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Coordinating the Dynamic Development of Energy and Industry in Composite Regions: An I-SDOP Analysis of the BTH Region

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Received: 24 May 2018; Accepted: 18 June 2018; Published: 20 June 2018

Abstract: In various regions of the world, there is an urgent need to address energy challenges by accelerating the transformation of energy and industrial systems. The problem is quite complex in rapidly developing composite regions, with the necessity to coordinate the dynamic development of energy and industry in several heterogeneous subregions. Through a typical case study on the Beijing–Tianjin–Hebei (BTH) region, this study attempts to form a referable methodology for the coordinated development of energy and industry for the sustainable development of rapidly developing composite regions. The concept of an Integrated strategy of Sustainable development objectives, Decision-making systems, Operation systems, and Physical systems (I-SDOP) is proposed to describe the multilayer dynamics of complex energy and industrial systems. A five-step I-SDOP analysis is conducted to determine an integrated strategy for the coordinated development of energy and industry in the BTH region, based on the analysis of its sustainable development objectives, decision-making systems, operation systems, and physical systems. The results indicate the importance of innovation sources and extensive communications to promote market reform and engineering projects that fulfill the strong political wills and strategic plans of China's central government.

Keywords: sustainable development; multilayer dynamics; coordinated development; energy; industry; composite region

1. Introduction

The world faces serious energy challenges in the 21st century, including (1) providing affordable energy services for the well-being of the world's human population; (2) increasing energy supply security for all parts of energy systems; and (3) reducing local and regional pollution and curbing so-called greenhouse gas (GHG) emissions in order to limit a global temperature rise below 2 °C above pre-industrial levels (make efforts to limit the temperature rise even further to 1.5 °C) [1]. Therefore, there is an urgent need for various regions to actively address these challenges, especially rapidly developing regions in which there are significant emissions of air pollutants and GHGs caused by concentrated fossil fuel consumption and heavy industries. The problem is quite complex in a composite region because there is an extra requirement to coordinate the development of energy and industry in several tightly connected and heterogeneous subregions. To solve this difficult problem, it is necessary to examine typical cases around the world and develop general methodologies.

The Chinese region of Beijing–Tianjin–Hebei (BTH) is a prominent case for the development of a suitable methodology. BTH includes Beijing City (the capital of China), Tianjin City (a municipality directly under the central government), and Hebei Province, which surrounds the two cities (they are referred to as Beijing, Tianjin, and Hebei in the following content). In 2013, the BTH region contributed 10.9% of China's total gross domestic product (GDP) and consumed 11.8% of the total energy, with 8% (109.2 million) of the population [2]. This region has several typical characteristics and its additional complexity is that, as a rapidly developing composite region, it is necessary to coordinate the development of energy and industry across several subregions. First, the BTH region is experiencing rapid development with a large population. In 2013, the annual growth rate of GDP reached 10.7% [2]. Second, there is serious air pollution, mainly caused by extensive coal burning and concentrated heavy industries. In recent years, the BTH region has frequently suffered from serious smog and haze [3]. Moreover, there is an urgent need for this region to reduce GHG emissions. As stated in the 13th Five-Year-Plan (FYP) of China [4], the BTH region must reach peak CO_2 emissions earlier than the whole country, before 2030. Third, there is a large regional disparity among the subregions of BTH. In particular, Hebei, whose development depends heavily on the iron and steel industry, is far less developed and more polluted than Beijing and Tianjin. Finally, as a capital circle, the coordinated development of energy and industry in BTH is intertwined with the development of the over-crowded capital city (Beijing), which brings extra complexities. Therefore, a detailed study of the BTH region would not only provide a referable methodology and implications for other composite regions in China, but also enlighten the sustainable development of capital regions and composite regions in developing countries and regions.

According to a recent policy review, the central government of China has already expressed a strong desire to promote the coordinated development of energy and industry in the BTH region, aiming at sustainable development. On 17 September 2013, the Ministry of Environmental Protection (MEP) of China published "Detailed rules for the implementation of air pollution control in the BTH region and its surrounding areas (2012–2017)" [5] as a special complement to the national-level policy, "Action plan of air pollution control", published by the State Council just five days previously [6]. Moreover, on 28 February 2014, President Xi Jinping emphasized that the coordinated development of the BTH region must be an important national strategy [7]. With this background, the coordinated development of energy and industry in the BTH region has become a policy issue of considerable interest. In this regard, several studies have been published with implications from various perspectives:

(1) From the perspective of technological innovation, Cui and Liu [8] suggested that the enterprises in Hebei should improve their technological innovation capability by constructing a regional innovation system with Beijing and Tianjin, transforming and upgrading traditional industries, and fostering strategic new industries.
(2) From the perspectives of urbanization and the environment, Wang et al. [9] explored the interactive relationship between urbanization and ecological aspects of the environment in the BTH region, and suggested the development of sustainable urbanization strategies that better balance urbanization and eco-environmental protection.
(3) From the perspective of air pollution control, Wu et al. [10] proved that joint regional air pollution control in the BTH region will reduce the expense of air pollution control compared with a locally based pollution control strategy.
(4) From the perspectives of industrial development and carbon emissions, Wang and Yang [11] concluded that, from 1996 to 2010, the economic output effect was the main contributor to the increase of industrial carbon emissions in the BTH region, whereas the declining energy intensity and energy structure adjustment resulted in a decline in carbon emissions by industry.

(5) From the perspectives of energy, economy, and ecology, Zhang et al. [12] identified the energy utilization characteristics of the three regions and their ecological roles by mapping the embodied energy flows among them in 2002 and 2007. They found that Hebei became the main provider of embodied energy (used mainly for its own non-transportation service and construction sectors) in 2007.

(6) From the perspectives of carbon reduction and carbon trading, Han et al. [13] constructed a comprehensive index and used an integrated weighting approach to simulate the carbon quota allocation of the BTH region. They suggested that Hebei should have relatively high carbon emission quotas in the future carbon trading market.

(7) From the perspective of government administration, Liu et al. [14] indicated that administrative decentralization and fiscal decentralization strengthen the phenomenon of governmental fragmentation, leading to the promotion of economic growth while presenting an obstacle to the collaborative reduction of air pollution in this region.

Combining the above works reveals the multidimensional and multiregional complexities of the problem, and demonstrates the relatively weak linkage between the modelling of energy and industrial systems and the discussion of policy and administration issues. Therefore, it is important to strengthen the cross-layer analysis by integrating research on governmental administration and policy, market-based operations of energy and industry, and physical systems of energy use and related emissions. By further considering multilayer dynamics, such studies would provide more systematic methods and deeper insights for the coordinated development of energy and industry in rapidly developing composite regions for sustainable development.

This manuscript proposes the concept of an Integrated strategy of Sustainable development objectives, Decision-making systems, Operation systems, and Physical systems (called I-SDOP in the following content). Using a case study of the BTH region, I-SDOP is then applied to develop a systematic method of analyzing how to coordinate the development of energy and industry in rapidly developing composite regions. In Section 2, we introduce the concept of I-SDOP and describe the five steps of I-SDOP analysis with respect to the BTH region. The results of each step are analyzed and discussed in Sections 3–7, respectively. Section 8 summarizes our main conclusions and suggestions.

The main contributions of this work include three points. First, this paper proposes a systems concept of I-SDOP to observe the dynamic development of energy and industry. This innovative concept emphasizes a systemic diagnosis of radical causes of problems by integrating the multiple layers of sustainable development, decision-making systems, operation systems, and physical systems. Second, based on this concept, a method of systems analysis of the coordinated development of energy and industry in rapidly developing composite regions is developed, which can provide a reference method for the analysis of other similar regions. Third, through the case study based on this method, the analysis puts forward several key issues of and recommendations on the integrated strategy for the coordinated development of energy and industry in the BTH region. Moreover, it points out the shortcomings and improvement directions of the current policy.

2. Methodology

2.1. Concept of I-SDOP

The I-SDOP concept is based on the integration of previous studies on development strategies for energy and industry in China. An early study on the problem of coordinating industrial development and energy in China [15] found that this issue can only be fully understood from the perspective of the whole economy and by learning from international experiences. The importance of a conceptual system model to derive an integrated energy strategy for the sustainable development of China has been emphasized, with such a model based on a comprehensive understanding of the relationships among energy and economic, environmental, and societal systems [16]. A system approach based on mapping energy/material flows and analyzing their influencing factors was proposed for the study of development strategies for oil [17] and iron ore [18] in China, and it was proved that such an approach could be applied in other countries such as Malaysia [19]. By reviewing China's energy systems over the period 2000–2015 [20], it was found that the dynamics of energy systems in China are indirectly driven by adjustments to the political aims and FYPs of China's central government. Based on these publications, we further conclude that several points are essential in promoting the development of energy and industry for the sustainable development of a dynamically developing region such as China:

(1) First, the challenges of this region must be clearly identified to fulfill the objectives of sustainable development, and the key is to understand the relationships between energy and economic, environmental, and societal systems.
(2) Second, strong political aims and the corresponding strategic plans and projects of the government are necessary to lead and motivate the whole region to address these challenges. Otherwise, the smooth realization of sustainable development will be delayed or hindered.
(3) Third, a proper stakeholder relationship among various operators in the market, such as enterprises, investors, customers, and research institutes, is important in realizing political aims, implementing strategic plans, and commercializing demonstration projects. Otherwise, governmental decisions will be suspended because of poor acceptance in the market, which is driven by operators' behaviors.
(4) Fourth, the realization of sustainable development is ultimately determined by physical systems of energy and material flows, which consume natural resources, produce products/services, and bring eco-environmental impacts. The performance of physical systems is influenced by operators and constrained by technical principles and engineering limits.
(5) Finally, the dynamics of the whole region are determined by the interactions of the above four layers, and an integrated analysis of those layers is the key to developing an integrated strategy for sustainable development.

According to these points, we propose the concept of I-SDOP (Integrated strategy of Sustainable development objectives, Decision-making systems, Operation systems, and Physical systems) as a system perspective for observing and analyzing the cross-layer problem. I-SDOP is illustrated in Figure 1, and can be explained as follows:

(1) Although the research purpose is to control energy consumption and related emissions from technologies, the technologies are actually driven by the organization systems that own and use them. The organization system refers to the overall economic and social system, a group of people and technologies connected to each other, inside a specific boundary, such as a region, sector, or company. Once the boundary is identified, things outside the organization system become the surroundings, such as the eco-environment and other organization systems.
(2) The basic function of an organization system is to realize the objectives of sustainable development by its outputs. However, there are always gaps between the ideal objectives and the practical outputs, which create challenges for the organization system to actively address. The outputs are determined by the activities and interactions of three subsystems, namely, decision-making systems, operation systems, and physical systems.
(3) The decision-making system is a collection of people's activities that lead others by making high-level decisions, such as the activities of the central government and key departments. This subsystem sets the social institutions and political aims regarding sustainable development (or not), formulates strategic plans, and promotes demonstration projects to push the operation system to consciously realize the political objectives.
(4) The operation system is a collection of people's activities in the market (operators) for daily operations inside the system and outside of physical systems to realize products/services, such as the activities of energy enterprises, energy consumers, finance institutes, and research institutes.

