Article

Nationwide Evaluation of Urban Energy System Resilience in China Using a Comprehensive Index Method

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Abstract: The carbon peak and carbon neutrality goals for China signify a critical time of energy transition in which energy resilience is a vital issue. Therefore, a comprehensive evaluation of urban energy system resilience (UESR) is important for establishing a theoretical foundation. To this end, in this paper, 309 Chinese cities were evaluated using a comprehensive UESR assessment framework composed of 113 indices that measured vulnerability and capabilities of resistance and restoration. The results showed that China’s UESR is distributed unevenly and that cities in the eastern region generally have higher resilience than those in other regions. The minimum and maximum UESR results corresponded to Tibet and Shandong, respectively, at the provincial level and Rikaze and Weifang, respectively, at the city level. Regression analysis showed a positive correlation among UESR, carbon dioxide emissions, and GDP.

Keywords: urban energy system resilience; comprehensive index method; resilience evaluation

1. Introduction

On 22 September 2020, President Xi Jinping announced that China would adopt more forceful policies and measures to reach the peak of carbon dioxide emissions by 2030 and to achieve carbon neutrality by 2060; these goals are referred to as the 3060 targets [1]. Energy structure transformation is key to achieving the 3060 targets. The main approaches include reducing the proportion and total amount of fossil fuel consumption, developing renewable energy, reforming the power system, and developing clean and green industries. These approaches assist in building resilient energy systems, as energy system resilience refers to the ability to maintain the essential functions and services of the energy system, ensure stable energy supply and demand with controllable fluctuations, and quickly adapt to new conditions when disruption occurs. Therefore, the 3060 targets, which involve all aspects of energy production, transmission, distribution, consumption, and storage, provide an important opportunity to enhance energy system resilience.

Cities are the macroscopic consumption unit of national energy systems and are responsible for 70% of global greenhouse gas emissions; thus, they should play an important role in this energy transition [2]. When cities meet various urban energy demands related to citizens’ daily lives and provide other infrastructures with enabling functions, a plethora of threats with natural, technical, or human causes might jeopardize the security of their energy systems, leading people to realize that urban energy system resilience (UESR) is becoming increasingly important in the process of urban development [3–5].

Billions of dollars in resilience investment are being mobilized globally, creating demand for a rigorous and decision-oriented resilience measurement [6]. However, the evaluation of UESR has not received much attention or research despite its importance. On the one hand, current research on the evaluation of urban resilience has mainly addressed disturbances due to climate change and natural disasters on cities [7,8], while...
UESR has been rarely studied. As a means of evaluation, the comprehensive index method has been applied to evaluate resilience at the community [6–9], region [10], city [11–13], and country [14,15] levels. For example, resilient city research for China has proposed a set of indicators such as networks and transportation [9,10]. However, the energy sector is usually not considered the major focus of urban resilience [9–13]. On the other hand, though energy system resilience has been defined by many researchers [14–20], and the quantification thereof is an important branch of energy system resilience research, there is still no consensus on a suitable and comparable evaluation methodology, and the mainstream quantitative methods have limitations of broad applicability and comparability for various cities. Apart from comprehensive index methods, [21] divided the evaluation methods into two categories: quantitative and qualitative. The quantitative methods are mainly time-dependent metric methods and consider resilience to be capacities of resistance, absorption, and restoration [22–24]. The metrics assess the system performance, which is ad hoc, i.e., system- or event-specific and backed by historical data [25–28]. The complexity and computability of the models and the requirement for historical data limit the broad applicability and comparability of these methods, especially across hundreds of cities. Besides, very few such qualitative methods have been applied to study at the city level. Though a dynamic energy balance-based model has been proposed to measure UESR, this methodology also requires input data and cannot sufficiently providing resilience enhancement strategies at the regional and national levels [29]. Qualitative methods have been less studied; these mainly include checklists and questionnaires [30], the matrix scoring system [31], and the analytic hierarchy process [32]. Case studies to verify feasibility are few as well. In summary, a broadly applicable and comparable quantitative method for evaluating energy system resilience of various cities has not hitherto existed.

