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# Smart Energy Urban Agglomerations in China: The Driving Mechanism, Basic Concepts, and Indicator Evaluation

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**Abstract:** The development of urban agglomerations and smart energy systems in China are tightly connected. However, basic concepts of this interdisciplinary connection are still lacking. To fill this gap, this paper proposed an item of "Smart Energy Urban Agglomeration" (SEUA), and studied its driving mechanism, basic concepts in China, and indicator evaluation of typical urban agglomerations. Firstly, by a theorical analysis, the driving mechanism of SEUA was concluded as of "internal and external driven by two axes", whereas national policies and cities' spontaneity are external and internal driving forces, and two axes are urban planning and energy system integration. Secondly, using system approaches, its concept connotation, development barriers, and action suggestions were proposed based on China's conditions. Thirdly, an indicator evaluation based on the driving mechanism was carried out to reveal the differences of four urban agglomerations, with relevant explanations. The results indicated that the Yangtze River Delta had the highest level of SEUA development because of its good performance in both axes. Meanwhile, the cities' spontaneity had a stronger driving force than national policies. Therefore, it is urgent for China's government to integrate the urban and energy planning among cities in urban agglomerations.

**Keywords:** smart energy systems; urban agglomeration; system approach; conceptual analysis; indicator evaluation



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## 1. Introduction

Aiming at a sustainable urbanization and low-carbon energy transition, China's national policies encouraged the development of urban agglomerations [1,2] and smart energy systems [1,2]. Obviously, there is a close connection between the two fields, as can be reflected by these points: (1) urban agglomerations are centers of energy consumption and practical forefronts of energy system integration, and (2) smart energy systems have become an important condition for sustainable development of urban agglomerations. Therefore, how to build smart energy systems within the scope of urban agglomerations has emerged as a potential issue for policy discussions and scientific research.

However, it is hard to find previous publications on this issue because it involves an interdisciplinary field. Currently, the research of urban agglomerations belongs to the field of urban planning, while the research of smart energy system belongs to the field of energy system integration. Though there are few papers related with the interdisciplinary research of these two fields, few of them discuss how to develop smart energy systems in urban agglomerations. By our literature review, energy-related research in the field of urban agglomerations mainly focuses on the macro level and hardly involves smart energy systems. For example, there are only discussions on the impact of spatial heterogeneity on energy efficiency [3,4], energy saving and emission reduction of urban agglomerations [5,6], inter-regional energy flows [7], and energy consumption structure of urban agglomerations [8]. Meanwhile, the research in the field of smart energy systems mainly focuses on spatial scopes of the nation [9,10], city [11–13], industrial park [14,15], and household [16], while none of them involves the spatial scope of urban agglomeration. Therefore, there is a lack of basic concepts and scientific evidence to explain how to build smart energy systems within the spatial scope of urban agglomerations.

In order to fill this gap, we refer to our previous research on "China's Smart Energy Town" (SET) [17]. This previous work is also interdisciplinary research of urban planning and energy system integration, but only focuses on the city level. One of its main contributions is the development of a system approach to clarify basics concepts of SET in China's conditions. Because the related concept of "smart energy city" [18–20] are already built internationally and also demonstrated in China, many examples of literature, policies, and demonstration projects are available to support the concept analysis of SET. Compared with the work on SET, the foundation of the research on the interdisciplinary field of urban agglomerations and smart energy systems is much weaker, and even a suitable item is lacking to describe the related issue. The focus of the SET research is the smart energy systems of cities. This study includes concept analysis and stakeholder analysis. In the concept analysis section of this article, SEUA's method steps proposed in SET will be referenced. However, due to the limited existing foundation in this study, the driving mechanisms of the SEUA concept will be explored first to verify the necessity of introducing this concept. Therefore, this paper attempts to propose a new item of "Smart Energy Urban Agglomeration" (SEUA) and verify its rationality both on theories and practices. First, by literature review, we discussed the driving mechanism of this item to verify its theoretical rationality. Second, we applied this driving mechanism to develop a system approach to clarify the connotation of SEUA, identify its development barriers, and propose action suggestions in the background of China. Third, considering the lack of projects demonstrating SEUA in China, we develop an indicator system based on the driving mechanism to evaluate, compare, and analyze the development potential of SEUA for four typical urban agglomerations, including Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, and Chengdu-Chongqing. These four urban agglomerations are China's first group of urban agglomerations designated by the Chinese government, and they are also relatively mature with a good foundation for building SEUAs. Among them, Beijing-Tianjin-Hebei has important political functions. The Yangtze River Delta and Pearl River Delta urban agglomerations have the best economic and technology foundation in China and they can develop SEUAs better. The Chengdu-Chongqing urban agglomeration is a leading region in the central part of China for development. It possesses abundant resources and a strong foundation for economic growth. The high-quality development of the Chengdu-Chongqing region also has the potential to drive the development of the entire central region of China, making it highly significant. Therefore, this article selects these four initial urban agglomerations in China as the research objects.

The most important contribution of this paper is that we proposed the item of SEUA and verified its rationality both on theoretical and practical perspectives. The driving mechanism is the main outcome, which can provide a theoretical basis for the item of SEUA and corresponding methodologies to explore the interdisciplinary field of urban agglomerations and smart energy systems, such as the conceptual analysis and indicator evaluation developed in our work. In addition, by the case study of China, this paper can help readers form a more systematic understanding of SEUA development and provide policy implications on SEUA development.

The following contents are as follows: Section 2 is a theoretical analysis to reveal the driving mechanism, Section 3 introduces the research methodology and data of the conceptual analysis and indicator evaluation for the case study, Section 4 presents the results and discussion of China's case, and Section 5 presents the conclusions and recommendations.

## 2. Theoretical Analysis

Since SEUA is a new item proposed in this paper, the first problem is its rationality. Therefore, we firstly discuss whether there is a consolidated driving force to raise this item. Considering this item originates from a combination of two existed concepts of "urban agglomeration" and "smart energy system", we firstly discuss their driving forces.

Urban agglomeration refers to a large-scale group of cities formed by the interconnection of infrastructure, exchange of economic factors, and unified management mechanisms between the central city and its surrounding cities. Urban agglomerations have become an important development model proposed by the Chinese government, and a smart energy system is one of the necessary conditions for the development of urban agglomerations. At the same time, the formation of a unified smart energy system for urban agglomerations can optimize the flow of energy system factors and improve energy system operational efficiency through economies of scale.

The driving forces of "urban agglomeration" are mainly the internal cities' spontaneous and external promotion by national policies. From an internal perspective, various cities within an urban agglomeration spontaneously form a development pattern of urban agglomeration due to economic complementarity, geographical proximity, cultural connections, and the need for urban expansion and development. Simultaneously, their energy systems also spontaneously interconnect and form the energy system of the urban agglomeration due to functional complementarity [21–23]. Externally, there is always a lack of clear administrative institution for urban agglomerations, and so the national government normally take this role [24–27]. For example, in recent years, China's central government strongly advocated the pattern of urban agglomerations to promote a new model of urbanization.

The driving forces of "smart energy systems" (SESs) are mainly the integration of energy systems and the overall planning of the region where the energy system is located. In the area of energy planning, SESs can be understood as a system approach of energy system integration. With the help of data, information, and communication technology [28–31], it realizes a global optimization of the energy system based on cross sectoral concepts (integrating various energy supply sectors and energy end-use sectors) [32]. In addition, SESs emphasize the integration of various energy networks (electricity, heat, and fuel, together with energy storage) [33,34] and respect the requirements of system flexibility to achieve high penetration of renewable energy [35]. The above elements will be included in the integration of future energy systems [36]. Therefore, the first driving force of an SES must be the integration of the energy system itself [37].