These activities follow existing market structures and rules, but the structures and rules can be changed by the operation system under the influence of the decision-making system.

(5) The physical system is a collection of energy/material flows using various technologies run by the operation system. It consumes natural resources, produces products/services, and brings eco-environmental impacts. There are specific technical structures and rules that determine the flows, but the structures and rules can be changed by the operation system based on technological innovation.

(6) The integrated strategy is a collection of messages formulated by users of the I-SDOP concept to observe and analyze the organization system with the aim of sustainable development. The strategy is then published and/or fed back into the organization system to allow for the smoother pursuit of sustainable development.

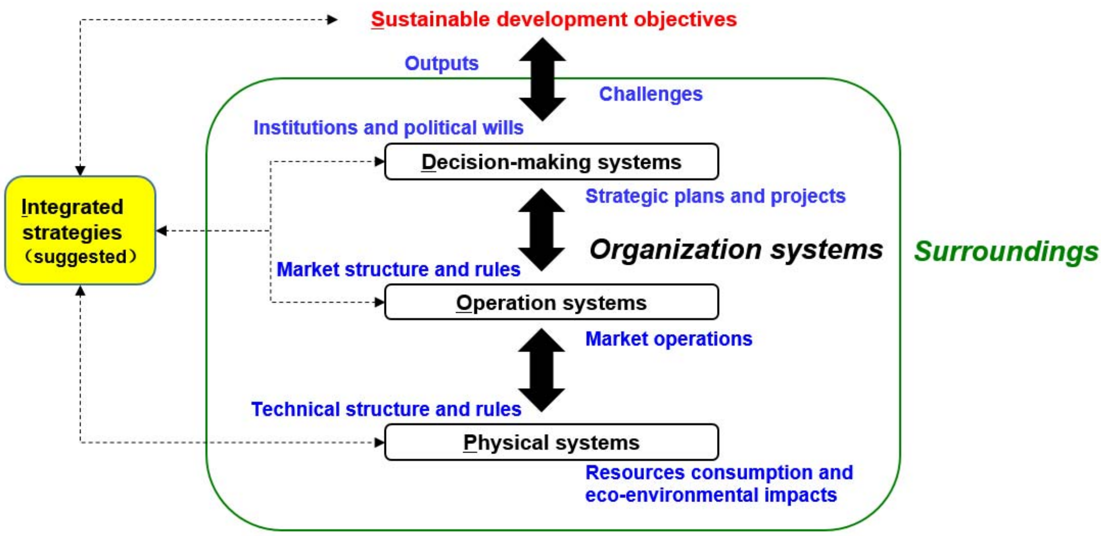

Figure 1. Illustration of the I-SDOP (Integrated strategy of Sustainable development objectives, Decision-making systems, Operation systems, and Physical systems) concept.

From the above, I-SDOP emphasizes the systematic thinking of multiple systems, especially the root causes of problems. Because of the dynamic changes of sustainable development objectives, decision-making systems, operation systems, and physical systems, it is difficult to discover the key issues during the dynamic development of energy and industry. From the perspective of integrated analysis, I-SDOP contributes to a better understanding of interaction relationships among different layers. Otherwise, it is one-sided to get expedients from only one or several layers.

2.2. Five Steps of an I-SDOP Analysis of the BTH Region

The I-SDOP concept provides a basic framework for observing and explaining complex phenomena in the dynamic development of energy and industry in developing regions. However, it is too abstract and general for practical applications. Taking the BTH region as an example, we design five operable steps to carry out an I-SDOP analysis, which can be referred to as a method for studying the coordinated development of energy and industry in rapidly developing composite regions. The five steps are as follows.

Step 1: Evaluating Sustainable Development Objectives

(1) Define the objectives: In this case, objectives are defined in the scope of China (the upper system of the BTH region), following the United Nations' (UN's) sustainable development goals and referring to the definition in previous studies.

(2) Identify the challenges: A set of indicators are developed to evaluate the gaps between the outputs of the BTH region and the objectives, through comparison with other regions and countries. Based on the results, the main challenges for sustainable development in the BTH region are identified.
(3) Identify the key issues: These indicators are used to compare Beijing, Tianjin, and Hebei, as well as further comparison with subregions of other composite regions in China. Further discussions enable the key issues to be summarized and the challenges addressed.

Step 2: Analyzing Decision-Making Systems

(1) Institutions and political wills: The current status is reviewed and recent trends in administrative institutions and the political aims of China's government for the coordinated development of the BTH region are examined.
(2) Strategic plans: The national strategic plans of the BTH region and the FYPs of Beijing, Tianjin, and Hebei are reviewed.
(3) Demonstration projects: Such projects are incidentally discussed in the review of political aims and strategic plans.

Step 3: Analyzing Operation Systems

The key is to understand the changing stakeholder relationship among various operators in the market, such as governments, enterprises, universities, and research institutes. Considering the difficulties of investigating market operators in energy and industry across various subregions, we use international experiences as a reference in the analysis of operation systems. The three selected cases are the Tokyo metropolitan area, the Rust Belt (Great Lakes) in the US, and the Ruhr Area of Germany. The focus is the smooth promotion of sustainable development in an over-crowded capital circle with a regional economy that is dependent on heavy industries, especially iron and steel, based on market mechanisms.

Step 4: Analyzing Physical Systems

(1) Current status: Energy Allocation Sankey diagrams of Beijing, Tianjin, and Hebei are mapped to understand the current situation regarding energy flows.
(2) Driving forces: The driving factors of industrial energy consumption growth in the BTH region are analyzed using the logarithmic mean Divisia index (LMDI) decomposition method.

Step 5: Determining Integrated Strategies

(1) Key messages: Based on the integration of the above findings, several key messages on the coordinated development of energy and industry in the BTH region are formulated.
(2) Scenario analysis: Two energy scenarios of the BTH region up to 2030 are analyzed to verify the rationality of the key messages.

Analysis, results, and a discussion of each step are introduced in Sections 3–7, respectively.

3. Sustainable Development Objectives: Challenges and Key Issues

According to the UN [21], Sustainable Development Goal 7 (affordable and clean energy) aims to ensure access to affordable, reliable, sustainable, and modern energy for all, and Goal 9 (infrastructure, innovation, and industrialization) is to build resilient infrastructure, promote sustainable industrialization, and foster innovation. Our previous studies [16,22] have set four sustainable development objectives for China's energy system: (1) meet the power requirements necessary to supply continuous economic growth; (2) ensure the security of China's energy supply;

(3) guarantee the protection of public health and the environment; and (4) eliminate energy poverty. Considering China's unsaturated demand for energy and infrastructure during the country's rapid economic growth [15], we define the following five sustainable development objectives for China's energy and industrial systems:

(1) **Objective A**: Meet the power and infrastructure (transport, irrigation, energy, information and communication technology, health, and education) requirements necessary to supply continuous economic growth;
(2) **Objective B**: Ensure the security of the energy supply and inclusive and sustainable industrial development;
(3) **Objective C**: Guarantee the protection of public health and the eco-environment;
(4) **Objective D**: Accelerate the technological progress of efficient and clean utilization of energy and resources;
(5) **Objective E**: Eliminate energy poverty and lack of infrastructure, especially in rural areas and small towns.

To identify the challenges of the BTH region in these objectives, we use three sets of indicators to quantitatively measure the outputs:

(1) **Economic growth** (Objectives A and B), including population, GDP per capita, and annual growth rate of GDP;
(2) **Eco-environmental performance** (Objectives C and D), including energy intensity (primary energy consumption per unit GDP) and emissions intensity (SO2 and CO2 emissions per unit GDP);
(3) **Infrastructure and industrialization** (Objectives A and E), including urbanization rate and the proportion of tertiary (service) industry in the total GDP.

Although these indicators do not strictly correspond to Objectives A–E, they are popularly used in China's government plans (see Section 4.3) and are supported by statistical data. Moreover, it will be difficult to establish a comprehensive system of indicators and find reliable data to evaluate all the outputs following the above objectives. To ensure the smooth progress of the I-SDOP analysis, we take these indicators to identify the challenges of sustainable development in the BTH region through a comparison with other regions and countries. We further use these indicators to compare subregions of the BTH region and those of other regions in order to identify key issues and address the challenges.

3.1. Challenges of the BTH Region in Realizing Sustainable Development Objectives

Using the indicators of economic growth, eco-environmental performance, and infrastructure and industrialization, the BTH region is compared with the Yangtze River Delta (YRD) region [23], the Pearl River Delta (PRD) region [24], and the whole of China, Japan, Germany, and the U.S., as listed in Table 1. (The Yangtze River Delta region includes Shanghai City, Jiangsu Province, and Zhejiang Province, while the Pearl River Delta region consists of nine cities in Guangdong Province, including Guangzhou, Shenzhen, Foshan, Dongguan, Zhongshan, Zhuhai, Huizhou, Jiangmen, and Zhaoqing.) Similar to the BTH region, the YRD and PRD regions are rapidly developing composite regions that form important poles of economic growth and urbanization in China [25]. As the data for the YRD region is difficult to obtain, we use data from Guangdong Province as an alternative. Japan, Germany, and the U.S. are typical developed countries, and also form the background to the international case studies in Section 5. The population size of the BTH region (109.2 million) is close to that of Japan (127.4 million) and greater than that of Germany (80.7 million).

Referring to Table 1, it can be seen that GDP per capita in the BTH region is above the average for China, but far behind that in developed countries and obviously behind that of the YRD region, although the BTH region has the highest annual growth rate of GDP. Second, the eco-environmental performance of the BTH region is almost the worst, with an energy intensity greater than the average across China and an SO_2 emission intensity much higher than those in the YRD and PRD regions. Finally, the infrastructure and industrialization of the BTH region is advanced in China, but still far behind the levels found in developed countries, and obviously behind that of the PRD region.

Table 1. Comparison of the outputs of the Beijing–Tianjin–Hebei (BTH) region with other regions and countries according to 2013 data.