To fill this knowledge gap, in this paper, a comprehensive index method is proposed to semi-quantitatively evaluate baseline UESR, which involves the capacities of resistance and restoration combined with vulnerability assessment. To do so, the system boundary of the urban energy system was clarified and UESR was defined; based on the definition, the capacities of resistance and restoration were qualitatively evaluated by three dimensions, namely the multifarious capabilities of the energy system within a city (CE), the interdependencies between other basic city subsystems and the energy system (CI), and the comprehensive vulnerabilities of cities and energy (CV); and these three dimensions were quantitatively evaluated by 113 indices, which were selected through a relatively thorough literature review under a set of selection principles. The applicability and comparability of the comprehensive index method are demonstrated through case studies of 309 cities in China.

2. Materials and Methods

The resilience discussion herein is proposed to be constrained to high-impact rare events (HR events), also called black swan events [4,33]. The system boundary is constrained on the city level, which represents an adequate unit for policy implementation and is convenient for the overall management of practical events in terms of China’s existing realities.

2.1. Characterization of Urban Energy System (UES)

The system boundary for an UES can be clarified, as in the working paper of the cross-center UKERC Energy 2050 project [17]. The energy resources, energy carriers, energy technologies, energy infrastructures (physical and virtual), and surrounding supporting facilities in a city are collectively referred to as the UES. Energy resources include fuels, such as coal, charcoal, gasoline, diesel, natural gas, biogas, uranium, and hydrogen, and natural energy sources, such as hydropower, geothermal power, solar power, and wind power. Energy carriers work in terms of electricity, heat, and cold in addition to fuels. Energy technologies are related to centralized power plants, distributed energy systems, and (micro)grids. Supporting facilities incorporate monitoring and protection devices, electric
energy storage supporting equipment, etc. Generally, the UES can also be traced through the energy flow through production, transmission, distribution, conversion, consumption, and storage within a city’s physical boundaries, while part of production, i.e., exploration, exploitation, transportation, and processing, usually occurs outside the UES.

2.2. Definition of UESR

In accordance with the essence of the definitions, UESR can be defined as the ability of a UES to resist HR events’ impacts, so as to maintain essential functions and services and ensure energy supply and demand within controllable fluctuations, and to quickly restore full energy production. With higher UESR, a UES has a greater capacity to handle foreseeable and/or unforeseeable impacts. From the time dimension, UESR requires the UES to reduce the probability of risk occurrence through measures of risk mitigation in the pre-event stage; diminish the direct and indirect impacts and shorten the duration when an HR event occurs; and withstand various sequential impacts, accommodate and recover from degradation, adapt to new conditions, and learn lessons for future mitigation strategies in the post event stage. In short, for UESs, resilience signifies the capacities of resistance and restoration.

When an HR event occurs, higher resistance helps the UES suffer less performance decline, and higher restoration helps the UES undergo quicker adaptation to new conditions, as shown in Figure 1. The height of the blue-shaded triangle is negatively related to resistance capacity, representing the decrease in system performance. The base of the blue-shaded triangle is negatively related to restoration capacity, representing the restoration of the system performance. As the reverse of the blue-shaded area depicts the simplified resilience level, resilience can be determined as follows:

\[
\text{Resilience} = \text{Resistance} \times \text{Restoration}
\]  

Figure 1. Time-based system performance in an HR event.