Meanwhile, there is also a driving force from the area of regional planning. The elements involved with SESs are quite wide, such as energy acquisition [38], conversion, end-use, and infrastructure [39], and they are normally integrated with the overall low-carbon and sustainable development of a region [40]. For example, some scholars think that departments of transportation, energy, and finance should be integrated together [41,42]. Therefore, regional planning becomes another important driving force for smart energy systems.

Obviously, the SEUA is an intersection of these two existed concepts. It can be understood as an urban agglomeration with smart energy systems. Therefore, the SEUA must integrate the driving forces of urban agglomerations and smart energy systems. From the perspective of urban planning, there are internal force of cities' spontaneity and external force of national policies. From the perspective of smart energy systems, there are two-axis driving forces for SEUAs. One axis is the integration of energy systems, and another axis is urban planning—also called regional planning of urban agglomerations and internal cities.

Combing the two perspectives together, the driving mechanism of an SEUA can be described as "internal and external driven by two axes", as shown in Figure 1. It explains that an SEUA is jointly promoted by national policies (external driving force) and cities' spontaneity (internal driving force). The external driving force refers to the macro policies of the government that guide the development of smart energy systems in various regions, and through mutual coupling, form a national smart energy system. The internal driving force is the spontaneous interaction of energy systems within urban agglomerations. Due to the differences in the economic, social, resource, and environmental conditions of each city, each city will have different characteristics in the construction of smart energy systems. They will also spontaneously integrate with the energy systems of other cities and achieve global optimization. Meanwhile, the external and internal driving forces are mainly realized along two axes, including one axis of urban planning and another axis of energy system integration.

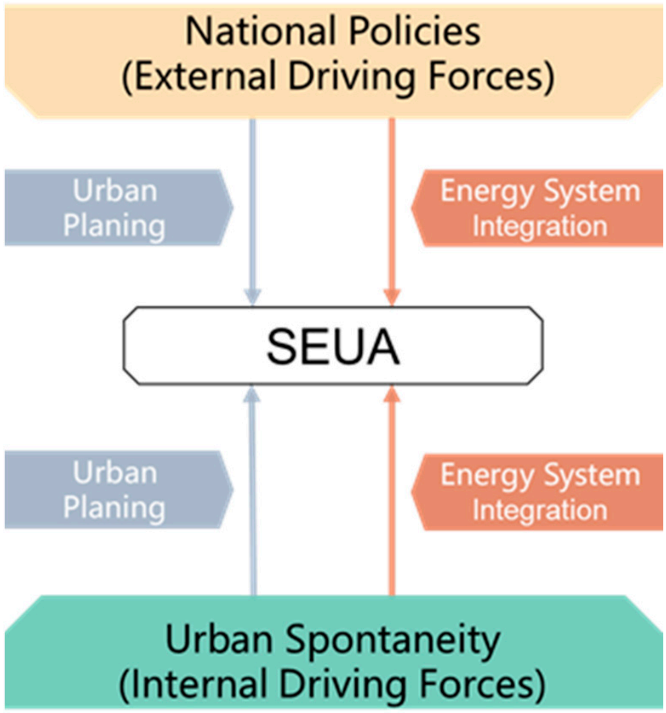


**Figure 1.** Driving mechanism of SEUA.

## 3. Methodology and Data

The above driving mechanism built a theoretical basis for the item of SEUA, explaining why it should be proposed and applied. However, the rationality of SEUA must be further proved by practices. Considering the lack of corresponding literatures, policies, and demonstration projects on SEUA, we decide to attempt two case studies on China to prove the practical rationality of SEUA. The first case is a conceptual analysis referring to the previous study of SET [17], aiming to qualitatively reveal the connotation, development barriers, and action suggestions of SEUA. It can also derive some policy implications for future development of SEUA. The second case is an indicator evaluation of main urban agglomerations in China, aiming to quantitatively verify the foundation and progress of SEUA development. It can help understanding the practical situation and differences of SEUA development in urban agglomerations, especially on the perspective of cities' spontaneity. In the following, Section 3.1 introduces the methodology and data of the conceptual analysis, and Section 3.2 introduces the methodology and data of the indicator evaluation.

### 3.1. Conceptual Analysis

The driving mechanism of SEUA, so-called "internal and external driven by two axes", decided the complexity of basic concepts of SEUA. Respecting many issues in the whole society are involved, it is more appropriate to use the soft system approach in systematics [43]. In the previous study of SET, Liang et al. [17] simplified the seven steps of traditional soft system approach into three steps, including concept analysis, barriers analysis, and action analysis. The concept analysis is the theoretical and ideal description of the system involved by the item, such as SET or SEUA. The barriers analysis is to compare the gap between reality and theory, and summarize the main obstacles in practices. The purpose of the action analysis is to identify potential changes and specific actions required to overcome barriers. However, unlike previous work on SET, which focused on existing items such as smart energy cities, the SEUA framework necessitates considering the driving mechanism of the SEUA concept within a system approach. As a result, this paper builds upon the three existing steps but introduces the concept of "internal and external drivers along two axes" to provide enhanced theoretical support.

The three steps of the conceptual analysis in this paper are illustrated by Figure 2. Firstly, the concept connotation is obtained by reviewing the literature referring to the driving mechanisms. We reviewed the examples of literature on regional energy system optimization [44–47] and collaborative optimization of smart energy systems and other systems [37,48]. Together with China's policies about urban agglomeration construction and energy system integration [24,26,49], we summarized driving forces of SEUA development. Secondly, the barriers are determined by comparing the results of conceptual analysis and the practice. Since there is currently a lack of SEUA projects, the first batch of "Internet Plus" smart energy demonstration projects in 2016 [50–52] is chosen as an alternative data source. Thirdly, the action suggestions are simply concluded from the respective perspectives of the country and the internal cities.

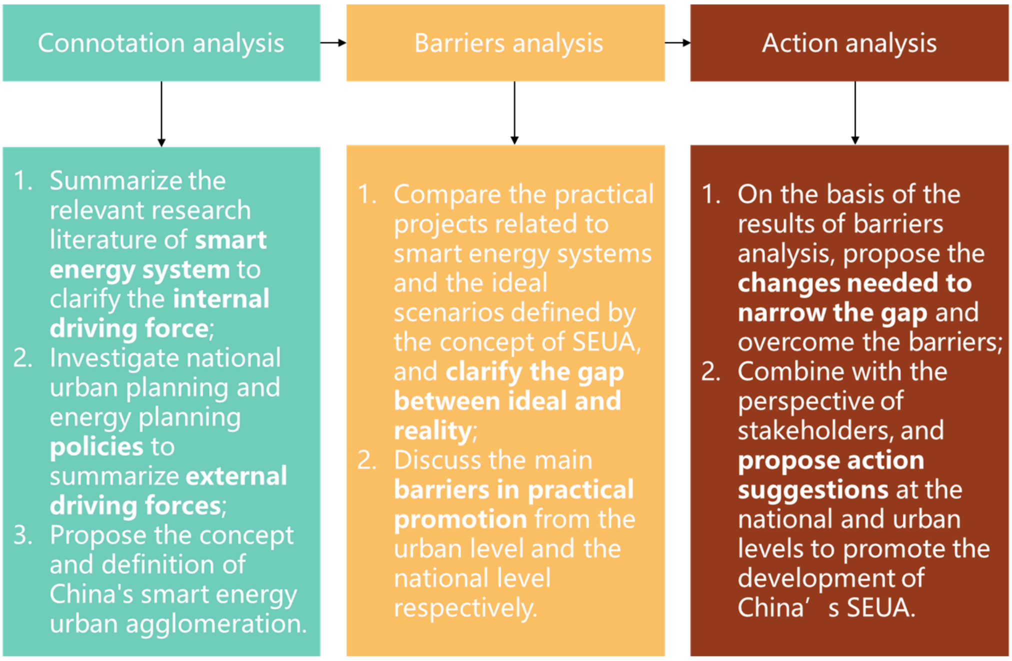


**Figure 2.** Research methodology for concept identification based on soft systems engineering methodology.

### *3.2. Indicator Evaluation*

On the basis of conceptual analysis, this paper further establishes a set of evaluation indicators with four main urban agglomerations in China [53]. This part introduces the construction of indicators and the method for determining the weight of each indicator.