Region	Economic Growth			Eco-Environmental Performance		Infrastructure and Industrialization	
	Population (Million)	GDP Per Capita (USD/Person)	Annual Growth Rate of GDP (%)	Energy Intensity (Million J/USD)	Emission Intensity (g/USD)	Urbanization Rate (%)	Proportion of Tertiary Industry in the Total GDP (%)
BTH	109.2 (8% of China)	9193	10.7	13.0	1.6 (SO_2)	60.1	51.4
YRD	158.5 (11.7% of China)	12,055	9.9	9.2	0.9 (SO_2)	68.0	48.3
PRD (Guangdong)	106.4 (7.8% of China)	9434	9.8	8.4	0.8 (SO_2)	84.0	52.7
China	1357 (global 19%)	7080	7.7	12.6	2.1 (SO_2) 1007 (CO_2)	53.2	46.7
Japan	127.4 (global 1.8%)	40,471	0.3	3.8	269 (CO_2)	92.5	71.8
Germany	80.7 (global 1.1%)	46,534	0.5	3.8	225 (CO_2)	74.9	68.9
The U.S.	316.2 (global 4.4%)	52,789	1.7	5.9	356 (CO_2)	81.3	77.9

Note: Data for BTH, Yangtze River Delta (YRD), Pearl River Delta (PRD) (Guangdong) and SO_2 emissions data in China are taken from China's statistical data [2,26]. Although only the emission intensity of SO_2 is compared here, the results for NO_x and soot/dust are similar. Data on the population, GDP, urbanization, and tertiary industry in China, Japan, Germany, and the U.S. are taken from the statistical data of the World Bank [27], and the country data on energy consumption and energy-related CO_2 emissions are taken from BP (one of the largest petroleum companies in the world) [28]. All currency data refer to 2013 values.

Therefore, we conclude that the BTH region faces three challenges to realizing the objectives of sustainable development:

(1) An immense and ever-increasing demand for energy and industrial upgrading, with a long-term task of economic growth and infrastructure building.
(2) Serious environmental pollution and large GHG emissions caused by energy use and industrial development.
(3) The urgent need to popularize modern energy services and infrastructure in the process of urbanization.

3.2. Key Issues in Addressing the Challenges of the BTH Region

By comparing the outputs from three subregions of the BTH region, it is found that a large disparity exists between Hebei and Beijing, Tianjin. Despite containing more than two-thirds (67.1%) of the population in the BTH region, Hebei contributes less than half (45.5%) of the total GDP. Moreover, Hebei consumes more than two-thirds (67.2%) of the primary energy, and emits 80.9% of SO_2, 77.6% of NO_x, and 89.9% of soot/dust in the BTH region [2,26].

The subregions of the BTH region can be further compared with those of the YRD and PRD regions. In this case, the lagging development of the large Hebei subregion is the main reason that the BTH region lags far behind the YRD and PRD regions in the sustainable development objectives, as illustrated by Figures 2–5 [2,26,29]. From Figure 2, it is apparent that Hebei has the lowest GDP per capita of all subregions in the three composite regions, which leads directly to a much lower GDP per capita in the BTH region than in the other two composite regions. Referring to Figure 3, the waste gas emission intensities and energy intensity of Hebei are much higher than those of Beijing and Tianjin, resulting in higher intensities in the BTH region compared with the YRD and PRD regions. Referring to Figures 4 and 5, the low rate of urbanization and low proportion of tertiary industry in the large Hebei district effectively reduce the level of infrastructure and industrialization in the BTH region.

In contrast, the development of the three YRD subregions is more balanced. Although the PRD region has undeveloped subregions such as Zhaoqing, the related population is quite small and does not significantly influence the whole region.

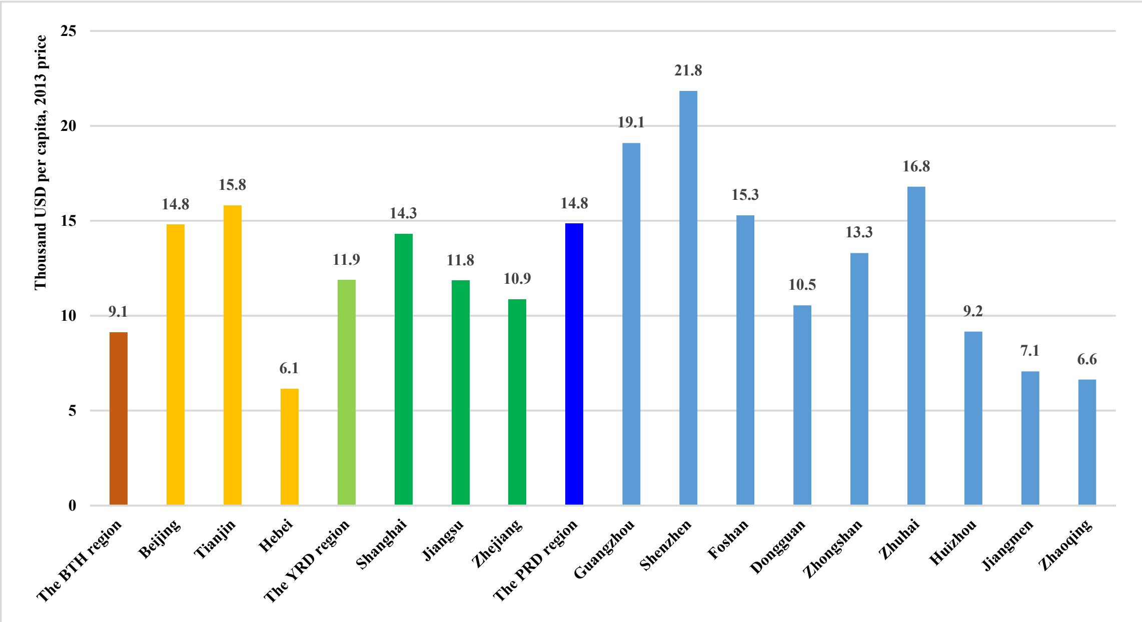

Figure 2. GDP per capita of the three composite regions and their subregions in 2013 [2,29]. Note: All currency data refer to 2013 values.

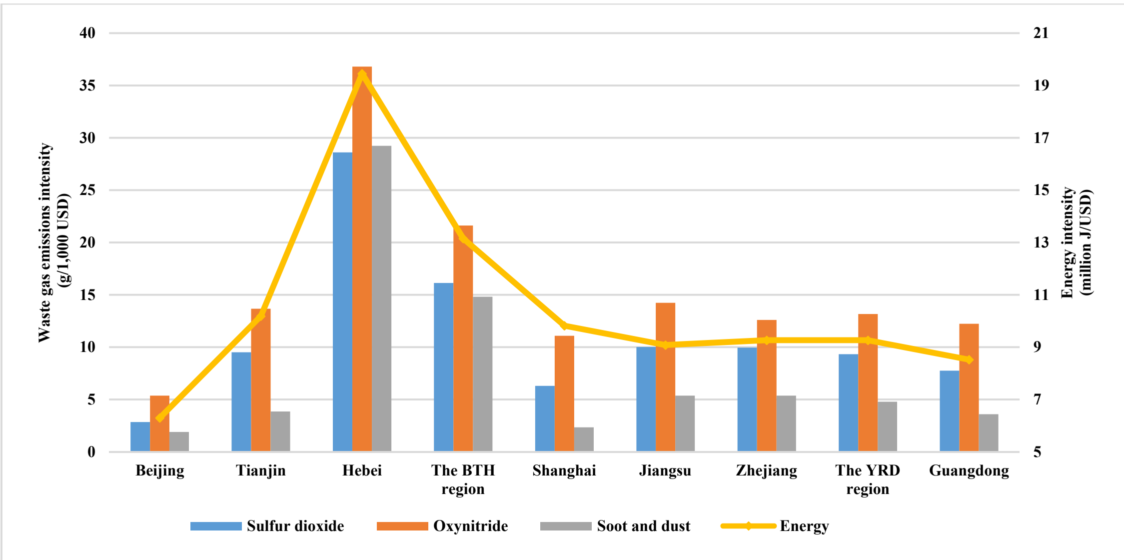

Figure 3. Eco-environmental performance of subregions in the BTH region, subregions in the YRD region, and the PRD region (Guangdong) in 2013 [2,26]. Note: It is hard to find data for PRD and its subregions, so Guangdong is taken as an alternative data source. Columns measure emission intensity by type, and refer to the left y axis. Curve measures energy intensity, and refers to the right y axis. All currency data refer to 2013 values.

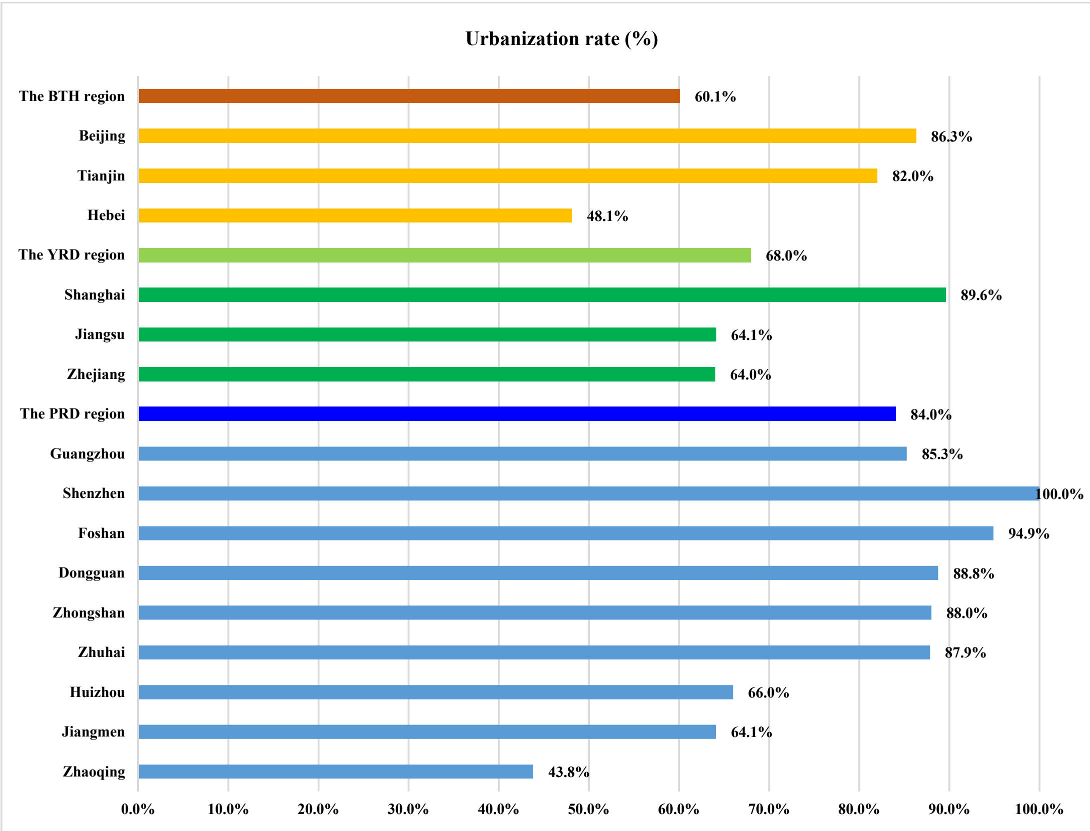

Figure 4. Urbanization rates of the three composite regions and their subregions in 2013 [2,29].