To evaluate the capacities of resistance and restoration, three dimensions are proposed: CE, CI, and CV. CE refers to the comprehensive quality of UESs, including robustness, diversity, flexibility, and availability: (1) robustness refers to the condition of hardware and its ability to resist external impacts to reduce the physical influence of disasters and prevent widespread grid outages and energy supply failures. Hardware refers to grid lines, transformers, energy practitioners, and power generation capacity in this framework. Energy reserves of various fuels play an important role in energy feedstock cutoff. Technological and financial feasibilities should also be considered, e.g., improving energy supply stability and enriching the fuel stock. (2) Diversity consists of energy generation and consumption as well as enterprise productive capacity. To evaluate energy diversity, the Shannon–Weaver index is applied, since it is widely preferred for variety and balance [34]. The Shannon–Weaver index is defined as [35,36]:

\[
D = - \sum p_i \ln(p_i)
\]
where $p_i$ represents the share of energy source $i$ in the mix of energy generation/consumption for an energy system. The higher the value of $D$ is, the more diverse a system is evaluated to be. (3) Flexibility is based primarily on the view of the UES as a complex and flexible integrated system that includes organizational, technical, and administrative factors. The system should have the ability to take precautions, study disaster prediction, and obtain the latest information before an event so that rational planning and allocation can be performed in advance in terms of equipment, technology, organization, personnel, resources, and capital. This quality enables the system to flexibly adapt to new internal and external conditions and find a new stable state when an HR event is about to end or after a long period of time following the event. Thus, many aspects at the system-management level are inspected. Evaluation of practice includes demonstration projects, energy savings, and equipment decommission. (4) Availability refers to the ability to adjust the system based on resource availability and financial feasibility. Resource exploitation and processing are considered for coal, petroleum, and other fuels. Financial feasibility is evaluated in terms of the fixed and current assets of energy industries.

CI involves basic city subsystems that closely interact with the energy system. The interdependencies between critical infrastructures should be taken into consideration since a powerful countermeasure of energy sector that does not explore potential synergies between other pertinent sectors may exacerbate the vulnerability or reduce the overall UESR [37–39]. Thus, CI refers to the capability of a city to cope with hazardous events, including interdependencies between UESs and other societal sectors, such as water, transportation, ecology, emergency services, medical services, and information and telecommunications [40,41]. Water systems are critical in an emergency, and they interact with energy systems via water flow, sewage discharge, cooling water, and circulating water. The transportation system is powered mainly by gasoline, diesel, natural gas and electricity; moreover, the accessibility of the transportation system plays a key role in emergency situations. Ecological systems can provide effective buffering, such as vegetation management and green open space [42]. Emergency services, medical services, and information and telecommunications are high priorities for energy supply and are essential for urban system restoration [43,44].

CV refers to the number of objects with regard to the basic urban conditions in the city and the energy infrastructures in the energy system, that could possibly be affected by hazard [45–47]. City vulnerability takes demographic, economic, and architectural factors into consideration. Energy vulnerability is associated mainly with pipeline and gas stations of various fuels. District heat and electricity consumption have direct impacts on urban residents’ daily lives when HR events occur.

According to the above, the greater the CE or CI, the faster the system performance is restored; the greater the CE or the smaller the CV, the less the system performance decreases. The evaluation of resilience, i.e., the UES’s capacities of resistance and restoration, is converted into the evaluation of CE, CI, and CV as shown in Figure 1 [48].

2.3. Index Selection

Comprehensive index methods have become a standard approach to simplifying governmental and organizational policy making, decision making, performance appraisal, and progress tracking at all levels [48]. This study proposes a comprehensive index method, providing each dimension with a series of indices for evaluation. In the early stage of developing the comprehensive index framework, a large number of proposed indices by other researchers and database were collected based on a literature review and data research. The index selection procedure is depicted in Figure 2. To organize a consistent UESR framework, indices must first suit the scope of UES. To this end, hundreds of primary indices were obtained. These primary indices were then classified according to the meaning and category into three dimensions: CE, CI, and CV. Each index was described in accordance with the referred literature as closely as possible. Following that, a set of selection principles was examined to evaluate the index’s systematism, unicity, feasibility, objectivity, and representation. To describe the overall dimension, the index set should
systematically reflect every subsystem and be neither too detailed nor too general [49].