This paper set two sets of evaluation indicators. This first set includes the development level indicators evaluating the overall development level of the four urban agglomerations towards SEUAs from the perspective of the two axes of energy system and urban planning. The second set includes the reason analysis indicators evaluating the internal and external driving forces of the four major urban agglomerations to further discuss the reasons for the difference in the overall development level of the four major urban agglomerations.

#### 3.2.1. The Development Level Indicators

The purpose of the indicator evaluation in this article is to evaluate the development status of the SEUAs in the four major urban agglomerations in China. Referring to the driving mechanism of "internal and external driven by two axes", this article believes that the development level of SEUAs can be reflected in two aspects: the development level of urban agglomerations and the level of energy system construction. Therefore, this article establishes "development of urban agglomerations" and "development of energy system integration" evaluation indicators [54].

Through literature research, the key aspects to evaluate urban planning include the economy, society, and environment [55–59], and key aspects to evaluate the integration of energy systems include energy efficiency, the proportion of renewable energy, energy facilities construction level, and energy service quality [60–63]. Moreover, the importance of the aspect of smart energy projects is also pointed out [64,65]. According to the aspects above, we set indicators for the development level of the two axes [66–69], as shown in Table 1. The weights of each indicator are determined using hierarchical analysis (Section 3.2.3), and the research objects are the four major urban agglomerations in China. The data are mainly obtained from the National Bureau of Statistics, statistical yearbooks, local statistical websites, yearbooks, etc. The details of data sources of each indicator are explained in Appendix A. The indicator data we have cited primarily pertain to the year 2019. However, due to the unavailability of updated data for some indicators up to 2019, we needed to make some compromises and select data that were closest in time to 2019. We aimed to ensure data consistency and represent the current development status of the four major urban agglomerations in terms of smart energy city development as accurately as possible.

**Table 1.** Evaluation indicators of SEUA and the Calculation Formula.

| Axis | Indicator Name | Calculation Formula |
|---|---|---|
| Indicators for development of urban agglomerations | GDP per capita | GDP/Permanent population |
| | Share of GDP in secondary and tertiary sectors | (GDP of secondary industry + GDP of tertiary industry)/GDP |
| | Urbanization rate of permanent population | Urban permanent population/ Permanent population |
| | Carbon emission intensity (negative indicator) | Carbon emissions/GDP |
| | Industrial waste gas emission intensity (negative indicator) | Industrial waste gas emissions/GDP |
| Indicators for development of energy system integration | Energy intensity (negative indicator) | Total energy consumption/GDP |
| | Share of renewable electricity (including hydropower) | Consumption of renewable energy power (including hydropower)/Electricity consumption of the whole society |
| | Urban gas penetration rate | Number of urban gas users/Urban permanent residents |
| | Per capita residential electricity consumption | Household electricity consumption/permanent population |
| | Ratio of urban energy industry investment to GDP | Investment in urban energy industry/GDP |
| | Number of smart energy system projects | Count directly |

### 3.2.2. The Reason Analysis Indicators

The above indicators can distinguish development differences of each urban agglomerations, but we also need to explain why there are differences. Therefore, we further develop the reason analysis indicators.

Referring to the driving mechanism of SEUA, we divide the indicators into two categories: one is the quantitative indicators of internal cities, and the other is the qualitative indicators of national policies.

(1) The internal driving force for the development of SEUAs comes from the individual cities within the urban agglomerations. This paper believes that the urban development and energy system integration level of the individual cities within the urban agglomerations can reflect the size of the internal driving force. These two indicators of the individual cities can refer to the evaluation indicators of the SEUAs (Table 1). We first referred to the indicators of SEUA, and we then simplified the evaluation indicators of SEUA considering the worse data availability of internal cities. We constructed a set of two axes indicators for the development level of internal cities as shown in Table 2. The research object is cities within the four major urban agglomerations, and the details of data sources of each indicator are explained in Appendix A.

**Table 2.** Indicators of Internal Cities of Urban Agglomerations and the Calculation Formula.

| Axis | Indicator Name | Calculation Formula |
|---|---|---|
| Indicators for development of city | GDP per capita | GDP/Permanent population |
| | Share of GDP in secondary and tertiary sectors | (GDP of secondary industry + GDP of tertiary industry)/GDP |
| | Urbanization rate of permanent population | Urban permanent population/Permanent population |
| Indicators for development of energy system integration | Power consumption intensity | Total electricity consumption/GDP |
| | Per capita domestic electricity consumption of urban residents | Domestic electricity consumption of residents in municipal districts/Urban permanent population |
| | Per capita gas consumption of urban residents | Domestic gas supply of artificial gas and natural gas in the municipal area/Urban permanent population |

(2) Based on the driving mechanism of SEUAs, we believe that when evaluating the development level of SEUAs, we also need to examine the degree of national support for the development of each SEUA to analyze the external driving force of SEUAs. The level of national support for the development of SEUAs can be observed through the inclusion of urban agglomerations in national policy documents. As of now, China does not have specific policy documents exclusively targeting the smart energy systems of individual urban agglomerations. Instead, the construction of smart energy systems encompasses various aspects of urban agglomerations as a whole. We believe that measuring the number and data of the country's guidance documents for the development of each urban agglomeration can reflect the external driving force level of the construction of each urban agglomeration. Therefore, we set up these qualitative indicators of national policies for the SEUAs.

### 3.2.3. Determination of Indicator Weights

The quantitative indicators described in this paper include indicators for urban agglomeration and internal cities. Firstly, the weights of the urban agglomeration indicators need to be determined. In this paper, there are only four evaluation objects of urban agglomeration, so there are only four data at each level of urban agglomeration. So, when assigning weights to the indicators, this paper adopted the hierarchical analysis method (AHP) [70,71], which is based on expert judgment and requires less data volume.

We invited 10 researchers engaged in energy strategy research as scoring experts, including 1 associate professor, 5 doctoral students, and 4 master students. They demarcated the importance of the indicators of the above urban agglomeration and gave everyone's judgment matrix. The eigenvector corresponding to the maximum eigenvalue of the above matrix was normalized to obtain the following vectors: $W = (w_1, w_2, \ldots, w_n)^T$, and $w_i$ is the weight of the indicator i of urban agglomeration. Finally, we tested the consistency of the weights given by everyone. The average of qualified data is the weight of each indicator, and the detailed content of the above method is shown in Appendix B. In order to ensure the rationality of the indicator weights determined through the Analytic Hierarchy Process (AHP), we further invited seven experts to examine the scoring results of the ten judges. This verification process confirmed the validity of the scoring results obtained through consistency checks in this study.

For the indicator weights of internal cities, we allocated them in equal proportion by referring to the corresponding indicator weights of urban agglomeration. For example, indicators at the urban level include GDP per capita, the proportion of GDP in the secondary and tertiary industries, and the post resident urbanization rate. We calculated the sum of the weights of these three indicators in the urban agglomeration indicators (0.806) and took the proportion of each indicator in the sum as their respective indicator weights at the city level. The results and discussion of indicator weights are shown in Appendix C.

## 4. Results and Discussion

### *4.1. Basic Concepts of SEUA*

#### 4.1.1. Concept Connotation

Based on the driving mechanism "internal and external driven by two axes", this paper analyzed the literature on urban agglomeration and energy system integration to summarize the driving forces that may help the formation and development of SEUAs, both at the internal urban level and at the external national policy level. Table 3 presents internal and external driving forces of SEUAs summarized through literature review in this article. The sources of each driving force have been annotated in the table.