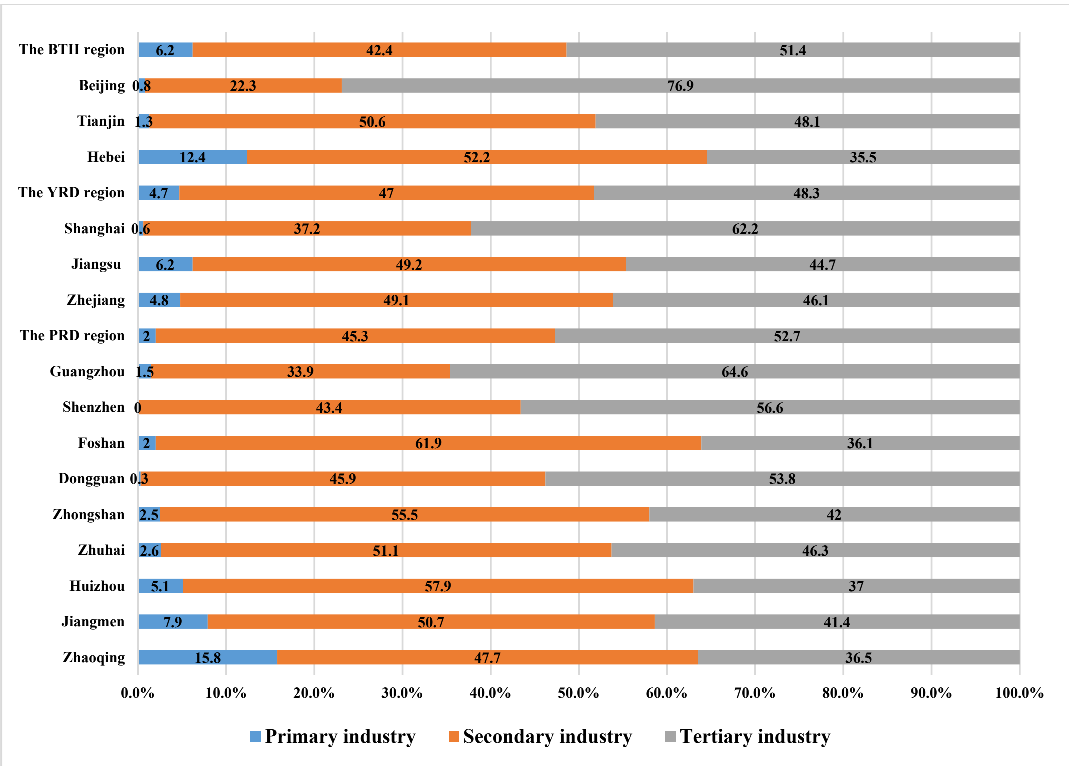

Figure 5. Industrial structure of the three composite regions and their subregions in 2013 [2,29].

In addition to Hebei's high proportion of primary industry (agriculture) and secondary industry (mining and manufacturing), its secondary industry is highly reliant on iron and steel production. The iron and steel industry accounted for 25.9% of the gross output value of all industrial enterprises above a specific size in Hebei [30]; indeed, Hebei is famously known as the "Steel Center" of China, producing 24% of China's crude steel in 2013 [2]. Although Tianjin also has a high proportion of secondary industry, its industrial structure is more diversified. For example, the two biggest sectors of the secondary industry in Tianjin are iron and steel making (15.4%) and electronic manufacturing (11.5%) [31]. Moreover, Hebei's energy supply is highly reliant on coal power generation and the end-use of coal (see Section 6.1). Thus, Hebei's energy and industrial structure exhibits a strong "One Coal and One Steel" phenomenon.

Therefore, the key issues in addressing the challenges of sustainable development in the BTH region include (1) reducing the regional disparity of economic growth and urbanization between Hebei and Beijing, Tianjin through the coordinated development of energy and industry among the three subregions, while maintaining rapid economic growth across the whole BTH region; (2) accelerating the transition of Hebei's energy system toward a clean and low-carbon model, especially by controlling coal consumption; and (3) accelerating the transition of Hebei's industrial system toward an inclusive and sustainable model, especially by diversifying the structure of secondary industry and increasing the proportion of tertiary industry.

4. Decision-Making Systems: Governmental Institutions, Political Objectives, and Strategic Plans

4.1. Administrative Institutions and Political Objectives

As a result of China's vertical and one-party system of government administration, governmental decisions on the development of the BTH region are heavily influenced by the central government and the Communist Party of China (CPC). In particular, China's central government and the Central Committee of the CPC (CCCPC) are located in Beijing. The power systems of governmental administration in the BTH region are mapped in Figure 6, according to the Constitution of the People's Republic of China [32], the Party Constitution of the Communist Party of China [33], and current organizations of the State Council [34], CCCPC [35], and the governments of Beijing, Tianjin, and Hebei [36–38]. Referring to Figure 6, the National People's Congress (NPC) is the highest authority in China. The NPC makes and revises basic laws, elects the President, selects candidates for the State Council, and approves FYPs and the state budget during its annual conference and quarterly meetings of its Standing Committee. The State Council is in charge of the daily administration of the government under the NPC's leadership. As the sole ruling party, the CPC greatly influences the central government by its party leadership in the government, and its highest authority is the National Congress of the CPC (NCCPC). The NCCPC makes supreme decisions during its five-yearly conference and yearly meetings of its Central Committee, and the Politburo is in charge of daily administration of the party. The General Secretary of the CPC, elected by the NCCPC from the Standing Committee of the Politburo, is normally the same person as the President elected by the NPC, and can be considered the spokesperson of the political objectives of China's central government. For example, Xi Jinping is currently both the President of China and the General Secretary of the CPC. Moreover, the Premier and Vice Premiers in the State Council are also served by members of the Politburo, thus ensuring strong leadership of the CPC in the central government.

The regional government and Communist Party of Beijing, Tianjin, and Hebei are all under the leadership of the central government and the CCCPC, although they are fragmented because of the division of regional administration. Another issue is that, as leaders of the municipality directly under the central government, the Secretary of the Standing Committee of the Communist Party (Party Secretary) and the mayors of Beijing and Tianjin are often served by members of the Politburo, and, therefore, they actually have a higher administrative position than Hebei's Party Secretary and Governor. Therefore, it has been asserted that governmental fragmentation in the BTH region [14] and the higher administrative position of Beijing and Tianjin [39–41] have contributed to a dual-core structure of urbanization [42] and the lagging development of Hebei. (A dual-core structure of urbanization means that, in the BTH region, Beijing and Tianjin are two core cities with large populations and more advanced development compared with other cities in this region (Hebei).)

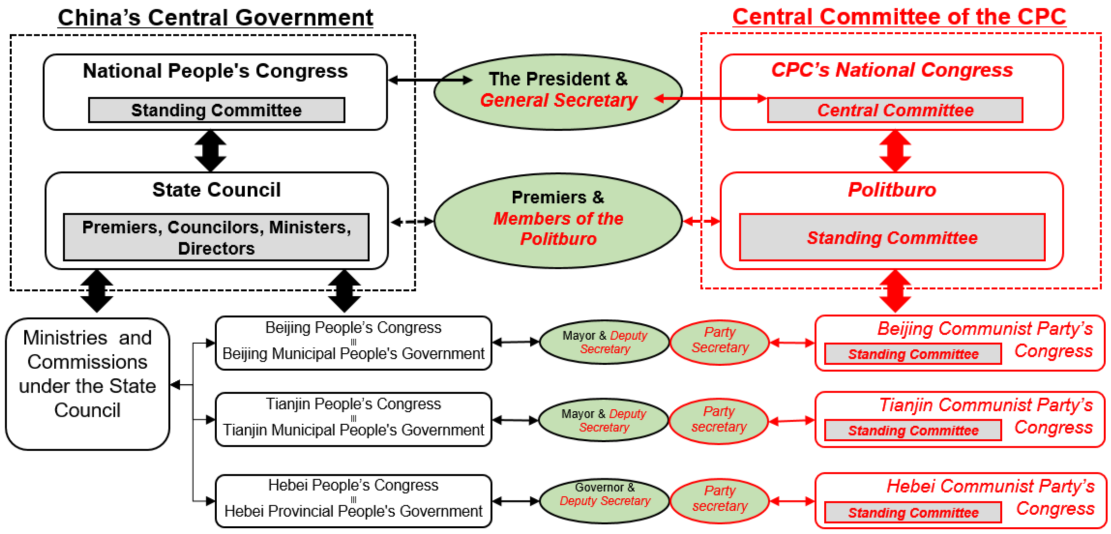

Figure 6. Illustration of the administrative institutions of the BTH region.

Referring to the political objectives announced by the Presidents of China during 2000–2015 [20], there is a noticeable change from emphasizing rapid economic growth to an increasing emphasis on sustainable development, such as the more efficient use of resources and protection of the eco-environment, as well as rapid economic growth. In February 2014, as a result of serious smog and haze and unsatisfactory economic growth in the BTH region, President Xi Jinping announced that the coordinated development of the BTH region must be an important national strategy [7]. In his speech, he proposed the promotion of coordinated development to break regional boundaries among Beijing, Tianjin, and Hebei, including the formation of strategic plans, enhancing communication, cooperation on industrial development, optimization of land use, protection of the eco-environment, construction of a transportation network, and the reform of market mechanisms. With this strong political direction, in August 2014, the State Council set up a Steering Group for the Coordinated Development of the BTH region, led by a Vice Premier (also a member of the Standing Committee of the Politburo), Zhang Gaoli [43]. Under the leadership and coordination of the Vice Premier, the governmental fragmentation in the BTH region has been eased. In 2016–2017, the positions of Party Secretary and mayors (or governors) of Beijing, Tianjin, and Hebei passed to new citizens with lighter backgrounds in central government.

Moreover, in April 2017, China's central government decided to build a Special Administrative Region (Xiong'an New Area) in Baoding City, Hebei [44], including Xiongxian County, Rongcheng County, and Anxin County, near Beijing and Tianjin. This will be a leading demonstration project of modern urbanization to promote the coordinated development of the BTH region, and will bear the non-capital functions of Beijing to accelerate the development of Hebei. In summary, the newly announced political objectives, adjustments in the administrative institutions, and abovementioned demonstration project will spearhead the governmental decisions on the coordinated development of the BTH region to address the key issues of sustainable development.

