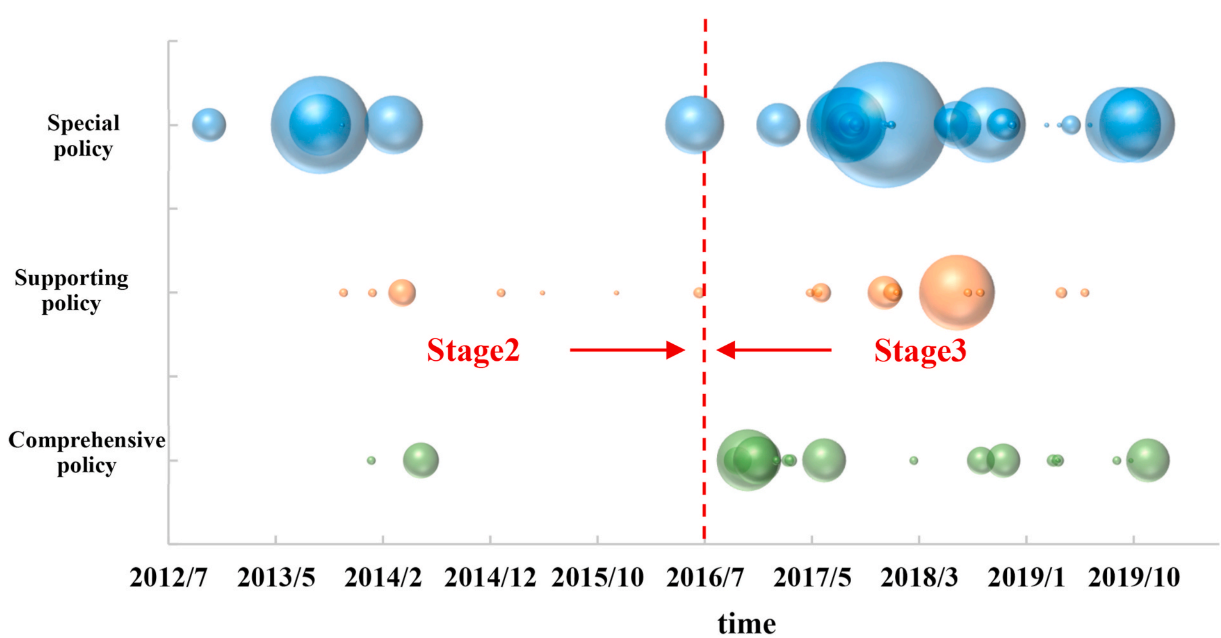

Fig. 2. Enforcement intensity of residential coal switch policy in China.