Unicity means that repeated indices should be removed. Feasibility refers to the availability of data from reliable sources with no obvious errors and the operability of quantitative methods and statistical approaches. To be objective, indices should conform to objective facts and not be interfered with subjective values. Representation means that limited indices should describe a dimension as comprehensively as possible. Indices that met the five selection principles were retained, and those that did not meet any principle were deleted. Detailed primary index selection records are shown in Tables A1–A3 (Appendix A).

The deletion of each index was related to its original meaning as it underwent the index selection process. There were two main reasons for deleting indices. Unicity is part of the reason, as most scholars generally attach great importance to output of renewable energy, application of distributed energy system, energy sources, energy diversity, etc. Feasibility was the main reason, because some indices were difficult to quantify, some were not suitable for too many measurement objects because the quantization process was too tedious or the quantization workload was large, and some did not apply to China’s actual situation. Therefore, 113 indices were finally retained for the UESR assessment index framework, as shown in Figure 3.

![Figure 2. Index selection procedure for UESR evaluation.](image)

The selected 113 indices are quantitatively measured and equally weighted, and they can be assigned differently to satisfy various assessment purposes through a dialogue process between decision makers and stakeholders.

2.4. Normalization of the Indices and Calculation of UESR

Indicators were divided into positive and negative indicators according to their supporting or inhibiting effects on resilience [50]. The higher the negative indicators, the lower the corresponding criteria and resilience, such as the share of imported electricity, daily water consumption per capita, and railway access index. All other indicators are positive. Min–max normalization is used to process the original data as follows.
Figure 3. Assessment index for resilience of urban energy systems.

For positive indicators:

\[ y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \]  \hspace{1cm} (3)

For negative indicators:

\[ y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \]  \hspace{1cm} (4)

where \(x_{ij}\), \(y_{ij}\) represent the original and normalized data, respectively; \(\max(x_{ij})\) is the maximum value of this indicator; and \(\min(x_{ij})\) is the minimum value of this indicator;

\[ CI = \sum_{i=1}^{n} I_i \times \omega_i \]  \hspace{1cm} (5)

\[ CE = \sum_{i=1}^{n} E_i \times \omega_i \]  \hspace{1cm} (6)

where \(I_i\) and \(E_i\) represent the normalized value of index \(i\) for CI and CE, respectively, and \(\omega_i\) represents the weight of index \(i\). According to the universal risk evaluation model, CV is determined as follows [47]:

\[ V^2 = \sum_{i=1}^{n} V_i \times \omega_i \]  \hspace{1cm} (7)
where $V_i$ represents the normalized value of index $i$ for city vulnerability or energy vulnerability. Then, resilience is determined as:

$$\text{Resilience} = \frac{(\sum_{i=1}^{n} E_i \times \omega_i) \times (\sum_{i=1}^{n} I_i \times \omega_i + \sum_{i=1}^{n} E_i \times \omega_i)}{(\sum_{i=1}^{n} V_i \times \omega_i)}$$

Based on data survey, statistics, and analysis, the UESR of a city can be obtained by substituting these 113 parameters into Equation (8).

3. Results

The energy resilience of 309 Chinese cities is shown in Figure 4. The entire country was divided into four regions according to the National Bureau of Statistics of China [51], namely, the western region (107 cities), the central region (81 cities), the eastern region (87 cities), and the northeastern region (34 cities). Several cities were more resilient than the surrounding areas. There were four types for different reasons. First, provincial capital cities generally had better political resources, management levels, and economic development advantages compared with their surrounding cities and thus had stronger comprehensive city strength and better performance in CI and CE. This applied to Changchun of Jilin, Harbin of Heilongjiang, Taiyuan of Shanxi, Kunming of Yunnan, and Fuzhou of Fujian. Second, Zhangjiakou of Hebei is close to the capital, Beijing, and serves as an important satellite city. It is located in the coal transport corridor, has abundant wind energy resources, has developed a number of microgrid projects, and has few energy-consuming industries, all of which made it a relatively energy-resilient city. Third, Zhuhai of Guangdong has relatively small population density, industrial density, and economic size in Guangdong province, resulting in low CV. As CE and CI were not significantly different, Zhuhai’s resilience value was higher. Fourth, Shenzhen of Guangdong was more resilient within the province because of its better performance in energy diversity, microgrid projects, and development of nuclear power.