4.2. National Strategic Plans of the BTH Region

Driven by political objectives, in April 2015, the Politburo approved the *Outline of Coordinated Development Plan in BTH Region* [45]. The key points [46,47] are as follows:

(1) To revise the regional functions of Beijing, Tianjin, Hebei, and define the regional function of the BTH region, as listed in Table 2, with the aim of becoming a world-level urban agglomeration and leading region of coordinated development.
(2) To evacuate the non-capital functions of Beijing to relieve its metropolitan pressure, and to evacuate aspects of general industry, logistics, and professional markets, certain public services, and certain governmental administrative institutions and enterprise headquarters.
(3) To increase coordinated investment in three key areas, namely, transportation, eco-environmental protection, and industrial upgrading and transferring.
(4) To formulate a collaborative innovation community among the three subregions based on the original innovation in Beijing, R&D and demonstration in Tianjin, and deployment and commercialization in Hebei.
(5) To improve public services in Hebei to reduce the large gap with Beijing and Tianjin, especially in education, medical, and cultural aspects.
(6) To promote demonstration projects such as the construction of Beijing New Airport Economic Cooperation Zone (across the three subregions) and Caofeidian Demonstration Zone of Coordinated Development (in Hebei).

Moreover, in 2016, the first cross-regional *13th FYP of the BTH region* [48] was issued, and an *Overall Plan of Land Utilization in the BTH region* [49] was published.

Table 2. Comparison of the revised and original regional functions of the BTH region.

Region	Revised Regional Functions	Original Regional Functions	Main Revisions
Beijing	Political center, cultural center, international exchange center, and technology innovation center [46]	Capital city, international city, cultural city, and livable city [50]	Emphasize the function of technology innovation
Tianjin	R&D base for advanced manufacturing, core zone for international aviation and shipping in North China, demonstration zone for financial innovation, and leading zone for reforming and opening [46]	International center of shipping and logistics, base of modern manufacturing and R&D, cultural city, and livable city [51]	Emphasize the function of financial innovation and the function of reforming and opening
Hebei	Important base for modern commerce and logistics, experimental zone for industrial transformation and upgrading, demonstration zone for new modes of urbanization and overall urban–rural planning, and supporting zone for ecology and environment in BTH [46]	Base of infrastructure and industry, key region of urbanization and ecological protective belt of Beijing and Tianjin [52]	Emphasize the development of commerce and logistics, and industrial transformation and upgrading
BTH	World-level urban agglomeration with Beijing as the core, leading region for reforms on coordinated development, new driver of economic growth by innovation, and demonstration area of ecological restoration and environmental improvement [47]	None	Define the regional function, aiming at a world-level and China-leading region

4.3. The FYPs of Beijing, Tianjin, and Hebei

In the regional 12th FYPs (2011–2015) [53–55], Beijing, Tianjin, and Hebei only considered their own development and benefits. Motivated by the political objectives and national strategic plans, they have now placed the coordinated development of the whole BTH region as a key part of the regional 13th FYPs (2016–2020) [56]. For example, Beijing places the optimization of capital functions and the evacuation of non-capital functions, and the promotion of coordinated regional development, as its prioritized strategic tasks for 2016–2020. Tianjin has placed the convergence of industrial development in the BTH region as a key factor in the strategic task of constructing a modern industrial system, and has taken the construction of a collaborative innovation community in the BTH region as a key component of the strategic task of promoting technology innovation. Hebei plans to build a collaborative innovation community in the BTH region and actively undertake the evacuation of Beijing's non-capital functions.

However, most of the main targets in the 13th FYP (2016–2020) of Beijing, Tianjin, and Hebei are still extensions of the past, as compared with the 12th FYP (2011–2015); see Table 3 for details. There are few new targets. The main exception is that Beijing has imposed redlines on its population, water consumption, and land use as the main targets in the 13th FYP. This implies that, though the coordinated development of the BTH region has become a key part of the regional FYPs, there is still a lack of quantitative targets to measure the progress of the coordinated development. This may affect the precise implementation of the strategic tasks to promote the coordinated development of the BTH region in the subregions.

Table 3. Some of the main targets of the 12th and 13th FYPs in Beijing, Tianjin, and Hebei.

Region	Economic Growth	Eco-Environmental Performance	Infrastructure and Industrialization
Beijing	• 12th FYP: 8% annual growth rate of GDP • 13th FYP: 6.5% annual growth rate of GDP; population redline (less than 23 million)	• 12th FYP: energy and emission intensity meet the state targets • 13th FYP: energy and emission intensity meet the state targets; redlines on water consumption <4.3 bt and land use of urban construction <2800 km^2	• 12th FYP: proportion of tertiary industry >78%; R&D investment >5.5% of total GDP • 13th FYP: proportion of tertiary industry >80%; R&D investment >6% of total GDP
Tianjin	• 12th FYP: 12% annual growth rate of GDP; population <16 million • 13th FYP: 8.5% annual growth rate of GDP	• 12th FYP: 18% reduction in energy intensity; emission intensity meets the state requirements • 13th FYP: CO_2 emission intensity meets the state requirements	• 12th FYP: proportion of tertiary industry >50%; R&D investment >3% of total GDP • 13th FYP: proportion of tertiary industry >55%; R&D investment >3.5% of total GDP
Hebei	• 12th FYP: 8.5% annual growth rate of GDP • 13th FYP: 7% annual growth rate of GDP	• 12th FYP: energy and emission intensity meet the state targets; 5% non-fossil energy in total primary energy consumption • 13th FYP: energy and emission intensity meet the state targets; 10% non-fossil energy in total primary energy consumption	• 12th FYP: proportions of tertiary industry and high-tech industry reach ~38% and 10%, respectively; urbanization rate reaches 54%; R&D investment >1.6% of total GDP • 13th FYP: proportions of tertiary industry and high-tech industry reach 45% and 20%, respectively; urbanization rate reaches 60%; R&D investment reaches 2.5% of total GDP

5. Operation Systems: International Experiences

Taking into account that it is difficult to investigate all market operators in the BTH region and satisfy the requirements of long-term strategic research based on stakeholder analysis of a dynamically evolving market, we mainly use international experience as a reference to analyze the operation systems of the BTH region. The case of the Tokyo metropolitan area in Japan is suitable for the analysis of coordinated development in a capital circle with an over-crowded population and urban functions in the central city. The Ruhr region in Germany and the Rust Belt in the U.S. are suitable for analyzing the transition of a regional economy depending on heavy industries (especially iron and steel). These three regions have all undergone a long period of regional transition in market-oriented economies, and so can provide lifecycle insights to enlighten the coordinated regional development of energy and industry in the BTH region.

5.1. Tokyo Metropolitan Area in Japan

The concept of a metropolis originated in Japan [57], and the Tokyo metropolitan area, as the most extensively urbanized region in Japan, is one of the most typical cases [58]. In a narrow sense, this area includes Tokyo and the three nearby cities of Kanagawa, Chiba, and Saitama. Covering just 3.5% of Japan's land area [59], this region nonetheless accounted for 33.5% of the total population in 2012. Its total GDP was 2.02 trillion USD in 2012, including 1.15 trillion USD in Tokyo, 0.374 trillion USD in Kanagawa, 0.293 trillion USD in Chiba, and 0.253 trillion USD in Saitama [60–63]. The GDP of Tokyo alone accounted for 19.4% of Japan's total GDP, and was greater than the total GDP of the BTH region in 2013.

After the Meiji Reforms, Tokyo became a crowded city containing almost all urban functions. This was further promoted by the Great Kanto Earthquake in 1923 and the Second World War [64]. From 1958 to 1999, the Japanese government enacted five plans for this metropolitan area to relieve the large pressure of a crowded population and concentrated urban functions, as listed in Table 4 [39]. The main lesson is that it is essential to establish a series of sub-core cities besides the core city and relocate over-concentrated urban functions from the center. These sub-core cities are not only required to have specific industrial clusters to support their economic growth, but also to have comprehensive urban functions to serve the population that has been dispersed from the core city, such as higher education, governmental administration, and international communications. Correspondingly, the land-use pattern of the whole area must transition from a single-pole structure to a distributed network structure.

Table 4. Five plans of the Tokyo metropolitan area.

Year and Plan	Main Planning Targets	Effects and Land-Use Pattern Formed
1958, the first plan	Take outer green belt as a boundary to prevent the extension of urban area and build new industrial cities outside the green belt.	**Effects:** The developmental levels of surrounding cities were directly related to their distances from the core urban area and so resulted in a series of big city diseases in the core. **Land-use pattern:** A single-pole structure with the growing urban area in the center, expanding like a pie.
1968, the second plan	Take Tokyo as the economic growth center and deconcentrate urban functions of Tokyo to surrounding areas, with the construction of a transportation system among all cities to enhance their linkage.	**Effects:** Tokyo remained the administrative center while other urban functions, such as industry, education, and culture, began to expand to outside cities. **Land-use pattern:** A single-pole structure with the urban functions and population dispersing outside continuously.
1976, the third plan	Build multipole urban compounds to take over functions (especially central administrative function) of Tokyo.	**Effects:** The functions of Tokyo as the administration center began to relocate, and several sub-core cities appeared to take over these functions. However, the population of Tokyo still increased rapidly as the headquarters of enterprises continuously moved to Tokyo. **Land-use pattern:** A polycentric and multipole structure (primary).
1986, the fourth plan	Accelerate the construction of sub-core cities and mandate a movement of comprehensive functions to those cities, including industrial administration, international communication, and higher education.	**Effects:** The functions of Tokyo as the financial and administrative center were enhanced while the sub-core cities were also greatly upgraded to be subcenters, accommodating urban functions and population in the whole area. **Land-use pattern:** A polycentric and multipole structure (thorough).
1999, the fifth plan	Build Tokyo metropolitan area as an independent and sustainable urban area, emphasize the development of surrounding sub-core cities, and enhance independence and cooperation among cities	**Effects:** The commercial and financial functions of sub-core cities were further enhanced and connections among cities were strengthened. **Land-use pattern:** A distributed network structure with a well-connected main core area, sub-core areas, suburban areas, and remote town areas.

5.2. The Rust Belt in the U.S.

The Rust Belt refers to an area of industrial decline, usually accompanied by severe damage to the local ecological environment. The area around the Great Lakes in the U.S. is a famous case. From the 1950s to the 1980s, economic recession and unemployment occurred because of industrial decline [65], pushing the transition of industrial development. Here, three typical cities (Pittsburgh, Toledo, and Cleveland) are selected to analyze their transition experiences. It appears that all three cities transformed from an economy based on heavy industries to an economy based on high-tech and service industries. These improvements were largely due to local innovation sources, including higher education and healthcare facilities, as listed in Table 5.

