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Views & Comments

Practices and Empirical Insights from the National Research Program for Key Issues in Air Pollution in Beijing–Tianjin–Hebei and Surrounding Areas

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1. Introduction

The United States began implementing policies against air pollution in earnest starting in the early 1970s, taking several decades and an economic recession to achieve reductions in air pollution. In contrast, China has reduced its air pollution by the same amount in only seven years [1]. Compared with foreign countries, air pollution prevention and control in China began late but developed rapidly. The rapid improvement of regional air quality in China is inseparable from the quick actions taken by regional multi-governmental entities and the precise support of national strategic scientific and technological forces.

The United States enacted the first federal pollution control law, the Air Pollution Control Act, in 1955. Then, in 1963, the United States enacted the Federal Clean Air Act, and the Air Quality Control Act was passed in 1967. In 1970, the US Congress passed the Clean Air Act, which has been revised and improved many times. Along with the three earlier laws promulgated, the addition of the Clean Air Act formed a complete, normative legal system. While developing and enforcing laws and regulations related to air pollution control, the United States attached great importance to the operating laws of the market economy, and combined environmental policies based on administrative control with economic policies [2].

The prevention and control of air pollution in China mainly began in the 1970s and can be roughly divided into four stages: the initial stage (1972–1990), development stage (1991–2000), transition stage (2001–2010), and tackling stage (2011–present). Since 2013, cross-regional and large-scale continuous multi-day haze weather has occurred in eastern China. Particulate matter with an aerodynamic diameter no greater than 2.5 μm ($PM_{2.5}$) caused this complex pollution. At this stage, the main targets of atmospheric control in China are haze, $PM_{2.5}$, and PM_{10}. Volatile organic compounds (VOCs) and ozone have gradually attracted attention as well. The goal of atmospheric regulation has shifted to a focus on improving the quality of the environment, coordinating the emission reduction of pollutants, and comprehensively carrying out joint prevention and control of air pollution [3].

Since 2017, heavy regional air pollution in Beijing–Tianjin–Hebei and surrounding areas in the autumn and winter has attracted widespread concern within the community. Air pollution is widely acknowledged as a shortcoming in the establishment of a well-off society [4]. The Central Committee of the Communist Party of China (CPC Committee) and the State Council of the People's Republic of China attached great importance to the project of improving air quality, and former Premier Li Keqiang personally declared that the Ministry of Ecology and Environment of the People's Republic of China (MEE) would take the lead in joining hands with various departments to carry out the National Research Program for Key Issues in Air Pollution (hereinafter referred to as the Air Pollution Control Program).

The Air Pollution Control Program was intended to solve the heart and lung issues seriously affecting the health of residents in the area. Through the implementation of this program, multi-departmental, multidisciplinary, and cross-regional joint research has been effectively carried out. This research has led to major breakthroughs, as the researchers uncovered the causes and sources of heavy air pollution by $PM_{2.5}$ in this area—which is of widespread concern to all sectors of society—and constructed a regional heavy pollution response technology system. In addition, the researchers developed a scientific decision-making method for comprehensive air pollution control and determined the acute health effects of heavy air pollution on the population. In this way, science and technology were used to support the rapid improvement of air quality in Beijing–Tianjin–Hebei and the surrounding areas, resulting in significant social, economic, and environmental benefits. The Air Pollution Control Program has put into practice the *Resolution of the Central Committee of the Communist Party of China on Major Achievements and Historical Experience of the Party's Centennial Struggle* [5], which proposes the need for "high-quality development in which innovation becomes the first driving force, coordination becomes an endogenous feature, green becomes a universal form, opening becomes the necessary path, and sharing becomes the fundamental purpose." The program provides a blueprint for the construction of

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an ecological civilization that can be copied, promoted, and used for reference.