**Table 3.** Internal and external driving forces of SEUAs.

| Internal Driving Forces | External Driving Forces |
|---|---|
| (1) Improve energy efficiency and the share of renewable energy in the region [17,44,45,47]. | (1) Promote the interconnection of transportation networks and energy pipeline networks among cities [26]. |
| (2) Strengthen the cooperation of energy, capital, and human resources among stakeholders in actual operation and production [17,44,46]. | (2) Achieving synergy between the electric, heat and fuel network [24,26,72]. |
| (3) Make cities actively participate in inter-city energy interaction [45,48]. | (3) Integrate the improvement in the share of renewable energy and optimize the synthetical efficiency for energy utilization [2,26,44,49]. |
| (4) Promote the involvement of information technology in the management of energy systems [37,48]. | (4) Develop the distributed energy resources and energy storage technologies [2,44,47]. |
| | (5) Build a unified and complete energy market [2,47]. |

Integrating the driving mechanism and internal and external driving forces of China's SEUAs, this paper attempts to summarize the definition of SEUAs: The development mode of energy systems in urban agglomeration with adaptation to local condition, regional coordination, efficiency, and sustainability.

The connotation of the above SEUA concept at least includes the following:

(1) The construction of SEUAs should be based on the construction of smart energy systems in internal cities. Each region within the urban agglomerations should adapt to its local condition, develop renewable energy, distributed energy, and improve the energy structure;
(2) With the goal of regional coordinated development, SEUAs should strengthen the energy interaction between cities, promote the sharing and co-construction of energy, transportation, and communication infrastructure between cities, and realize the integration of electricity, heat, and fuel networks;
(3) The government should innovate the business model of energy within SEUAs and among urban agglomerations, build a larger unified energy market, and use information and communication technology to participate in management and decision-making. The overall energy system can achieve high energy efficiency and high renewable energy ratio.

#### 4.1.2. Development Barriers

It is necessary to analyze the practical obstacles to the development of SEUAs by comparing the concept connotation and actual situation of SEUAs.

At present, smart energy system projects for urban agglomeration are lacking in China. What we can refer to now is China's first "Internet plus" smart energy projects in 2016 [50–52]. These projects are the demonstration and basis for the construction of China's smart energy system, 12 of which are urban comprehensive demonstration projects [50]. The projects mentioned above have employed various technical approaches, such as thermoelectric conversion, clean energy-based heating, photovoltaic power generation, heat storage technology, and information and communication technology, for participating in the operation and management of the energy system. However, it should be noted that most of these projects only focus on specific technical solutions, resulting in a lack of comprehensive technical application. At the same time, the final implementation of the above projects is not ideal. The first batch of "Internet plus" smart energy projects had more than 300 projects declared at the earliest; 55 projects passed the approval, but only about 14 projects finally passed the acceptance [45].

It is found that the gaps in project practice mainly include the following:

1. The smart energy system project is still in the small-scale demonstration stage, and the cross-regional project is still in the conceptual design stage. The energy system of most projects is simple, most of which are industrial zones;
2. The technical scheme of smart energy system applied in some projects is relatively simple and not comprehensive. Some projects pay too much attention to information and communication technology, and relatively neglect energy technology;
3. Most smart energy projects lack appropriate business models, market mechanisms, and financial coordination mechanisms.

Since the internal and external drivers for the development of SEUAs come from the urban level and the national level, this paper speculates that the barriers at these two levels are the main reasons for the above gaps.

1. At the national level, energy policy makers lack a clear design of the overall structure, development path, and operation mode of building smart energy system at the urban agglomeration level. The aforementioned projects have utilized diverse technical approaches, including thermoelectric conversion, clean energy-based heating, photovoltaic power generation, heat storage technology, and information and communication technology, to contribute to the operation and management of the energy system. However, it is important to acknowledge that the majority of these projects tend to concentrate on specific technical solutions, thereby lacking a comprehensive

application of technology, but there are few plans at the level of urban agglomerations in the national smart energy system planning. The makers of regional planning policies should establish a more efficient system of communication, cooperation, and co-construction among cities in urban agglomeration to improve the process and effect of building SEUA.

2. At the urban level, the policy executors of the energy system should strengthen the guidance of the smart energy system of enterprises to help enterprises cope with the problems of low return on projects, insufficient operating experience, and immature technology. The makers of regional planning should fully integrate the construction and operation of smart energy systems into urban planning.

4.1.3. Action Suggestion

In response to the above-mentioned barriers, this paper argues that reasonable and feasible changes include three main aspects. Firstly, the government should strengthen top-level design and introduce smart energy system planning and policies at the level of urban agglomeration as soon as possible. Secondly, industrial support and market construction, and the enthusiasm of enterprises to participate in the construction of smart energy system projects need to be strengthened. Thirdly, the investment in scientific research should be increased to promote innovation of smart energy system technology.

Combining the stakeholder perspectives, this paper considers the national-level planning department, the finance department, and the science and technology department, as well as the urban-level local governments, state-owned enterprises, and private enterprises as the main stakeholders in the development of SEUAs in China. Therefore, this paper gives some action suggestions for each of these six parties, as shown in Figure 3.

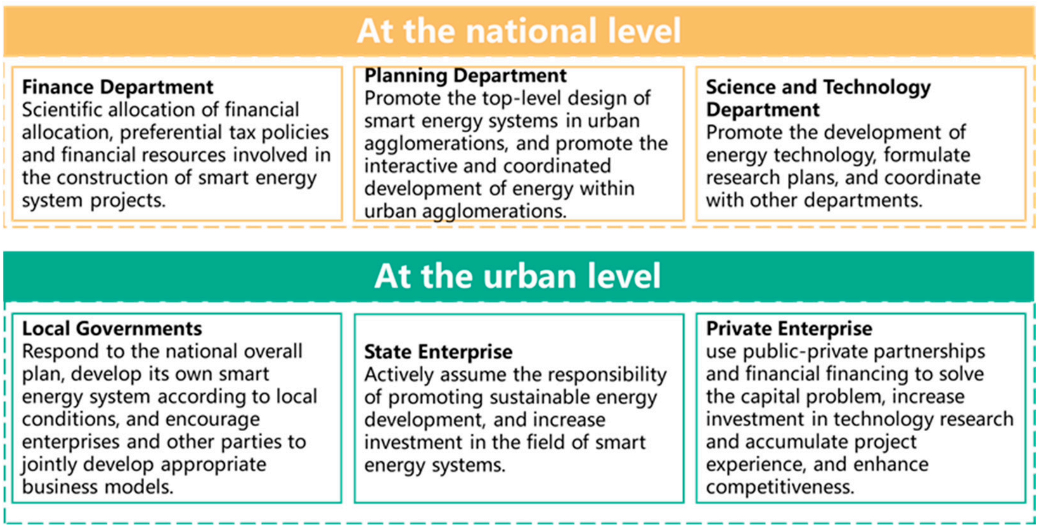


**Figure 3.** Action suggestions of major stakeholders in the development of China's SEUAs.

## *4.2. Evaluation and Analysis of Indicators for SEUAs in China*

4.2.1. Indicator Evaluation for the Development of the Four Major SEUAs in China

In order to unify the dimensions, this paper uses the normalization method to process the indicator data of the SEUAs and the internal cities. Due to the limited data of each city within the urban agglomerations, we cannot accurately calculate the accurate data of each urban agglomeration. We appropriately expanded the scope of the four major urban agglomerations.

According to the indicator evaluation method in Section 3.2.1, this section evaluates the overall level of the development of Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, and Chengdu-Chongqing urban agglomerations from the perspective of two axes of urban development level and energy system integration level. The results are shown in Table 4 and Figure 4. The weights and data of each indicator are shown in Appendix C.

As shown in Figure 4, in this paper's evaluation indicator system, the Yangtze River Delta urban agglomeration, has a higher level of both urban development and energy system integration, and is overall closer to the state of China's SEUA. The Pearl River Delta urban agglomeration is relatively prominent in the urban development level axis and the Chengdu Chongqing urban agglomeration in the energy system integration axis, while the Beijing-Tianjin-Hebei Urban Agglomeration is relatively backward in both axes.