The main experiences are summarized as follows:

(1) **Diversification of industrial structure:** Noticing that traditional manufacturing was losing its competitiveness and regional pollution was becoming severe, each city emphasized the development of new industries such as information, biological medicine, robotics, and finance. With higher added value and lower emissions, these industries provided employment opportunities and improved the attractiveness of the cities.

(2) **Role of innovation sources:** During the transformation, local innovation sources played an important role in attracting talent and advanced enterprises. For example, the computer science discipline at Carnegie Mellon University and the life sciences disciplines at the University of Pittsburgh were very active in attracting worldwide talent and enterprises into Pittsburgh. Along with solar energy research and education at the University of Toledo and the efforts of two hospitals in Cleveland, this aided the transformation to a knowledge-based economy.

(3) **Propel extensive communications and public–private partnerships:** The transformation of the Rust Belt was facilitated by extensive communications and public–private partnerships among local government, business, and academia. For example, the Carnegie Endowment in Pittsburgh supported a network composed of nongovernmental organizations and private companies to

forge a connection between the direction of economic development and leaders of government and community and to provide funding and employment instructions for workers.

Table 5. Industrial transformation in Pittsburgh, Toledo, and Cleveland.

City	Pittsburgh	Toledo	Cleveland
Main industry before transformation	Iron and steel industry, which provided over 60% of steel products from the U.S. in 1910	Glassmaking and automotive industry	Traditional manufacturing industry
Main industry after transformation	Education, healthcare, and commerce, which together occupied 36% of the total employment in 2014	Solar energy industry	Education, healthcare, and commerce, which together occupied 31% of the total employment in 2014
Innovation sources	Carnegie Mellon University (computer science) and University of Pittsburgh (life sciences)	University of Toledo (solar and renewable energy research) and Owens Community College (training courses for solar energy industry)	Case Western Reserve University and Cleveland State University, while the employment of healthcare ranks sixth in the U.S.

5.3. The Ruhr Region in Germany

The Ruhr Region was once a world-famous industrial area. Because of its favorable geographic conditions and abundant coal resources, the Ruhr Region became the center of the coal and steel industry in Germany and across Europe. This occurred in conjunction with the progress of industrialization in Germany during the second half of the 19th century and the first half of the 20th century. However, after the 1950s, the coal and steel industries in this region declined because of the increased cost of production, international competition, and market changes. Consequently, the Ruhr Region faced serious problems with unemployment, environmental pollution, and ecological destruction.

From the 1960s, the Bundestag, North Rhine-Westphalia, and the Ruhr Region collaborated to propel an economic and social transition in this region. Currently, though the Ruhr Region is still an energy production and industrial area in Germany, its economy is mainly dependent on service and knowledge-based industries. Manufacturing represented 21% of the total employment of this region in 2011. The main experiences of the Ruhr Region are summarized as follows (Appendix A):

(1) **Strengthening of legislation and policy of environmental protection:** Before the 1960s, the only environmental protection laws came from the federal government. Facing severe environmental pollution, the government of North Rhine-Westphalia State legislated for stricter environmental protection standards than the federal standards, and requested old factories to close within a certain time limit according to their pollution control measures.

(2) **Building of innovation sources:** Before 1960, there were no universities in the Ruhr Region because it was positioned as an industrial base. Initiated by some local experts, Ruhr-University Bochum was built in 1962 as the first university in this region and, in the following years, more than 20 universities were built. After 1970, regional authorities invested in three R&D centers to further enhance innovation.

(3) **Improvements in working and living environment:** To increase regional attraction, from the 1970s, the regional government began to improve the construction of economic and transportation infrastructure, in addition to reconstructing abandoned industrial estates and coal mines into innovation centers or leisure and tourist attractions. After 1980, improving the environment and living quality became the main targets of this region.

6. Physical Systems: Current Status and Driving Forces

To understand the physical system shaped by the operation system in the BTH region, we map the energy flows of Beijing, Tianjin, and Hebei in the form of Sankey diagrams. We then use the LMDI decomposition method to analyze the driving forces of industrial energy consumption growth [66] in Beijing, Tianjin, and Hebei.

6.1. Current Status—Energy Flows of Beijing, Tianjin, and Hebei

Sankey diagrams have been widely used in previous studies on physical energy systems [67,68]. A programmed data processing method for mapping Energy Allocation Sankey Diagrams of China has been built by the authors [69]. Based on this, we used statistics from the energy balance tables [70] and tables of the final energy consumption by industrial sector [30,31,71] in Beijing, Tianjin, and Hebei to map the flows from energy sources to energy end-use, as illustrated in Figures 7–9. These diagrams reveal obvious differences in the energy use in Beijing, Tianjin, and Hebei (in the year of 2013). The main conclusions are as follows:

(1) **Beijing (1.9 EJ of total primary energy consumption, Figure 7):** Beijing's energy supply, including electricity supply, is mostly reliant on imports, with an energy import dependency of 93.9% and electricity import dependency of 67.1%. The main end-user of energy is buildings (51.4%), followed by manufacturing (24.4%) and transportation (24.2%). Electricity (41.1%) and oil products (28.1%) are the major energy carriers to end-use.

(2) **Tianjin (2.26 EJ of total primary energy consumption, Figure 8):** Tianjin is a net exporter of crude oil and oil products, but almost all of its coal is imported, and the import dependency of natural gas is 40.5%. The electricity supply of Tianjin is mostly (79%) reliant on domestic generation, 96.3% of which is from coal-fired power plants. The main energy end-user is manufacturing (71.2%), followed by buildings (19.7%) and transportation (9.2%). Electricity (32.5%), coal (28.2%), and oil products (22.8%) are the major energy carriers to end-use.

(3) **Hebei (9.78 EJ of total primary energy consumption, Figure 9):** Hebei's import dependencies of raw coal, crude oil, and natural gas are 78%, 57.2%, and 68.8%, respectively. The electricity supply of Hebei is mostly reliant on domestic generation (78.1%), 91.1% and 6.8% of which are from coal-fired power plants and renewable power (mainly wind), respectively. The main end-user of energy is manufacturing (81.3%), followed by buildings (14.1%) and transportation (4.6%). Coal (54.4%) and oil products (31.6%) are the major energy carriers to end-use.

Because of Hebei's large scale of energy consumption, the energy structure of the BTH region is mainly determined by that of Hebei. Moreover, Hebei has a "One Coal and One Steel" feature to its energy structure, as its energy supply is highly reliant on coal and the iron and steel industry; taken as one single department, this accounts for 47.3% of total primary energy consumption. The coal burning and the iron and steel industry would appear to be priorities in terms of reducing emissions.

6.2. Driving Forces of Industrial Energy Consumption Growth in Beijing, Tianjin, and Hebei

To understand the driving forces of industrial energy consumption growth in the BTH region, we applied the LMDI method based on the energy Sankey diagrams developed in our previous work [72] to decompose the factors driving the growth in energy demand across the whole of industry. Consider the following equation (the symbols in the equation are explained in Table 6).

$$E_{SQ,\ industrial} = \sum_{ij} P \cdot \frac{GDP}{P} \cdot \frac{GDPi}{GDP} \cdot \frac{E_{SQ,i}}{GDP_i} \cdot \frac{E_{SQ,ij}}{E_{SQ,i}}$$

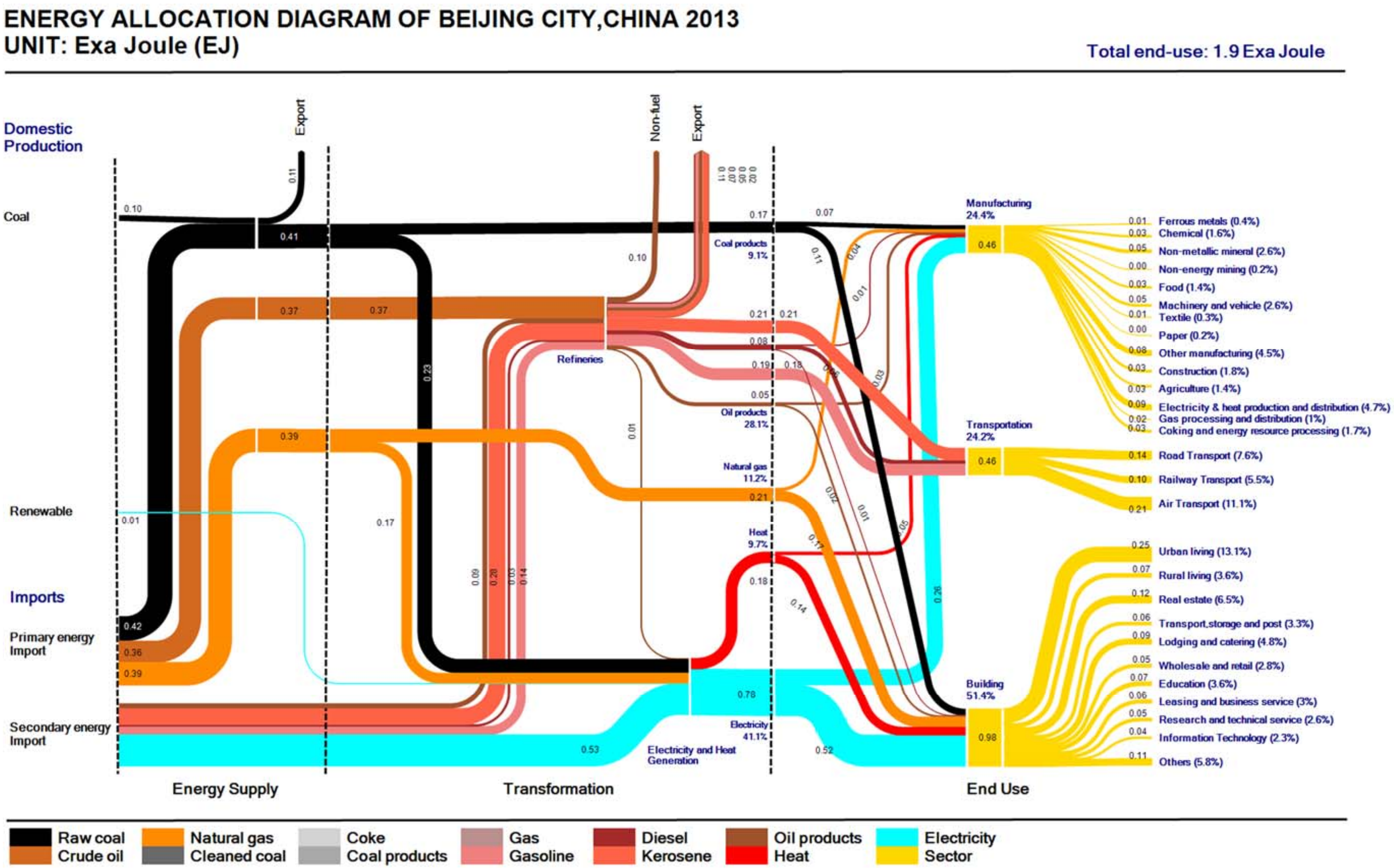

Figure 7. Energy allocation diagram of Beijing in 2013.