2. Practical results of the Air Pollution Control Program

After three years of research, the Air Pollution Control Program has achieved a number of key technological breakthroughs in the following areas: causal mechanisms; impact assessment, prediction, and forecasting; decision-making support; and precise solutions to address air pollution. The program has succeeded in clarifying the causes of heavy regional air pollution in autumn and winter, accurately identifying the characteristics of regional pollution emissions and key problems, and putting forward proposals for improving air pollution prevention and control. In 2020, $PM_{2.5}$ concentrations in China's "2 + 26" cities (i.e., Beijing, Tianjin, and 26 main surrounding cities in Hebei Province) in the Air Pollution Control Program implementation area dropped by 30% compared with 2016, and the number of heavily polluted days was reduced by 60%. The Air Pollution Control Program research accurately supported the in-depth treatment of air pollution in key industries and areas, and the model has been replicated domestically and overseas.

The Air Pollution Control Program's research has comprehensively and systematically clarified the characteristics and mechanisms of the whole process of the generation, evolution, and dissipation of heavy pollution in autumn and winter in the studied areas. It also comprehensively describes the influence of the terrain, atmosphere, and thermal structure on the process of regional heavy pollution, and quantifies the contribution of pollution emissions, chemical transformations, meteorological conditions, and regional transmission. A technical system for tracking, analyzing, and assessing heavy pollution processes was established. In addition, the Air Pollution Control Program has clarified the root causes of frequent regional heavy pollution, the necessary conditions for heavy pollution processes to occur, and the key factors for the rapid growth of secondary $PM_{2.5}$.

With the involvement of a number of stakeholders in the Air Pollution Control Program, a broad scientific consensus was achieved to provide scientific and technological support for coordinated regional pollution control and precise pollution control [4,6–10]. A regional dynamic emission inventory with high temporal–spatial resolution was established for tackling key problems; the inventory provides a basis for improving the accuracy of heavy pollution process forecasting, accurately controlling pollution sources, and supporting precise pollution control. The program also constructed a comprehensive scientific decision-making support platform on the atmospheric environment for multi-data collection, as well as a heavy air pollution weather emergency system for monitoring and forecasting, consultation analysis, early warning, and tracking evaluation. As a result of these systems, forecast timeliness has been significantly improved [11].

The Air Pollution Control Program team also released the *Research Report on the Causes and Treatment of Heavy Air Pollution* [4], which integrates the latest and most authoritative research results in the field of atmospheric environmental studies, summarizes air pollution control models and solutions with Chinese characteristics, and contributes Chinese knowledge on air pollution control to that of other countries around the world. The specific practical results are provided in Appendix A.

3. Principle approaches of the Air Pollution Control Program

3.1. Establishing organizational structures and clarifying subject relationships

The first step in implementing a program based on the model of the Air Pollution Control Program is to establish a three-level organization and management structure and to form a mechanism linking management, technology, and governance in order to promote coordination between the central government, research centers, and local governments, as shown in Fig. 1.

3.1.1. Forming a leadership group for the program

In 2017, the CPC Central Committee and the State Council set up a Premier's Fund project called "Research on the Causes and Treatment of Heavy Air Pollution." Under the leadership of the State Council, a Leading Group was established with officials in charge of the MEE as the leaders and the Ministry of Science and Technology (MOST), the Ministry of Agriculture and Rural Affairs (MARA), the National Health Commission (NHC), the Chinese Academy of Sciences (CAS), and the China Meteorological Administration (CMA) as the deputy leaders responsible for the organization, leadership, coordination, assessment, and acceptance of research tasks. The Office of the Leading Group was set up to formulate the rules of work, prepare the research program, and supervise and assess the research process. A high-level coordination and unified leadership mechanism was formed with the central government at its core.

3.1.2. Forming a research center with the "1 + X" innovation model

Through an organizational model known as the "1 + *X*" model, multidisciplinary intersection, and multi-departmental integration, the Air Pollution Control Program Center (herein after "the Center") was established with the Chinese Research Academy of Environmental Sciences (CRAES) as the main body ("1"), in collaboration with units directly under the MEE, relevant universities, and research institutes ("*X*"). The Center set up a leading body, an academic committee, and an advisory committee. The Center's focus is on the overall objective of identifying the causes of and treating heavy air pollution. Toward this end, it has brought together 295 units and 2903 scientists from various disciplines, including environmental science, geology, meteorology, chemistry, health, and economics. The three-tier structure of the Center, the Research Department, and the Research Office operates in a unified way. The structure includes a management department and five research departments, with 28 city-based stationary point tracking research offices for tracking stationary pollution sources. The Center operates according to a collaborative research model that combines virtual institutions with physical operations and the joint operation of large bodies of people; in this way, it promotes an approach from fundamental research to technological development and then to application and implementation.