**Table 4.** Development level indicators of China's four major urban agglomerations.

| Name of Urban Agglomeration | Beijing-Tianjin-Hebei Urban Agglomeration | Yangtze River Delta Urban Agglomeration | Pearl River Delta Urban Agglomeration | Chengdu and Chongqing Urban Agglomeration |
|---|---|---|---|---|
| Urban development level indicator | 0.443 | 0.532 | 0.562 | 0.432 |
| Energy system integration level indicator | 0.393 | 0.550 | 0.451 | 0.449 |

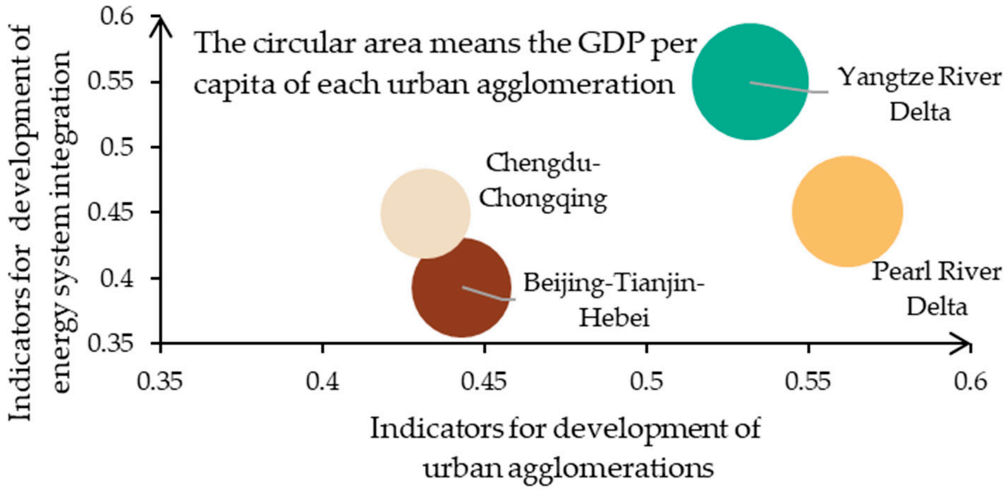


**Figure 4.** Development level of China's four SEUAs.

As shown in Figure 5, according to the calculation of this paper, the Yangtze River Delta and Pearl River Delta urban agglomerations both have good economic standards. The economic foundation of the Chengdu-Chongqing urban agglomeration is relatively weak; in terms of environment, since energy intensity, carbon emission intensity, and industrial waste gas emission intensity are negative indicators [69,73], so their higher values represent lower corresponding intensities. The above three intensities are lower in the Pearl River Delta urban agglomeration, mainly due to the relatively high proportion of low-energy-consuming industries. However, all three intensities are higher in the Beijing-Tianjin-Hebei urban agglomeration, mainly due to the fact that energy consumption in Hebei Province is dominated by coal and oil, and the proportion of high-energy-consuming industries is larger.

As shown in Figure 6, the energy intensity of urban agglomerations in the Pearl River Delta and Yangtze River Delta are relatively low, and the Chengdu-Chongqing urban agglomeration has abundant hydropower resources and high renewable energy power consumption. In terms of energy system integration, the Yangtze River Delta urban agglomeration occupied 16 projects of the first 55 "Internet Plus" smart energy demonstration projects in China in 2016, with a high willingness to develop smart energy systems. The urban energy industry investment in Beijing-Tianjin-Hebei and Chengdu-Chongqing urban agglomerations accounts for a relatively high proportion of GDP, indicating that the energy systems of these two urban agglomerations are accelerating their construction.

To sum up, we believe that the Yangtze River Delta and Pearl River Delta urban agglomerations have better development foundations and can serve as the model for developing China's SEUAs by summarizing experience. For Chengdu-Chongqing urban agglomeration, we should focus on improving the overall economic level; for the Beijing-Tianjin-Hebei Urban Agglomeration, we should accelerate the low-carbon transformation of the energy system.

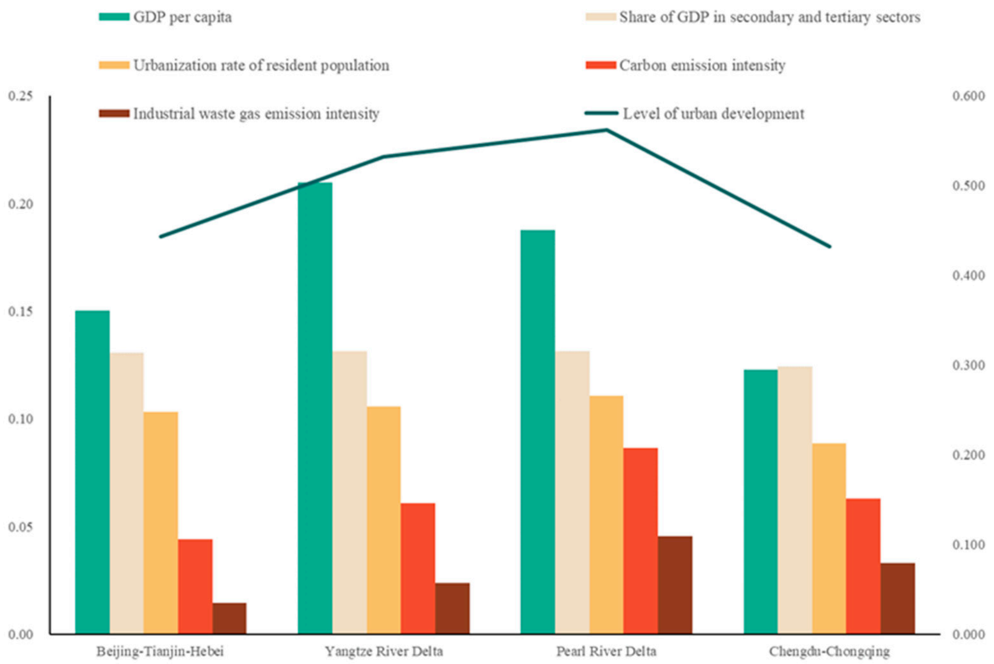


**Figure 5.** Structure of the urban agglomeration development level indicators for the four major urban agglomerations.

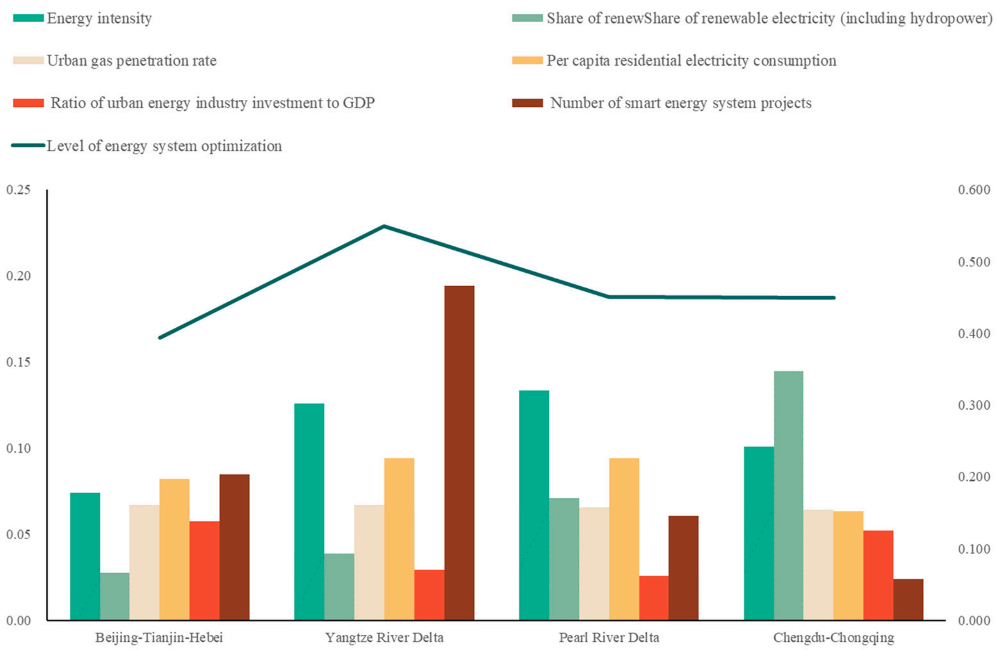


**Figure 6.** Structure of the energy system integration level indicators for the four major urban agglomerations.

4.2.2. Reasons for the Different Development of the Four Major SEUAs in China

This section shows the results of indicator evaluation of urban development within the four major urban agglomerations in China, reflecting upon the differences in the internal driving forces of SEUAs. The detailed method is shown in Section 3.2.2, and the results are shown in Figure 7.