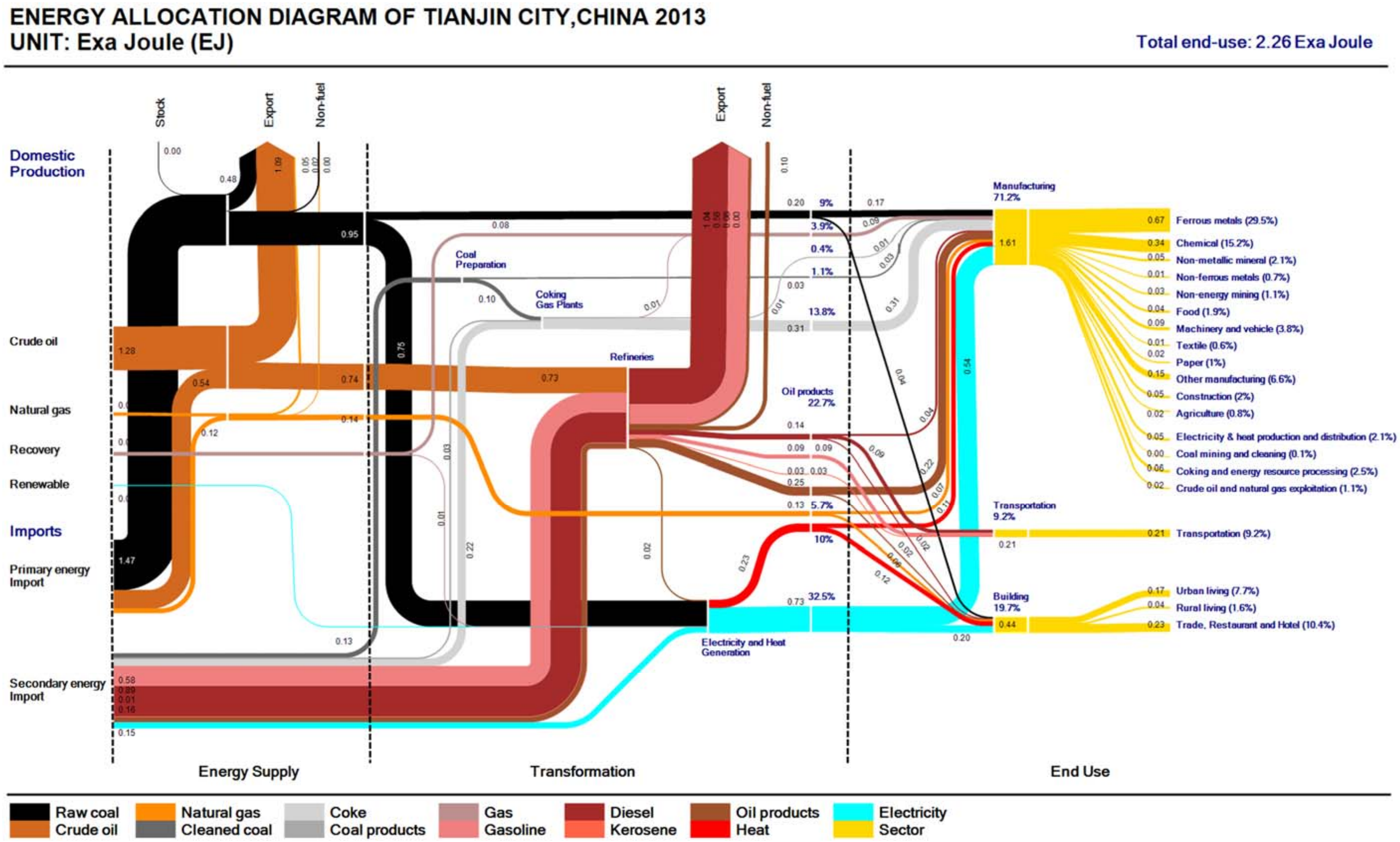

Figure 8. Energy allocation diagram of Tianjin in 2013.

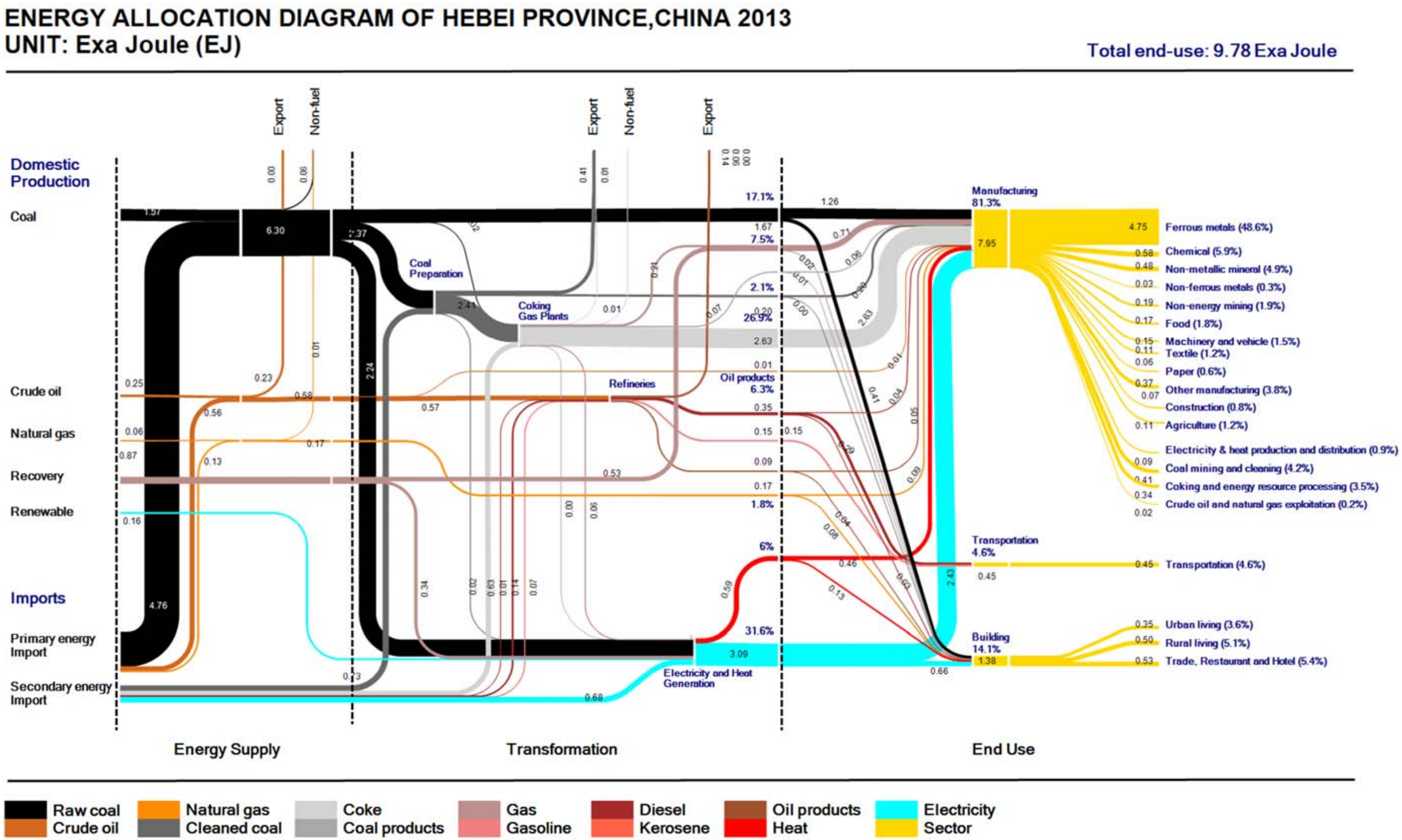

Figure 9. Energy allocation diagram of Hebei in 2013.

Using supplementary data from 2003 [73], we calculated the results for 2003–2013; see Figure 10. During this period, the total primary energy consumptions of all industry in Beijing, Tianjin, and Hebei increased by factors of 1.3, 2.2, and 2.6 (ΔDtot), respectively. This increase was mainly driven by the growth of GDP per capita (ΔDaff) in each region. The population growth (ΔDpop) in Beijing and Tianjin and the optimization of energy structure (ΔDmix, such as the increase of electricity and heat use) in all three regions also contributed to the growth. Moreover, reductions in industrial energy intensity (ΔDint), adjustments to the industrial structure (ΔDstr), and improvements in energy supply efficiency (ΔDpeq) helped slow the growth, especially in Beijing and Tianjin. The adjustment of the industrial structure in Hebei is an exception, as this increased growth.

Table 6. Symbols in the equation.

Items	Descriptions
Subscript *i*	Primary, Secondary, and Tertiary industries
Subscript *j*	Sixteen energy types, including raw coal, cleaned coal, briquettes, gangue, coke, coke oven gas, blast furnace gas, converter gas, other gas, other coking products, crude oil, oil products, natural gas, LNG (liquid natural gas), heat, and electricity
Subscript SQ	Standard quantity of energy
P	Population
GDP	Gross domestic product
GDP_i	Value added of industry *i*
$E_{SQ,i}$	Energy consumption of industry *i* expressed in SQ type
$E_{SQ,ij}$	Fuel *j* consumption of industry *i* expressed in SQ type

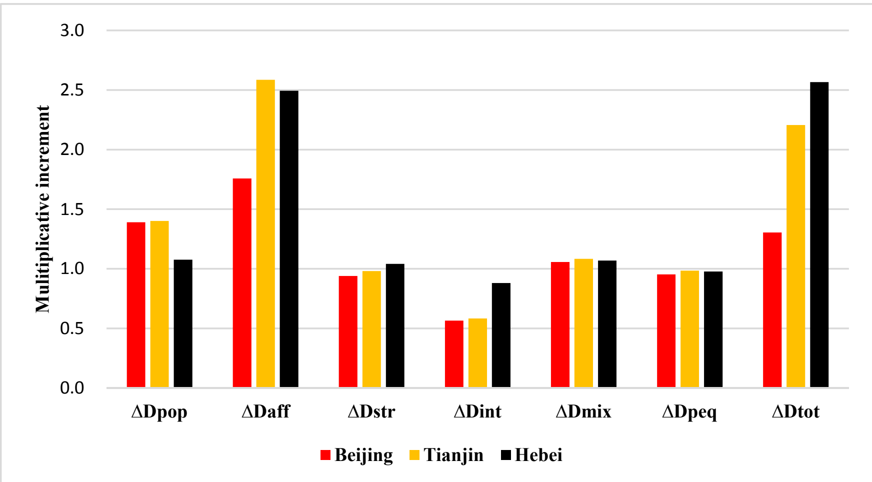

Figure 10. Logarithmic mean Divisia index (LMDI) decomposition results of industrial energy consumption growth (2003–2013) in the BTH region.