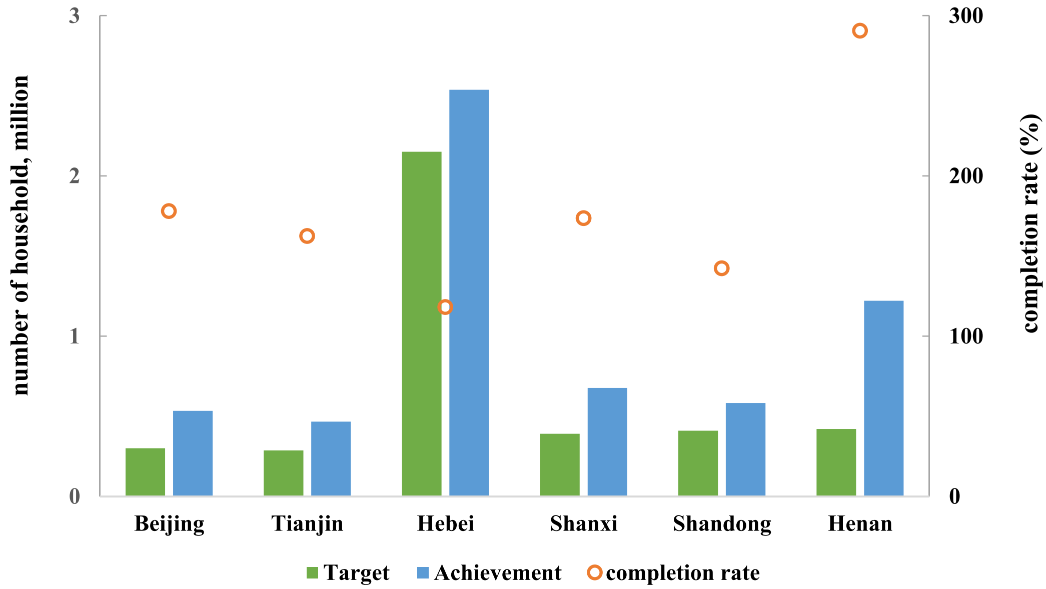

Fig. 3. The quantitative target and achievement in B-T-H and surrounding area in 2017.
Note: The data of objectives of residential coal switch is from *Action and Inspection Plan for Tackling and Comprehensive Management of Air Pollution in Beijing–Tianjin–Hebei and Surrounding Areas during 2017–2018 Autumn/Winter*; The data of Completions of residential coal switch is from local media.

4.2. *Factors affecting achievement*

What drove the success of RCSP? Four elements, summarized as follows:

4.2.1. *Government command and control*

The distribution of management responsibility among different decision-makers generates different incentives and outcomes. In the largely decentralized political system, leadership relationships are often not with vertical administrative superiors (*Tiao*), but with horizon local governments (*Kuai*) at the same administrative level. Despite the central government's efforts to tackle air pollution and implement RCSP, there are frequent obstacles. Inevitably, local governments care most about their own interests, such as economic growth, and engage in selective policy implementation (Kostka, 2014; Mertha, 2005).

However, in this case, we observed that the governance system was dynamically developed under different backgrounds. For example, the Beijing municipal government was the main policymaker in Stage 1, while it shifted to comply with central government guidance in Stage 2. In Stage 3, the central government continued to reform the environmental management system, better clarifying responsibility and strengthening supervision.

The first innovative measure was the environmental cadre responsibility system. A similar strategy had been applied since 2010 to help realize the nation's energy-saving and emission-reduction plan (Chen et al., 2016a; Meng et al., 2019). In March 2017, the central government issued the *Work plan for air pollution prevention and control in Beijing, Tianjin and Hebei and surrounding areas in 2017*. This work plan included top-down distribution targets for local government. Local governments were required to produce a detailed plan and further disaggregate the goal to its communities, state-owned enterprises, and others. Fulfillment of the detailed goals and targets would be linked to the performance and promotion of local officials. This strategy created strong incentives to abide by the cadre responsibility system.

The second tool was an environmental supervision system. In January 2016, the central environmental supervision group was established formally to strengthen supervision. The central inspection team sent numerous law enforcement officers to 28 major cities in the BTH and surrounding areas to inspect air-pollution control work during the years 2017–2018. New monitoring indicator and evaluation systems for environmental protection were created to ensure the achievement of the target goals. Failing to achieve the goals would lead to punishment of officials. For example, if the environmental issues found by the inspection team were not resolved very well, local officials could be publicly interviewed and held accountable. In 2018, more than 5000 local officials were interviewed and approximately 8644 officials had accountability demanded of them by the central environmental supervision group (Liu, 2018).

Financial support

Continuous increases in financial support from the government provided economic incentive that helped households switch from coal-based heating to other fuels. For example, in Stage 1, residents who participated in the coal-switch program were subsidized and did not need to pay for the switch. As shown in Fig. 4, the central and local governments jointly undertook the financial burden to cover the partial cost of the coal-switch program after 2012.