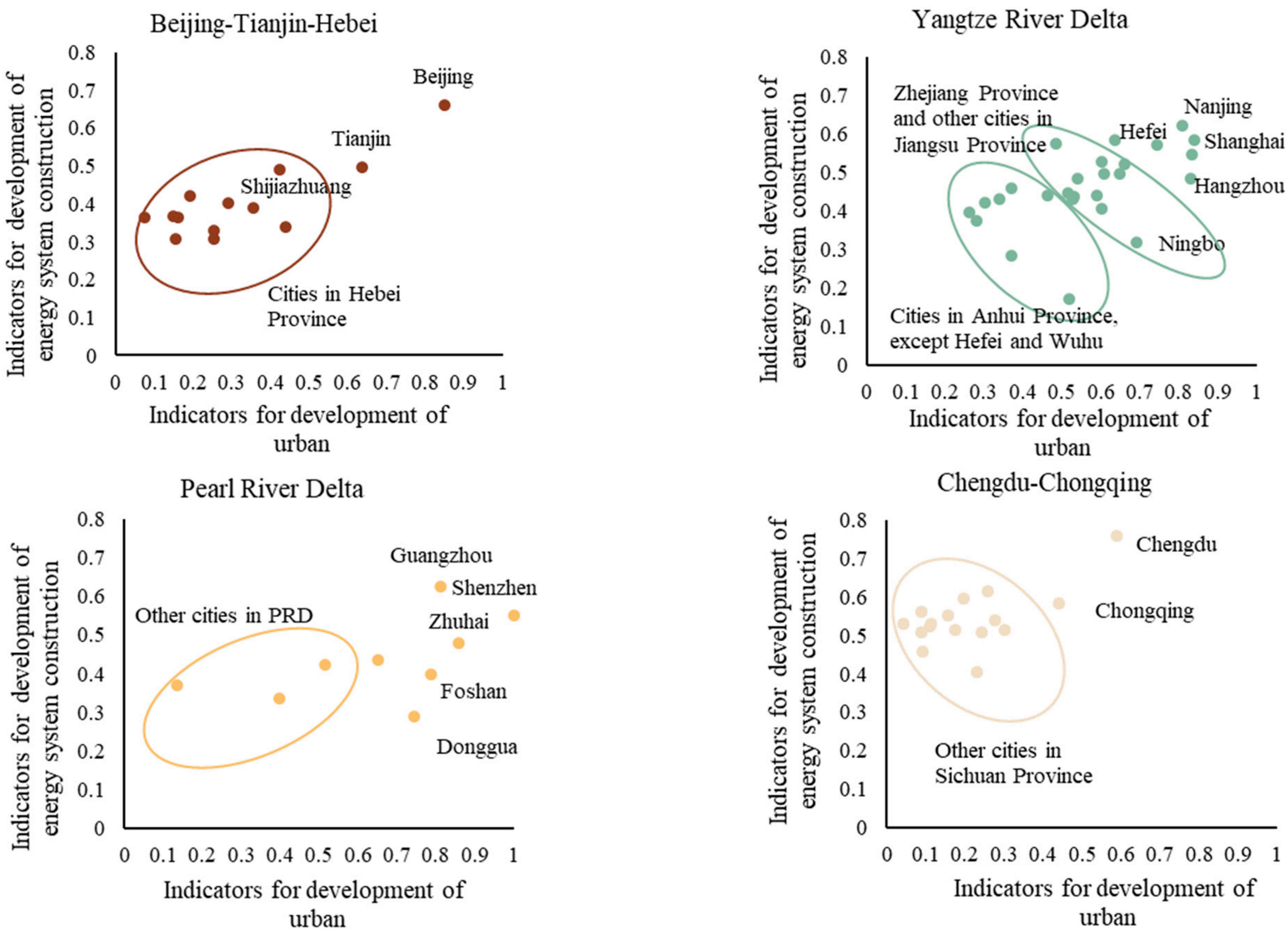


**Figure 7.** Urban differences within the four major urban agglomerations.

In Figure 7, according to the calculation of this paper, the regional gap within the urban agglomerations in the Yangtze River Delta and the Pearl River Delta is relatively small, and the coordinated benefits of the surrounding cities driven by the radiation of the core cities and the central cities are gradually emerging. It can be initially judged that the internal driving force of the urban agglomerations in the Yangtze River Delta and the Pearl River Delta is strong. However, the polarization of Beijing-Tianjin-Hebei and Chengdu Chongqing urban agglomerations is relatively severe, and the degree of coordinated development is insufficient [72], so the intrinsic driving force is weaker. This also shows that the internal driving force of the four urban agglomerations relatively corresponds to their development level of SEUAs in Section 4.2.1.

For the qualitative analysis of the differences in the external driving forces of the four major urban agglomerations, we counted the number of central policies and regulations related to the four major urban agglomerations included in the" China Legal Retrieval System" database to approximate the differences in the external drivers of each urban agglomeration. As of 1 June 2021, in terms of quantity, the Beijing-Tianjin-Hebei urban agglomeration has the largest number of central regulations, followed by the Yangtze River Delta and Pearl River Delta urban agglomerations. The number of regulations involving the Chengdu Chongqing urban agglomeration is relatively small, but also shows an increasing trend. From the perspective of policy description, China has explicitly proposed to build three world-class urban agglomerations in Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta [26,74] to form a replicable experience [75]. The 13th Five-Year Plan emphasizes the coordinated development of Beijing-Tianjin-Hebei [75], while the Chengdu-Chongqing urban agglomeration is defined as the fourth economic growth pole [14] and the focus of Western Development [44,76].

Initially, it is judged that the external driving force of the development of the four major SEUAs at the national level are, in descending order, Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, and Chengdu-Chongqing urban agglomerations. This analysis cannot adequately explain the results in Section 4.2.1. The development level of Beijing-Tianjin-Hebei smart energy city cluster is not prominent.

To sum up, this paper believes that the internal driving force effect of China's SEUAs is stronger than the external driving force. Therefore, when developing China's SEUAs, we should pay attention to the effect of internal driving forces. Firstly, it is necessary to guide the reasonable integration of energy systems among cities within the urban agglomeration. This involves developing a comprehensive energy planning for the urban agglomeration, promoting interconnection of energy infrastructure among cities, establishing coordinated policies and regulations for the integration of energy systems, and fostering technological innovation and sharing among cities. At the same time, we should make up for our shortcomings in terms of external driving forces, develop top-level design that is more realistic at the national level, formulate guiding policies, and establish a coordination mechanism between urban agglomerations.