7. Integrated Strategies: Key Messages and Energy Scenarios

7.1. Key Messages

Based on the above analysis, six key messages can be formulated. These are as follows:

(1) Promoting economic growth and the urbanization in the BTH region remains a long-term task. The main challenge of sustainable development is the serious air pollution and large GHG emissions generated during the push to increase and popularize modern energy services and infrastructure.

(2) Accelerating the development of the "large and poor" Hebei is the key to addressing the challenge of developing a clean and low-carbon energy system and an inclusive and sustainable industrial system. This requires coordinated development with Beijing and Tianjin to reduce the regional disparity.
(3) The Chinese government has already signaled a strong political desire to coordinate the development of the BTH region, with corresponding institutional reform, strategic plans, and demonstration projects. However, detailed plans and accurate project implementation are still required.
(4) International experiences demonstrate that the key to realizing coordinated development in the BTH region through market mechanisms is threefold. First, it is important to strengthen the construction and functioning of innovation sources, including universities, hospitals, and R&D institutes (especially in Hebei, which has few first-class universities, while there are many in Beijing and Tianjin). Second, it is necessary to propel extensive communications and public–private partnerships among local government, business, and academia. Third, there is an urgent need to construct a series of sub-core cities with comprehensive urban functions, such as higher education, administration, and international communications, to disperse the population and functions from the core city. Current policy is mainly focused on the third aspect, and there is a lack of attention to the first and second points.
(5) Both policy and the market must target the optimization of the energy and industrial structures of Hebei. The ultimate goal is to control the use of coal and diversify its industrial structure in order to control emissions. More detailed engineering projects must be planned and commercialized to deliver real progress. Bottom-up innovation is urgently required in the BTH region, according to sustainable development objectives and political objectives, by enhancing the construction of innovation sources, especially in Hebei.

7.2. Energy Scenarios to 2030

To verify the above messages, especially for the question of whether the acceleration of Hebei's development and its optimization of energy and industrial structure can reduce emissions in the BTH region, we have developed two energy scenarios for the period up to 2030 for comparison.

The first is a business-as-usual (BAU) scenario, which considers Beijing, Tianjin, and Hebei to optimize their development of energy and industry according to their respective goals. The second is a coordinated development (CD) scenario, which considers the holistic optimization of all subregions for the sustainable development of the whole BTH region, mainly targeting the acceleration of economic growth and the reduction of CO_2 emissions. The key settings of the two scenarios are listed in Table 7. In view of the lack and scattered distribution of renewable energy in the BTH region, including solar and wind resources, we think that this region has inadequate conditions for the large-scale development for local renewable energy and nuclear power in a relatively short period. As shown in the analysis of physical systems, it is necessary to consider the switch from coal to natural gas in a relative short period in the BTH region. As a result, we mainly discussed the decrease of coal and increase of natural gas in the two scenarios.

The calculations are based on a simplified calculator of the future energy flows in Beijing, Tianjin, and Hebei, previously published in a research report delivered to the Chinese Academy of Engineering [74]. The calculator was developed based on our understanding of the physical energy systems. The results indicate that, in the BAU scenario, the energy consumptions of Beijing, Tianjin, and Hebei in 2030 will be 3.0 EJ, 3.7 EJ, and 11.6 EJ, respectively. In the CD scenario, the energy consumptions will drop to 1.8 EJ and 1.9 EJ in Beijing and Tianjin, respectively, and rise to 12.6 EJ in Hebei. The significantly reduced energy consumptions of Beijing and Tianjin in the CD scenario are a result of their stricter control of the population and economic growth rate. Although the energy consumption of Hebei will increase in the CD scenario because of rapid economic growth, the total energy consumption of the BTH region will be reduced to 16.3 EJ, as compared with 18.3 EJ in the

BAU scenario. Because of the reduction in coal use (from 7.8 EJ in the BAU scenario to 4.8 EJ, mainly because of the increase in natural gas use from 2.5 EJ to 4.9 EJ), the CD scenario reduces energy-related CO_2 emissions to 1.11 billion tons, as compared with the 1.35 billion tons emitted in the BAU scenario.

Table 7. Key settings of the two energy scenarios of the BTH region (2013–2030) [74].

Region	Scenario	Economic Growth (GDP in 2030 as a Multiple of that in 2013)	Population in 2030 (Million)	Urbanization Rate in 2030 (%)	Proportion of Tertiary Industry in 2030 (%)	Natural Gas Proportion in Local Thermal Power Generation in 2030 (%)	Reduction of Energy Intensity over the Period 2013–2030 (%)
Beijing	BAU	3.5	28	94	88	100	69
	CD	3	18	96	92	100	79
Tianjin	BAU	4.5	25	90	85.7	50	66
	CD	4	18	92	80	50	80
Hebei	BAU	3.5	81.2	60	85	10	67
	CD	5	100	70	60	70	75
BTH	BAU	3.71	134.18	73	63.7	-	68
	CD	4.13	136	76	71.8	-	74

Although the scenario analysis faces the problem of a lack of data, it at least presents one possibility of coordinating the development of energy and industry in the BTH region with the shared target of higher economic growth and lower emissions.

8. Conclusions and Suggestions

In this work, we have proposed the concept of I-SDOP and applied it to the development of an analysis method for coordinating the sustainable development of energy and industry in the BTH region. Finally, five key messages were formulated based on the analysis of four system layers, namely, *Sustainable development objectives*, *Decision-making systems*, *Operation systems*, and *Physical systems*, and two energy scenarios were analyzed to verify these messages. The concept and method of I-SDOP is proposed and applied for the first time, based on our previous study on China's energy and industrial systems, which is the main innovation point of this paper.

In the case study of the BTH region, it is revealed that considerable attention has been focused on the challenges of sustainable development, and China's central government has already signaled a strong political desire and proposed policy actions to promote the coordinated development of the energy industry. At present, the main question is whether a proper market mechanism and feasible engineering projects can be formed according to these actions to enhance the transformation of the physical system of energy and material use. The key answer to this question lies in the construction and function of innovation sources, as well as close communication and cooperation between the government, enterprises, and academia.

Based on the above integrated analysis of multiple layers, we propose the following points as a complement of current policies for decision-makers. First, the national and regional plans, such as the FYPs, still lack action plans and project plans, which bring difficulties for implementation. We suggest that specific action plans and engineering technical measures should be involved in the FYPs, considering the views of stakeholders. Second, it is necessary for Hebei to build a number of subcenters. It is insufficient to only pay attention to Xiong'an solely or excessively. In the future, the construction of multiple subcenters should be emphasized. Third, the key issues of construction in Hebei includes not only the demonstration projects, such as Xiong'an New Area, but also the innovation resources. Therefore, it is essential to carry out overall planning and detailed arrangement to improve the innovation ability of Hebei in the following policies.

It is also noticeable that, according to the multilayer dynamics, there is a great time lag in the regional response to sustainable development objectives. It typically takes a long time from changes in the outputs of physical systems until the perception of sustainable development challenges, then the policy adjustments of decision-makers, and, finally, the response of the market to optimize physical systems. To accelerate this process, it is vital to promote the development of regional think-tanks and apply information and communication technologies in physical systems to efficiently inform the government and public of the latest changes and trends in the market and physical systems.

The I-SDOP concept and method developed in this study can be utilized for the analysis of the coordinated development of energy and industry in rapidly developing composite regions. In future research, it is of importance to study more cases from around the world to generalize the concept and method, and use the research experiences to develop architecture models of I-SDOP analysis based on recent advances in complex system modeling and analysis.

Author Contributions: X.L., C.C. and L.M. coordinated the main theme of this paper and wrote this manuscript. L.M. proposed the I-SDOP methodology and identified the major sustainable objectives in the framework. X.L. analyzed the key issues in the sustainable development, decision-making systems, and operation systems in the BTH region. C.C. mapped the Sankey diagrams and used the LMDI decomposition method to analyze the physical systems. X.S., Z.J. and C.W. polished the analysis of developmental status in the BTH region and international experience of Tokyo. X.L., C.C. and L.M. integrated the results and constructed the energy scenario analysis method. L.M. and P.L. gave the conclusions and suggestions of this research. Final review was done by Z.L. and W.N. All the authors reviewed and approved this final manuscript.

Funding: This work was supported by the Chinese Academy of Engineering (Project No. 2014-ZD-12-2, from 2014 to 2015).

Acknowledgments: This work was supported by the Chinese Academy of Engineering (Project No. 2014-ZD-12-2, from 2014 to 2015). The authors also gratefully acknowledge support from BP regarding the Phase II & Phase III Collaboration between BP and Tsinghua University, and support from Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BAU	Business-as-usual (scenario)
BTH	Beijing–Tianjin–Hebei Region, including Beijing City, Tianjin City, and Hebei Province
CCCPC	Central Committee of the Communist Party of China
CD	Coordinated development (scenario)
CPC	Communist Party of China
FYP	Five-Year-Plan
GHG	Greenhouse gas
GDP	Gross domestic product
I-SDOP	Integrated strategy of Sustainable development objectives, Decision-making systems, Operation systems, and Physical systems
LMDI	Logarithmic Mean Divisia Index
NCCPC	National Congress of the Communist Party of China
NPC	National People's Congress
PRD	Pearl River Delta Region, including nine cities of Guangdong Province (Guangzhou, Shenzhen, Foshan, Dongguan, Zhongshan, Zhuhai, Huizhou, Jiangmen, and Zhaoqing)
YRD	Yangtze River Delta Region, including Shanghai City, Zhejiang Province, and Jiangsu Province

Appendix A. Personal Interviews

1. Expert, Wuppertal Institute, Wuppertal, Germany, 14 December 2015.
2. Senior Manager, Innovation City, Bottrop, Germany, 14–15 December 2015.
3. Expert, Institute for Work and Technology, Gelsenkirchen, Germany, 15 December 2015.
4. Senior Manager, RWE, Essen, Germany, 16 December 2015.
5. Senior Official, RVR, Kronprinzenstraße, Germany, 16 December 2015.
6. Senior Official, Cluster Energy Research of Energy Agency of NRW, Düsseldorf, Germany, 17 December 2015.
7. Senior Official, Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of NRW, Düsseldorf, Germany, 18 December 2015.

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