According to *APPCAP* requirements, the central government has set up special funds for tackling air pollution (i.e. using for the replacement of coal-fired boilers and the substitution of scattered coal) since 2013. In general, the central and local governments shared the subsidy burden in determined proportions; the local government undertook a relatively higher share for local affairs. The total fiscal expenditure was 11.9 billion Yuan in 2013 and reached 89.5 billion Yuan in 2018 with an extremely high annual growth rate of 49.7%. Both central and local expenditures accelerated in 2017 and 2018, driven primarily by increasing expenditures on clean heating. This trend of financial support is consistent with the trajectory of policy intensity in the same time period, as shown in Fig. 2.

4.2.2. *Introducing competitive funds*

It is not easy for vertical administrative superiors (Tiao) to motivate horizon local governments (Kuai) to implement a new policy under China's decentralized political system. Fortunately, the reform experience proved that providing competitive funds could be an effective way to encourage local government initiative. Policymakers attract local

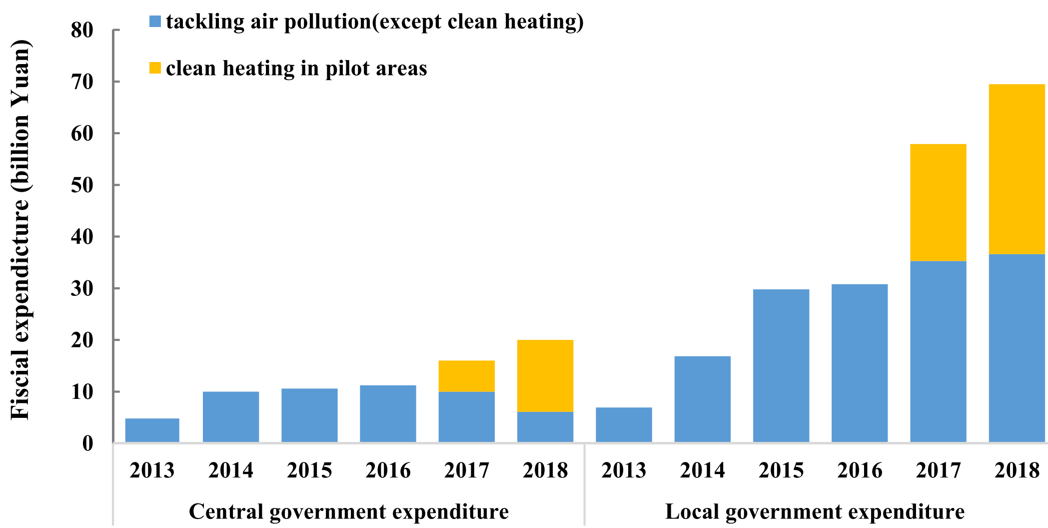

Fig. 4. Fiscal expenditure on air pollution prevention and clean heating.
Note: The data of special funds for tackling air pollution in central government and funds for clean heating are obtained from the website of the MOF, the other data are obtained from Wind database.

governments to participate in and implement new policy by providing competitive funds. Local governments that respond and cooperate actively are allocated special funds (Zhou, 2010).

In 2017, the Ministry of Finance (MOF), jointly with other ministries, created competitive special funds for clean heating to address the problem of winter haze caused by coal-fired heating in northern China. The competitive funds would mainly support cities in the BTH and surrounding areas. Cities with plentiful clean fuels and sufficient financing investment, making more proactive and scientific plans for clean heating, could have priority to be selected as pilot areas and receive allocated special funds. The MOF selected three batches of 42 pilot cities to receive subsidies for clean heating during the years 2017–2019 (as shown in Fig. 5). Municipalities received 1 billion CNY in subsidies each year, provincial capital cities received 0.7billion CNY, prefecture-level cities were granted 0.5billion CNY, and cities in the Fenhe and Weihe river plain received 300 million CNY. These subsidies, with a wide scope and high intensity, were provided primarily for programs transitioning from coal to gas and coal to electricity. In 2018, in