### *4.3. Policy Implications*

This paper suggests that in the process of developing China's SEUAs, action should be taken at the national, urban, and urban agglomeration levels. At the national level, the top-level design of China's SEUAs driven by two axes should be researched, the development policies should be formulated as an aid, coordination mechanisms should be established as a guarantee, and smart energy urban demonstration projects in major urban agglomerations should be accelerated. At the urban level, we should formulate and implement systematic planning and project design that integrate urban planning and smart energy, strengthen collaboration among enterprises and other parties, and actively participate in interregional collaborative development. At the level of urban agglomerations, strategic management, coordination, and communication should be strengthened, and on the basis of smart energy cities, policy mechanisms to achieve the overall optimization of smart energy systems in urban agglomerations should be further introduced.

### *4.4. Limitations of this Study*

Because the current research on SEUAs is limited and our knowledge level and practice are relatively deficient, the concept of SEUAs we put forward is only a starting point in this field. We hope to have more research on SEUAs in the future.

When this paper constructs the evaluation index system, although the main aspects of the urban development level and the energy system development level are considered comprehensively, the final indicator system is not perfect due to the limitations of the availability and timeliness of the data required by the indicators. Therefore, in future research, we should collect as much relevant data as possible, and further improve the construction method of the evaluation index system on this basis. Secondly, this paper adopts the analytic hierarchy process when setting the index weight. Although this method has been widely used, it will have a certain impact on the results due to its strong subjectivity. Therefore, in future research, we can reduce the impact of subjective factors by inviting experts from multiple relevant fields to give a judgment matrix, or we can try to use objective weighting method to make the research results more convincing.

## 5. Conclusions and Recommendations

This paper proposes a new concept of SEUA and identifies the driving mechanisms for its development and application. On this basis, a concept analysis approach is used to study the connotation of the concept, development barriers and action suggestions in China. The SEUA development level of the four major urban agglomerations in China and the evaluation of the reasons for differences are verified by indicator evaluation. Finally, policy implications are derived for the future development of SEUAs.

The main findings of this paper are as follows:

1. The development of China's SEUAs is driven by the external national policies of urban agglomerations and the internal construction of cities, and the driving forces of these two levels are realized along the two axes of urban planning and energy system integration.
2. China's SEUAs are a kind of urban agglomeration that aim at regional coordinated development, take the construction of internal urban smart energy system as the foundation, and realize high operation quality, high energy efficiency, and high renewable energy proportion through innovation of information and communication technology, energy technology, and market mechanism.
3. The Yangtze River Delta and Pearl River Delta urban agglomerations are closer to the development requirements of China's SEUAs.
4. The internal driving force of cities in China's SEUAs is stronger than the external driving force from the national policies.

Meanwhile, we also put forward the following policy recommendations:

1. The construction of SEUAs should be promoted from the aspects of energy system integration and regional construction at the national level and internal city level.
2. In the process of building SEUAs, we should take the Yangtze River Delta and Pearl River Delta as the demonstration of building SEUAs.
3. We should take advantage of the effect of spontaneous construction of internal cities and strengthen the guidance of national policies on SEUAs.

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## Appendix A

**Table A1.** Year and source of indicator data of SEUA.

| Axis | Indicator Name | Data | Year | Data Resource |
| --- | --- | --- | --- | --- |
| Indicators for development of urban agglomerations | GDP per capita | GDP; Permanent population | 2019 | ① |
| | Share of GDP in secondary and tertiary sectors | GDP of secondary industry; GDP of tertiary industry; GDP | 2019 | ① |
| | Urbanization rate of permanent population | Urban permanent population; Permanent population | 2019 | ① |
| | Carbon emission intensity (negative indicator) | Carbon emissions; GDP | 2017 | ②; ① |
| | Industrial waste gas emission intensity (negative indicator) | Industrial waste gas emissions; GDP | 2015 | ③; ① |
| Indicators for development of energy system integration | Energy intensity (negative indicator) | Total energy consumption; GDP | 2018 | ④; ① |
| | Share of renewable electricity (including hydropower) | Consumption of renewable energy power (including hydropower; Electricity consumption of the whole society | 2019 | ⑤; ① |
| | Urban gas penetration rate | Number of urban gas users; Urban permanent residents | 2019 | ④; ① |
| | Per capita residential electricity consumption | Household electricity consumption; Permanent population | 2018 | ① |
| | Ratio of urban energy industry investment to GDP | Investment in urban energy industry; GDP | 2017 | ④; ① |
| | Number of smart energy system projects | Count directly | | ⑤ |

Note 1. Data sources: ① statistical yearbooks of provinces and cities, ② CEADs, ③ Ministry of Ecological Environment, ④ National Bureau of Statistics, ⑤ National Energy Administration. Note 2. Due to the limited data accuracy, the scope of the four major urban agglomerations is appropriately expanded in this paper: 1. The Beijing-Tianjin-Hebei urban agglomeration is considered to be composed of Beijing, Tianjin, and Hebei Province; 2. The Yangtze River Delta urban agglomeration is considered to be composed of Shanghai, Jiangsu, Zhejiang, and Anhui Province; 3. The Pearl River Delta urban agglomeration is considered to be composed of Guangdong Province; 4. The Chengdu-Chongqing urban agglomeration is considered to be composed of Chongqing and Sichuan Province. Note 3. Our plan was to have all the data in this article from the year 2019. However, due to the lack of timely updates for some indicators, we had to select the closest available updated data to 2019. And we think that these data can also reflect the current situation and highlight the main issues.

**Table A2.** Year and source of indicator data of internal cities.

| Axis | Indicator Name | Data | Year | Data Resource |
| --- | --- | --- | --- | --- |
| Indicators for development of urban agglomerations | GDP per capita | GDP; Permanent population | 2019 | ①; ② |
| | Share of GDP in secondary and tertiary sectors | GDP of secondary industry; GDP of tertiary industry; GDP | 2019 | ① |
| | Urbanization rate of permanent population | Urban permanent population; Permanent population | 2019 | ② |

**Table A2.** *Cont.*

| Axis | Indicator Name | Data | Year | Data Resource |
|---|---|---|---|---|
| Indicators for development of energy system integration | Power consumption intensity | Total electricity consumption; GDP | 2016 | ③; ① |
| | Per capita domestic electricity consumption of urban residents | Domestic electricity consumption of residents in municipal districts; Urban permanent population | 2016 | ③; ② |
| | Per capita gas consumption of urban residents | Domestic gas supply of artificial gas and natural gas in the municipal area; Urban permanent population | 2018 | ③; ② |

Note. Data sources: ① National Bureau of Statistics, ② statistical bureaus of cities, ③ China's urban statistical yearbook.

## Appendix B

The introduction to AHP for determining indicators weight is as follows:

1. Construction of the judgment matrix.

The experts calibrate the relative importance of two indicators based on empirical judgments using integers from 1 to 9 or their inverse; 1 represents the same importance for both indicators and a larger number indicating a stronger level of importance. The judgement matrix A is obtained that reflects the priority of each indicator.

$$
\begin{array}{ccccc}
 & A_1 & A_2 & & A_n \\
A_1 & 1 & a_{12} & \ldots & a_{1n} \\
A_2 & a_{21} & 1 & & a_{2n} \\
 & \vdots & & \ddots & \vdots \\
A_n & a_{n1} & a_{n2} & \ldots & 1
\end{array}
$$

$a_{ij}$ denote the importance of indicator $i$ relative to indicator $j$.

The experts invited in this paper are the staff engaged in energy strategy research in the work team of the author. There are 10 people in total, including 1 associate professor, 5 doctoral students, and 4 master students. Experts gave judgment matrices for the importance of the above indicators of urban development level and energy system integration level.

2. Calculation of indicator weights.

Calculate the eigenvector corresponding to the maximum eigenvalue of judgment matrix A and normalize it. Then, obtain the eigenvector $W = (w1, w2, \ldots, wn)^T$, and $wi$ is the weight of the indicator i of urban agglomeration.