3.1.3. Signing the "four-party agreement" to clarify subject matter, rights, and responsibilities through an administrative contract

The so-called "four-party agreement" is a collaborative and multifaceted management system based on management decisions, scientific research, and pollution control, as shown in Fig. 2. The four parties in the "four-party agreement" are as follows: the central government representative (i.e., the project-management office); the local governments of the "2 + 26" cities; the research center; and the city-based stationary point tracking teams. The Center is the connecting thread between these institutions, linking the central government, local governments, and science and technology teams both vertically and horizontally. The city-based stationary point tracking research teams are stationed in each city to promote orderly synergy between the local administrative units.

Through administrative contracts, the relationship between power and responsibility among the central government, project centers, and local governments has been solidified. These contracts establish a multi-funding approach in which national and local investments in fundamental research drive the industry and enterprises to invest in governance research. This approach strengthens

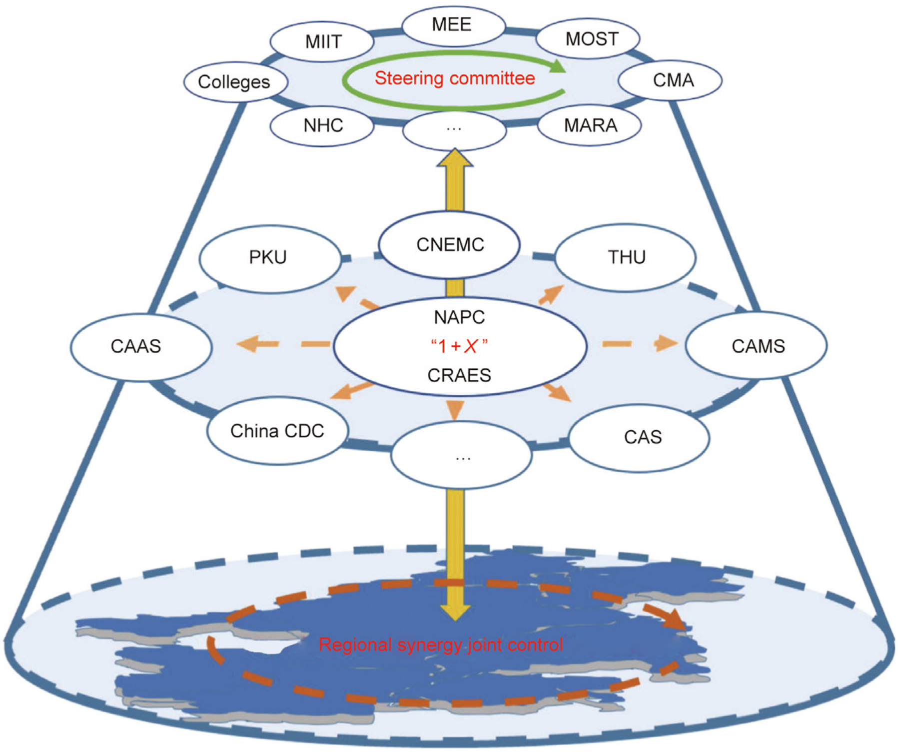

Fig. 1. Framework diagram of the organization and management of the Air Pollution Control Program. The Air Pollution Control Program Center and Chinese Research Academy of Environmental Sciences (CRAES) as the main body "1;" relevant ministries, universities, and research institutes as "X;" MEE: Ministry of Ecology and Environment; MOST: Ministry of Science and Technology; CMA: China Meteorological Administration; MARA: Ministry of Agriculture and Rural Affairs; NHC: National Health Commission; MIIT: Ministry of Industry and Information Technology; NAPC: National Joint Research Center for Tackling Key Problems in Air Pollution Control; CNEMC: China National Environmental Monitoring Centre; PKU: Peking University; THU: Tsinghua University; CAAS: Chinese Academy of Agricultural Sciences; CAMS: Chinese Academy of Meteorological Sciences; China CDC: Chinese Center for Disease Control and Prevention; CAS: Chinese Academy of Sciences.