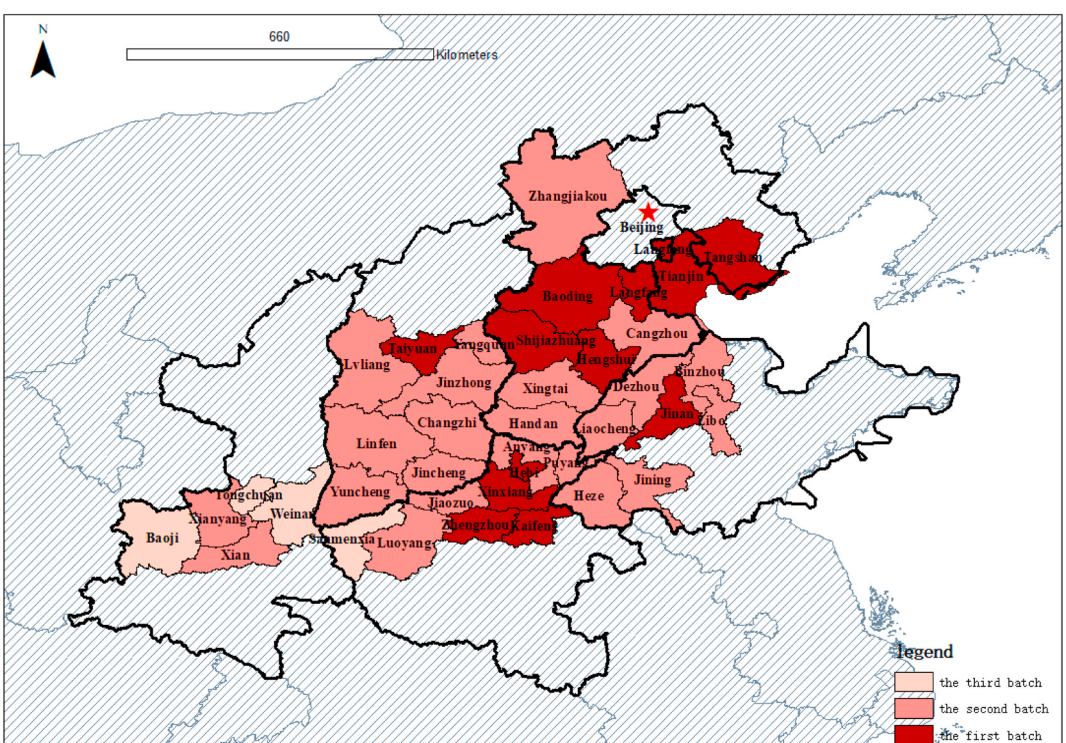

Fig. 5. The distribution of pilot areas within competitive funds for clean heating.

some rural pilot areas the clean-heating rate reached more than 60%, higher than in non-pilot areas.

4.2.3. Residents' willingness to pay for air quality

The central government called upon citizens to recognize their own environmental responsibilities. If a sense of environmental responsibility can be introduced into the public's life and work, the smooth implementation of air-pollution prevention and control can be largely accomplished by individual-level action (Sun et al., 2016). The willingness to pay (WTP) for air protection is regarded as an extremely important measure of environmental-protection awareness. WTP also reflects the motivation of residents to participate in RCSP (Laroche et al., 2001; Roe et al., 2001; Wang and Zhang, 2009). Existing studies have shown that with improved living standards, residents in China prefer to pay for pollution abatement (Sergi et al., 2019; Zhang et al., 2017). Chen et al. (2019) used national survey data and found that a 1 $\mu g/m^3$ improvement in tomorrow's air quality will increase average individual WTP to approximately 6.2% of annual household income, or approximately 4410 CNY. Wang et al. (2019a) mentioned that residents' WTP were affected by realization level to environment as well as their trust degree to government management. For now, the measures implemented by the government have achieved an ideal effect and public engagement will increase. Increased WTP is influenced by subjective feelings and income (Xie et al., 2020). With an increase in total income, families have a certain economic capacity to afford equipment and clean energy expenses. With increasing awareness and income levels, the residents in northern China have been shown to prefer to support RCSP.