After calculating the weights of urban agglomeration development level evaluation indicators, we refer to the weights of urban agglomeration indicators to calculate the weights of urban development level evaluation indicators. For example, indicators at the urban level include GDP per capita, the proportion of GDP in the secondary and tertiary industries, and the post resident urbanization rate. We calculated the sum of the weights of these three indicators (0.806) in the urban agglomeration indicators and took the proportion of each indicator in the total as their respective indicator weights at the city level. The results and discussion of indicator weights are shown in Tables A3 and A4.

3. Consistency inspection

The consistency of importance sequences among all indicators can improve the reliability of the weights data. So, the consistency indicator *CI* and the consistency ratio *CR* need to be calculated. Tables A3 and A4 shows the value of random consistency indicator RI.

$$CI = \frac{\lambda_{max} - n}{n - 1},\ CR = \frac{CI}{RI}$$

If the consistency ratio *CR* is less than 0.1, the data pass the consistency test and have high reliability.

**Table A3.** Weight value and consistency test results of indicators for urban development.

| Expert No. | GDP per Capita | Share of GDP in Secondary and Tertiary Sectors | Urbanization Rate of Permanent Population | Carbon Emission Intensity (Negative Indicator) | Industrial Waste Gas Emission Intensity (Negative Indicator) | CR |
|---|---|---|---|---|---|---|
| 1 | 0.106 | 0.293 | 0.037 | 0.352 | 0.212 | 0.099 |
| 2 | 0.373 | 0.373 | 0.171 | 0.054 | 0.029 | 0.042 |
| 3 | 0.559 | 0.186 | 0.160 | 0.061 | 0.034 | 0.050 |
| 4 | 0.303 | 0.255 | 0.148 | 0.093 | 0.200 | 0.317 |
| 5 | 0.366 | 0.160 | 0.366 | 0.060 | 0.049 | 0.080 |
| 6 | 0.165 | 0.241 | 0.453 | 0.073 | 0.069 | 0.057 |
| 7 | 0.473 | 0.214 | 0.214 | 0.050 | 0.050 | 0.021 |
| 8 | 0.494 | 0.141 | 0.243 | 0.082 | 0.040 | 0.071 |
| 9 | 0.377 | 0.377 | 0.128 | 0.080 | 0.038 | 0.035 |
| 10 | 0.162 | 0.347 | 0.077 | 0.372 | 0.042 | 0.043 |

**Table A4.** Weight value and consistency test results of indicators for energy system integration.

| Expert No. | Energy Intensity (Negative Indicator) | Share of Renewable Electricity (Including Hydropower) | Urban Gas Penetration Rate | Per Capita Residential Electricity Consumption | Ratio of Urban Energy Industry Investment to GDP | Number of Smart Energy System Projects | CR |
|---|---|---|---|---|---|---|---|
| 1 | 0.196 | 0.207 | 0.044 | 0.095 | 0.055 | 0.402 | 0.050 |
| 2 | 0.128 | 0.237 | 0.033 | 0.075 | 0.033 | 0.494 | 0.051 |
| 3 | 0.268 | 0.397 | 0.020 | 0.174 | 0.052 | 0.089 | 0.074 |
| 4 | 0.231 | 0.415 | 0.070 | 0.101 | 0.136 | 0.046 | 0.126 |
| 5 | 0.036 | 0.130 | 0.323 | 0.323 | 0.130 | 0.056 | 0.014 |
| 6 | 0.362 | 0.168 | 0.071 | 0.168 | 0.062 | 0.168 | 0.008 |
| 7 | 0.493 | 0.037 | 0.149 | 0.218 | 0.066 | 0.037 | 0.032 |
| 8 | 0.297 | 0.058 | 0.049 | 0.131 | 0.143 | 0.323 | 0.033 |
| 9 | 0.141 | 0.081 | 0.428 | 0.245 | 0.078 | 0.027 | 0.075 |
| 10 | 0.072 | 0.196 | 0.072 | 0.094 | 0.163 | 0.402 | 0.031 |

**Table A5.** The value of random consistency indicator RI.

| n. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| *RI* | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 |

## Appendix C

**Table A6.** Weight of indicators for urban development.

| Indicator | GDP per Capita | Share of GDP in Secondary and Tertiary Sectors | Urbanization Rate of Permanent Population | Carbon Emission Intensity (Negative Indicator) | Industrial Waste Gas Emission Intensity (Negative Indicator) |
|---|---|---|---|---|---|
| Weight | 0.342 | 0.259 | 0.205 | 0.131 | 0.063 |

Note: When evaluating the level of urban development, the per capita GDP (economic level), the proportion of GDP in the secondary and tertiary industries (industrial structure) and the urbanization rate of the permanent population (urbanization level) are considered to have a large impact, while the carbon emission intensity and industrial exhaust emission intensity used to describe the impact of climate and environment are considered to have a small impact. The possible reason is that these two indicators mainly describe the level of urban industry and are not comprehensive.

**Table A7.** Weight of indicators for energy system integration.

| Indicator | Energy Intensity (Negative Indicator) | Share of Renewable Electricity (Including Hydropower) | Urban Gas Penetration Rate | Per Capita Residential Electricity Consumption | Ratio of Urban Energy Industry Investment to GDP | Number of Smart Energy System Projects |
|---|---|---|---|---|---|---|
| Weight | 0.222 | 0.168 | 0.132 | 0.169 | 0.087 | 0.222 |

Note: When evaluating the development level of the energy system, the energy intensity and the number of smart energy system projects have the greatest weight. Energy intensity can evaluate energy utilization efficiency [64]. The reduction in energy intensity generally benefits from the progress of energy-related technology and the adjustment of industrial structure [65]. Therefore, this indicator can reflect the technical level and management level of the energy system. The number of smart energy system projects can reflect the enthusiasm of the region to build smart energy systems and the degree of transformation to smart energy systems.

**Table A8.** Weight of indicators for urban development and energy system integration.

| Indicator | GDP per Capita | Share of GDP in Secondary and Tertiary Sectors | Urbanization Rate of Permanent Population | Power Consumption Intensity | Per Capita Domestic Electricity Consumption of Urban Residents | Per Capita Gas Consumption of Urban Residents |
|---|---|---|---|---|---|---|
| Weight | 0.424 | 0.321 | 0.254 | 0.424 | 0.323 | 0.252 |

**Table A9.** Normalized results of indicator evaluation for the development of the four SEUAs.

| Axis | Indicator Name | Beijing-Tianjin-Hebei | Yangtze River Delta | Pearl River Delta | Chengdu-Chongqing |
|---|---|---|---|---|---|
| Indicators for development of urban agglomerations | GDP per capita | 0.4395 | 0.6137 | 0.5491 | 0.3588 |
| | Share of GDP in secondary and tertiary sectors | 0.5045 | 0.5074 | 0.5070 | 0.4805 |
| | Urbanization rate of permanent population | 0.5045 | 0.5157 | 0.5400 | 0.4335 |
| | Carbon emission intensity (negative indicator) | 0.3383 | 0.4647 | 0.6608 | 0.4826 |
| | Industrial waste gas emission intensity (negative indicator) | 0.2328 | 0.3794 | 0.7248 | 0.5259 |

**Table A9.** *Cont.*

| Axis | Indicator Name | Beijing-Tianjin-Hebei | Yangtze River Delta | Pearl River Delta | Chengdu-Chongqing |
|---|---|---|---|---|---|
| Indicators for development of energy system integration | Energy intensity (negative indicator) | 0.3335 | 0.5677 | 0.6006 | 0.4537 |
| | Share of renewable electricity (including hydropower) | 0.1641 | 0.2305 | 0.4223 | 0.8612 |
| | Urban gas penetration rate | 0.5073 | 0.5069 | 0.4984 | 0.4871 |
| | Per capita residential electricity consumption | 0.4874 | 0.5573 | 0.5586 | 0.3739 |
| | Ratio of urban energy industry investment to GDP | 0.6610 | 0.3398 | 0.2969 | 0.5996 |
| | Number of smart energy system projects | 0.3830 | 0.8755 | 0.2736 | 0.1094 |

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