Fig. 2. Diagram of the relationship between the four parties signing the "four-party agreement."

a multi-body collaborative governance mechanism with science and technology as the pivot. In this way, clear administrative contracts, governance areas, task objectives, implementation plans, and assessment methods have been clarified, providing a basis for two-way interaction between administrative and scientific decision-makers.

3.2. Tackling key scientific and technological blockages in regional air pollution control through research

With science and technology as the driving force, management and governance needs as the guide, and local governance and industry control as the target, a scientific research system based on multidisciplinary intersection between science and technology and environmental protection has been built. The aim of the system is to open up resources and data-sharing channels, establish a unified technique system, and create scientific and technological synergy in order to address the key causes of haze and draw up a battle plan for regional air pollution prevention and control.

3.2.1. Setting scientific and technological research tasks and building a research system

The overall objective of the research project was set by focusing on the most urgent scientific and technological problems in regional air pollution control, with the "2 + 26" cities in Beijing–Tianjin–Hebei and surrounding areas as the research and treatment targets. Based on related research, a multidisciplinary scientific and technological research foundation platform was built and a complete research system for the Air Pollution Control Program was constructed. A total of 28 topics were established within four major themes: the causes and sources of heavy atmospheric pollution, key industries and pollutant emission control technologies, comprehensive decision-making support for atmospheric pollution, and the effects of atmospheric pollution on people's health. Each research team signed a task letter written by the Prime Minister's Project Fund, specifying the content of the task, the time frame, and the assessment mechanism.

3.2.2. Establishing a fundamental research platform to promote data sharing and multidisciplinary integration

China has built the largest multifactorial, comprehensive observation network for the atmospheric environment by seizing key information resources for atmospheric management. The network includes observation satellites (air), 28 ground-based laser radar stations (sky), 252 conventional air quality monitoring stations, 38 particulate matter component stations, four observation stations, and five walking observation vehicles (ground). Based on these resources, a comprehensive observation and quality control system integrating joint field observation, laboratory analysis, and data management has been established. This system is the first to complete the collection and integration of scientific research data across institutions, industries, and departments in the field of domestic atmospheric research. The total number of units of data shared has exceeded 2.1 billion, effectively breaking the barriers to access to scientific research data, addressing the key problem of multidisciplinary synergy, and forming the basis for regional heavy air pollution prediction. This process has informed China's basic scientific research capability for regional heavy air pollution prediction, monitoring, and the rapid analysis of causes.

3.2.3. Drawing a map of air pollution prevention and control operations in Beijing–Tianjin–Hebei and surrounding areas

The technical system of the Air Pollution Prevention and Control Program was constructed based on a system of problem identification, target proposal, emission reduction analysis, program proposal, and evaluation and optimization. This approach covers region–city partnerships, dynamic inventory preparation, verification technology, multi-technology integration, comprehensive source analysis technology, control methods for key industries, and regional air quality two-way regulation and control. The technology supports the development and implementation of the three-year action plan for improving autumn and winter air quality in the "2 + 26" cities.

3.3. Promoting the rapid transformation of scientific and technological innovation by stationary tracking

The innovative "one city/one solution" (i.e., where an individual solution for precise air pollution control is provided for each city) stationary point tracking research mechanism promotes close links between science and technology decision-making and local administrative decision-making. This mechanism forms a new pattern of regional air pollution management.

3.3.1. Proposing a research mechanism for stationary point tracking and implementing the "one city/one solution" differentiated treatment

Based on the "four-party agreement," the Center played a technical role and dispatched 39 expert teams to Beijing–Tianjin–Hebei, the Fenwei Plain, and surrounding areas to conduct follow-up studies and provide technical support. Local governments played an executive decision-making role in the agreement, with the municipal party secretary or mayor personally taking charge and organizing relevant departments to establish a channel for organization, coordination, and information feedback. In this way, the local governments formed a linkage mechanism and worked closely with the stationary point tracking teams.