5. Future challenges

Despite the residential coal-switch policy being continuously revised and updated to enhance its feasibility and response, it still encounters substantial challenges, especially under uncertain economic contexts. We summarize three issues that should be highlighted and investigated further.

5.1. Availability of financial resources

Economic growth has slowed since China entered a new norm stage. During the years 2013–2018, the GDP growth rate in Beijing and Hebei were fell to 6% and the GDP growth rate in Tianjin decreased from 12.5% to 3.6%. Meanwhile, the growth rate of local public revenue in Beijing decreased from 10.4% to 6.5% and decreased from 18.1% to 10% in Tianjin during the years 2013–2018. The average growth rate of local public revenue in Hebei was less than 10% during the years 2013–2018. The BTH region is facing aggravated downward economic pressure and financial stress. While subsidies of residential clean-heating programs are still provided by local and central government, there are many obstacles remain.

The local government subsidized the purchase and installation of heat pump to replace traditional coal heating stoves. Some surveys have reported that most of the residents in the BTH region are willing to replace coal heating only when they are subsidized (Clean Air Asia, 2019). It is a great challenge for local government with low fiscal revenue to subsidize the clean-heating program. The local government also subsidizes electricity or gas rates for more than three years after a heat pump is installed. However, it is doubtful that local government has abundant or even sufficient funds with which to subsidize in the long term. For example, compare Tianjin with Hebei in the BTH region. In 2018, the per capita fiscal revenue in Hebei was 4000 CNY and in Tianjin it was 15,000 CNY, almost four times as much as in Hebei. And the numbers of coal switch program in rural in Hebei is higher than that in rural in Tianjin. The Tianjin municipal government has relatively low financial pressure for providing subsidies for residents. In November 2019, the Tianjin Bureau of Energy announced that it will continue to subsidize electricity or gas rates for another three years, from November 2020 to March 2023. However, the Hebei province represented by Tangshan will gradually remove subsidies beginning in 2020. In November 2019, the Tangshan government declared that appropriate funds should be arranged to support the clean-heating program in urban and rural areas after the previous three-year subsidy policy period ended (Tangshan Municipal Development and Reform Commission, 2019). During the years 2020–2022, the subsidy will be reduced by 50% in the first year, and further reduced to 25% in the second year. No subsidy will be provided in the third year.

With the COVID-19 pandemic, fiscal revenues and expenditure in China have been significantly reduced. The fiscal revenues in the BTH and surrounding areas still have a negative growth rate in the third quarter of 2020. As heating subsidies increase, local governments will feel more financial pressure, especially in the winter of 2020. For most local governments in the BTH and surrounding areas, if the local government continues to subsidize clean-heating program, the government will experience fiscal trouble. But, if governments do not continue to subsidize, households may revert to using coal for heating. According to the official news from the MEE in 2019 in Baoding, without abundant funds, more than 36.1% of the households that had replaced coal with gas or electricity returned to using coal for heating again. There are reasons to worry that similar regression is inevitable in other areas in the future.

5.2. Need for building-reconstruction investment

Investment in building insulation performance is a fundamental cost-effective measure in the long-term (Su et al., 2018; Zhou et al., 2018). However, this measurement has not been accounted for in previous coal-switch programs.

In northern China, most rural residents build their houses by themselves. These buildings follow no uniform standards and have poor thermal-insulation performance. Even when rural residents replace coal heating with gas or electricity, the heating energy intensity in rural house is two to three times more than that in urban house (Natural Resources Defense Council, 2019). The governments in the BTH and surrounding areas have subsidized the initial installation and operation of coal-to-gas or coal-to-electricity home heaters. But the subsidies for upgrades energy-conservation reconstruction are mainly for urban areas, not for rural areas. Only Zhengzhou, Kaifeng, Hebi, Puyang, and Xi'an, have subsidized energy-conservation reconstruction for rural house. Without this building-insulation investment, the effectiveness of financial subsidies may be lowered and may result in inefficient energy consumption.