The stationary point tracking teams collected 58 000 filter samples from 109 sampling points in the "2 + 26" cities and closely analyzed the causes of air pollution in each city. The teams assisted local governments in quickly establishing air pollution source emission inventories and carried out front-line research and comprehensive mapping of heavily polluting industries. They also assisted local governments in establishing emergency plans for heavy pollutants, and proposed "one city/one solution" solutions for air pollution prevention and control, thereby creating the region's capacity for long-term decision-making support. At the same time, the teams assisted the local government in training talent and promoting the local technical force.

During the period of the Air Pollution Control Program, the stationary point tracking teams provided more than 2000 consultancy reports and countermeasure suggestions to local governments and industry enterprises on energy structure adjustment, industrial and traffic structure optimization, industry pollution control, emission reduction, heavy pollution process response, and so forth. The teams established a standardized information database for stationary point tracking cities in order to share science and technology, identify issues, and suggest solutions, thereby significantly enhancing the scientific and technological decision-making ability of local governments related to local precision pollution control. The efforts made to reduce emissions in the "2 + 26" cities have been remarkable. In comparison with 2015, the number of heavy pollution days in each city were significantly reduced in 2019. For example, in Beijing, Dezhou, and Baoding, the number of heavy pollution days decreased by 91%, 75%, and 71%, respectively.

3.3.2. Establishing a system of standards to promote orderly collaborative pollution management

Establishing a unified, standard system for stationary point tracking and research was essential to the success of the Air Pollution Control Program. Based on the systematic research results of the program, a unified research system of standards, methods, and quality control for comprehensive solutions to urban air pollution prevention and control was developed. This standardization resulted in the *Workbook for Tracking Research on Air Pollution Prevention and Control in the "2 + 26" Cities* and the *Technical Guide for Developing Comprehensive Solutions to Air Pollution Prevention and Control*. The tracking research teams for each stationary point implemented unified technical standards, technical guidelines, technical methods, and quality management, allowing them to fully realize the synergy of differentiated governance through unified methods.

In this way, the Air Pollution Control Program established a system of national, local, and industry standards for air pollution control. For example, for the control and management of air pollution in key industry sectors such as thermal power, building materials, and iron and steel, 304 relevant standards, specifications, and guidelines were developed and released to promote standardization and convergence of the whole process of regional pollution management and to regulate the collaborative management of air pollution in various industries.

3.3.3. Setting up a unified consultation platform to enhance the collaborative response to regional air pollution

At the regional level, the consultation platform brings together experts in environmental studies, chemistry, meteorology, industry, transportation, and other disciplines and makes it possible for them to integrate important environmental issues, information, and practical results from each station city. This process focuses on expert analysis and consultation related to heavy air pollution and creates collaborative response mechanisms in the “2 + 26” cities, forming a consultation model that involves pre-forecasting, in-event analysis, and post-event interpretation. These meetings between experts help to promote information sharing and collaborative management among the cities in the region, in order to achieve both peak reduction and frequency reduction of heavy air pollution in the region. At the local level, onsite meetings are organized in each city to coordinate the main lines of urban governance and provide systematic solutions for differentiated and precise pollution control. The “2 + 26” cities conduct daily meetings during periods of heavy pollution to quickly improve the emergency response capacity of each city in the region.

During the period of the Air Pollution Control Program, 38 regional meetings on heavy pollution were organized, and consultations on regional heavy air pollution by experts were arranged. A total of 1540 information reports, cause analysis reports, and expert interpretations were published.

4. Experience and insights from the Air Pollution Control Program

The Air Pollution Control Program is a major practical exploration in the new national system of haze management. It involves the close integration of scientific research and management decision-making, the mutual promotion of scientific research and governance plans, and the collaborative innovation of organizational management and institutional mechanisms under the national socialist market economic system. This is an important attempt in China’s ongoing war with air pollution, and it provides a valuable reference for national pollution-prevention efforts and the comprehensive promotion and construction of a sustainable civilization.

First, the establishment of a national research center, with science and technology as the guiding force, has transformed the government into a so-called “ternary synergy” (i.e., synergy between the three entities of the central government, the Center, and local governments). This center plays the key roles of an initiator (i.e., starting projects), a central system (i.e., a big data platform), and an intelligent decision maker (i.e., a collection of expert wisdom), promoting the local governments of China’s “2 + 26” cities to work toward the same goals, resulting in a flywheel effect.

Based on the theory of collaborative governance and the theory of intergovernmental relations [12,13], a governance system known as “one point, two circles, and triple synergy” was constructed, as shown in Fig. 3. In this system, “one point” refers to the Air Pollution Control Program Center. The “two circles” refer to the division of the synergistic body into two circles, where the “inner circle” is a ternary relationship between the central government and local governments, which are connected through the Center, and the “outer circle” is composed of multiple social entities including enterprises, social organizations, and citizens. Finally, the “triple synergy” refers to the “ternary synergy” of government entities as the core of the system.

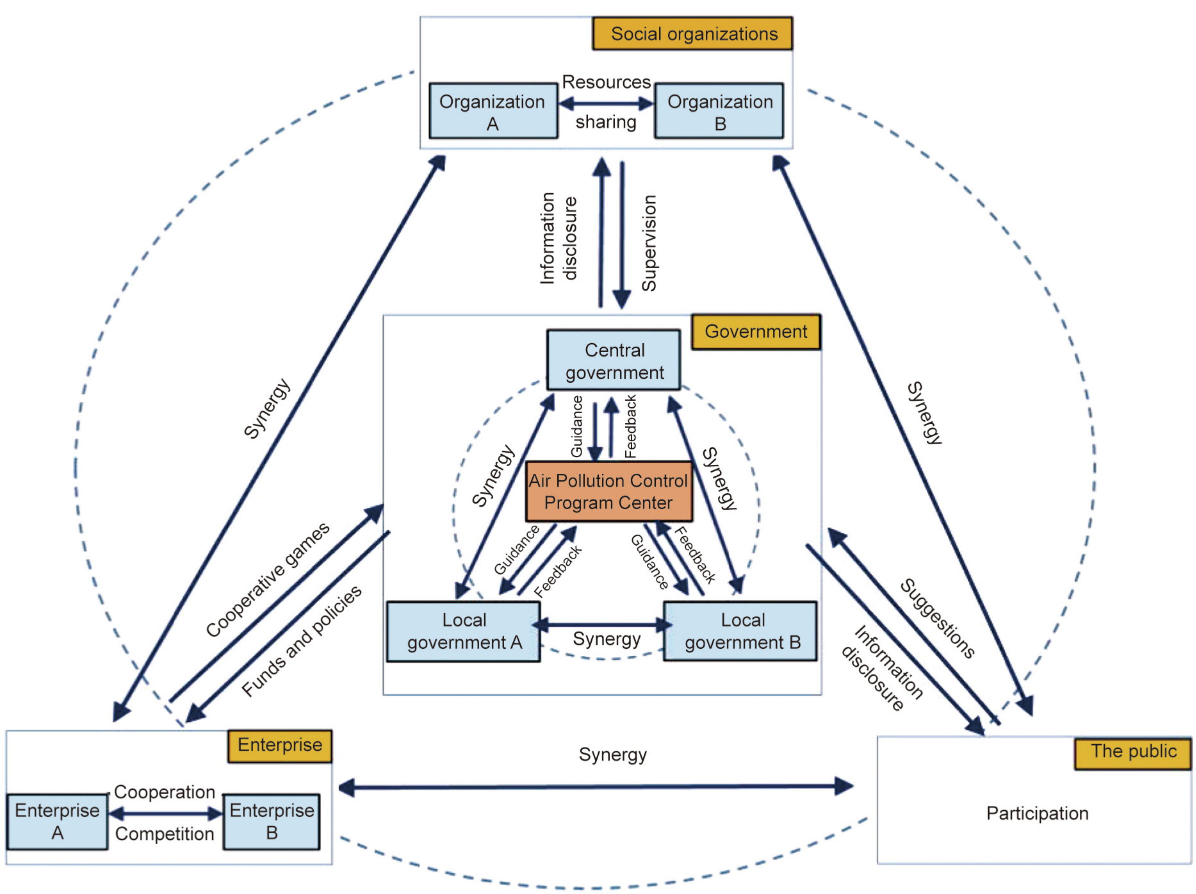

Fig. 3. The “one point, two circles, triple synergies” governance system.