5.3. Scarcity of clean energy

Continued implementation and application of RCSP inevitably increases the demand for natural gas. The number of households participating in the coal-to-gas program in Hebei accounted for nearly 90% of the total coal-switch program in 2017. The total demand for natural gas in Hebei's heating season in 2017 was 8.2 bm^3 with a year-on-year increase of 234%. However, the natural gas supply for clean heating was 6.5 billion m^3 and met only 79% of demand (Wu, 2017). The widespread shortage of natural gas that resulted from the coal-to-gas program in the winter of 2017, especially in the northern regions, has created a severe threat to China's gas security (Wang et al., 2013; Yao and Chang, 2014).

The severe gas shortage in China forces policymakers to consider resource limits and constraints as higher priorities and accept these limits as a precondition to what comes next. The most recent updates to policy have introduced more alternative technical options that better utilize local energy resources. These measures may reduce dependence on natural gas in the short term. However, given the vast heating demand and limited clean energy, how to secure a sufficient energy supply for the resident coal-switch program remains a long-term challenge.

6. Conclusion and policy implications

This study presented how the RCSP has developed since the 1990s, summarizing policy-change trends in three development stages. RCSP coverage expanded widely from a local pilot to overall adoption, also expanding from urban to rural areas. Coal-to-gas and coal-to-electric transitions are no longer the only technical options that can be considered given the economic cost and feasibility of the coal-switch program. More quantitative goals of RCSP have been proposed, indicating that policymakers are becoming more sophisticated in identifying specific target groups with additional target-management tools.

The study also established the PEII to illustrate the policy's dynamic changes during the years 2012–2019. Analysis showed that RCSP has been proposed intense focus and dedication, the supporting policies that followed initial rollout have been pre-designed and synchronized with the special policies, particularly in Stage 3. The coal-switch effort has been given high priority and integrated into various policies.

The RCSP has achieved the target to which it is currently committed. We have proposed four factors that impacted this achievement. First, environmental governance instruments, such as an environmental cadre responsibility system and an environmental supervision system, are innovations that clarify responsibility and strengthen supervision. Second, continuous increases in financial support from the government provides economic incentive that helps households switch from coal-based heating to other fuels. Third, policymakers have created competitive special funds to attract local governments to participate actively in RCSP. Fourth, residents prefer to support RCSP more as their levels of environmental awareness and income increase.

However, RCSP still encounters substantial challenges, especially under the current uncertain economic context. Financial resource limitations, the absence of building-reconstruction investment, and the scarcity of clean energy are three highlighted issues that need to be put on a near-future policy agenda.

Our research on RCSP shed light on the continuous and wide public debate about the coal-switch policy in China. We summarize three policy implications, as follows.

First, in order to create incentive compatibility, the present rigid top-down governance pattern must become more integrated with bottom-up innovation and flexibility. Our analyses indicated that the entire RCSP process has been led by central government, a typical top-down governance model; research revealed some asynchronized connection between central government and local governments in the early stage of this policy implementation. This asynchronicity is consistent with common arguments that the responsibilities of central government vs local government are unclear and that the control targets for regional coal consumption are contradictory to central government targets (Kostka and Nahm, 2017; Sun et al., 2004). Another criticism is that inconsistent and erratic policy changes since 2013 discouraged the participation and enthusiasm of local governments and residents (Davis and Shearer, 2014; Zeng et al., 2018). These issues may be attributed partially to the patterns of top-down governance that leave final executors less room to respond to the inevitable uncertainty that policy-designers had not accounted for (Wong and Karplus, 2017). Relying on top-down implementation alone may lead to inconsistent objectives or even to potential conflict between the central government and local governments.

This history of RCSP offers clear evidence that the coordination and synergy among policies have greatly improved in the policy's latest stage. In Stage 3, RCSP was more frequently mentioned in comprehensive policies, which indicates that it was given high priority and incorporated in other, wider-ranging, policies. In the future, a more flexible system may be needed to create incentive compatibility for central government, ministries, local government, and other agencies. For example, the bottom-up governance pattern with clear responsibility definitions encourages local decision-makers to adopt innovation plans not only to better utilize local energy resources and fit local circumstance, but also to meet the central government's guidance. Historically, these bottom-up efforts and innovations have proven to be successful supplements to the top-down plan. Some have evolved into original templates of next-round national strategy.

Second, cost-effectiveness calls for more stricter enforcement of rules and guidelines, market-based instruments, and social tools. Our analysis identified clearly that the government's command-and-control policy contributed to the achievement of the switch policy significantly. However, current policy, driven by strong regulatory measures and subsidy stimulants, is not a long-term sustainable plan from a cost-effectiveness view. It has been argued that the lack of laws and the lack of detailed law-enforcement implementation requirements hampered the coal-switch program (Tang et al., 2015). How to remove long-term high subsidies for RCSP gradually, especially under an environment of tighter finance revenue, is another burning issue. These concerns call for a comprehensive solution package, aside from a command-and-control policy, to respond to both rising cost challenges and increasing uncertainty. For example, designating some components of RCSP bylaws and then carrying out enforcement of the bylaws will ease the overall transaction cost. The realization of RCSP's goals at the lowest cost may rely on more market-based instruments, which include but are not limited to efforts such as: encouraging the creation of new cost-effective tools, designing low-interest loan programs, issuing special RCSP bonds, allowing for private investment, facilitating technology research and development for energy-saving and low-emission stoves and furnaces, and promoting market competition among equipment manufacturers. Finally, it is also important to welcome the involvement of different individuals and social groups to gain more broad acceptance and support.

Third, the present narrow targeting of fuel-substitution options should be enlarged to include a broad focus on efficient improvements of fuel-related equipment and building. We have found that RCSP adopts coal-to-electricity and coal-to-gas substitutions primarily. These choices are the main competitive technical alternatives among all options (Jeong et al., 2011; Leth-Petersen, 2002). However, the options of other local and abundant energy and renewable energy sources as substitutions should be kept open, from an energy-security and long-run sustainable development view. Especially in rural area, it is important to develop solar heating and biomass heating, options that are more cost-sensitive. Overall, the choice of substitute fuels instead of traditional coal should be made by systematic comparison considering energy accessibility, affordability, and potential environmental benefits (Gao et al., 2016; Valentine, 2011).

More investment is needed for improving the efficiency of stoves, appliances, and other fuel-related equipment, as well as in buildings' thermal performance. For example, a heating-stove replacement program, and interior decoration that includes a thermal-insulation program should all be highly encouraged. These measures will increase expenditures in the short-term, but will help to cut the overall economic cost and energy consumption substantially, eventually improving long-term social welfare.

CRediT authorship contribution statement

Chang Liu: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Writing - original draft, Writing - review & editing. **Bei Zhu:** Data curation, Formal analysis, Software, Visualization, Writing - original draft, Writing - review & editing. **Jinlan Ni:** Conceptualization, Supervision, Visualization. **Chu Wei:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing - review & 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.

Acknowledgments

Chang Liu thanks the support by the National Natural Science Foundation of China (71904159) and the Science Foundation of Ministry of Education of China (19YJC790199). Bei Zhu thanks the support by the 2021 Graduate Scientific Research Fund Project of Renmin University of China (21XNH192) Chu Wei thanks the support by the National Natural Science Foundation of China (71622014, 41771564) and the National Statistical Research Program of China (2019LD09).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112165.

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