Through the establishment of the Air Pollution Control Program Center, the traditional binary relationship between the government and its subjects has been changed into a ''ternary synergy'' relationship. In other words, the original binary relationship between the central government and local governments has been changed to a ternary synergy between the central government, the Air Pollution Control Program Center, and local governments. This synergistic approach breaks through organizational, geographic, disciplinary, technical, and information barriers to regional haze control and results in a joint effort to combat pollution [14]. With the government's ''ternary synergy'' at the core, government enterprises, social organizations, and the public are joining to participate in regional air pollution prevention and control practices, eventually achieving an internal and external connection between intergovernmental and intra-governmental/institutional/citizen synergy.

Second, the comprehensive use of the stationary point tracking and research mechanism known as ''one city/one solution,'' along with the expert consultation mechanism, comprises a brilliant plan that will promote scientific decision-making and precise policy implementation. Moreover, the approach helps in the development of technological innovations and in their application, promoting a shift from silos to convergence.

The institutional barriers between scientific and technological transformation and linkages in China should not be ignored, as they result in a governmental, industrial, academic, and research system that has not been effectively connected [15]. Such institutional barriers urgently need to be bridged in order to connect the ''silos'' of scientific and technological innovation and pollution control. The Air Pollution Control Program innovatively uses a stationary point tracking research model to bring scientific research to the local industry level, assigning scientific research forces in each city to participate deeply in local decision-making and industry emission reduction. The combination of all the different elements of the Air Pollution Control Program allows information to flow freely among the stakeholders involved. Scholars have conducted corresponding studies on the stationary point effect, concluding that it has significant benefits for centrally stationed agencies [16]. The practice has also shown that environmental management is more effective in the cities where stationary point tracking teams are.

Third, it is necessary to adhere to a mechanism involving research, output, application, feedback, and improvement in order to complete the approach from fundamental research to applied research, regional practice, and policy development. This is the first part of the research and output approach, which brings together the strategic forces of science and technology to quickly identify the causes of heavy atmospheric pollution, carry out source lists and source analysis, and lay the foundation for precise pollution control.

The second part of the approach is the rapid construction of an air pollution control technology system based on local conditions. This system can support the formulation of a three-year action plan to improve the air quality of China's ''2 + 26'' cities. Using an application and feedback mode through stationary point tracking research with a ''one city/one solution'' focus, the rapid application of technology for air pollution control practice has been achieved in these stationed cities. Thus, the applicability of technology was assessed in practice, shortages were identified, and technology was improved or updated. This is the third key to regional practice. Finally, through regional consultation and internal assessment, city-based teams can promote the overall perfection of scientific and technological research and provide central and local governments with advisory reports, countermeasures, and recommendations to support management decisions, forming the fourth step of the closed relay loop.

5. Conclusions

To sum up, the Air Pollution Control Program is a key component of China's new national system for haze control. Practical application has verified the ability of the ''1 + *X*'' model to tackle atmospheric problems by breaking through the organizational, regional, academic, technical, and information barriers in regional haze governance. This model effectively connects fundamental research, technology research, development, and application to solve the problems caused by the siloing of institutions and the government.

At present, given the necessity for China to present a unified effort toward pollution prevention, to actively participate in global climate governance, and to construct a sustainable civilization, it is necessary for the new national system to constantly identify areas for self-improvement in the practice of national governance. It is vital to continuously explore the top-level structural design of the national strategic scientific and technological systems in various major fields, cultivate strategic scientific and technological power with a wide lens, develop the nation's complex-system decision-making ability, and further consolidate the core driving force of the national system. Under the guidance of research, China will continue to deepen the role of market players and improve methods to align diverse interests, drive breakthroughs in applied technologies, and build and improve a new national system that integrates scientific research, technological innovation, technological integration, and practice. To do so, it is necessary to further strengthen the key driving role of strategic scientific and technological forces in government entities such as the central government, local governments, markets, and social organizations, and to form a modern governance pattern in which multiple subjects coordinate and govern together.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.08.021.

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