![Figure 4. Resilience of urban energy systems for 309 Chinese cities. (Note: The gray areas were not included in the assessment because of lack of data.).](image-url)
3.1. Regional Level

In general, a majority of the 309 cities, especially those in the northeastern and western regions, had relatively low energy resilience. In contrast, UESR in the eastern region was generally higher. The average resilience (R) result of the eastern region was more than twice that of the northeastern and western regions. The resilience variance ($S^2$) of the eastern region was nearly an order of magnitude higher than that of the other three regions. The most evenly distributed cities were located in the central region. The differences in CV among the four regions were not significant in terms of average, maximum, minimum, or variance, with the eastern region only slightly higher than the other three regions. From the perspective of CE, there were no obvious distribution characteristics. The eastern region had the highest average. The central region had the lowest variance. The situations of the western and northeastern regions were similar. The highest CI average occurred in the eastern region as well. The statistics of the evaluation results are shown in Table 1. The detailed data and evaluation results can be seen in Tables S1–S4 of the Supplementary Materials.

Table 1. Statistics of the evaluation results.

<table>
<thead>
<tr>
<th>Region</th>
<th>Resilience</th>
<th>$S^2$</th>
<th>CV</th>
<th>CE</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nationwide</td>
<td>0.32</td>
<td>0.022</td>
<td>0.36</td>
<td>0.20</td>
<td>0.36</td>
</tr>
<tr>
<td>Western</td>
<td>0.24</td>
<td>0.0053</td>
<td>0.35</td>
<td>0.16</td>
<td>0.34</td>
</tr>
<tr>
<td>Central</td>
<td>0.28</td>
<td>0.0028</td>
<td>0.35</td>
<td>0.18</td>
<td>0.36</td>
</tr>
<tr>
<td>Eastern</td>
<td>0.50</td>
<td>0.022</td>
<td>0.38</td>
<td>0.28</td>
<td>0.40</td>
</tr>
<tr>
<td>Northeastern</td>
<td>0.22</td>
<td>0.0035</td>
<td>0.37</td>
<td>0.16</td>
<td>0.33</td>
</tr>
</tbody>
</table>

3.2. Provincial Level

Among the evaluated 27 provinces/autonomous regions:

- The highest average resilience occurred in Shandong (0.69), and the lowest, in Tibet (0.039). The distribution of resilience development was most balanced in Qinghai, with the lowest variance (0.000050) and the smallest range (0.020), and least balanced in Yunnan, with the second-highest variance (0.0046) and the largest range (0.26).
- The highest average CV occurred in Shandong (0.40), and the lowest, in Guizhou (0.32). The distribution of CV was most balanced in Tibet, with the lowest variance (0.000098) and the smallest range (0.028), and least balanced in Guangdong, with the highest variance (0.0046) and the largest range (0.24).
- The highest average CE occurred in Shandong (0.36), and the lowest, in Tibet (0.049). The distribution of CE was most balanced in Qinghai, with the lowest variance (0.000057) and the smallest range (0.018), and least balanced in Ningxia, with the highest variance (0.0019) and the second-largest range (0.12).
- The highest average CI occurred in Jiangsu (0.41), and the lowest, in Tibet (0.26). The distribution of CI was most balanced in Hainan, with the lowest variance (0.000045) and the smallest range (0.016), and least balanced in Guangdong, with the highest variance (0.0038) and the largest range (0.25).

3.3. City Level

- Among the 309 cities, 107 (35%) had higher energy resilience than the national average, while 202 (65%) had lower energy resilience than the national average.
- The four municipalities, Tianjin, Shanghai, Chongqing, and Beijing, ranked 88th, 84th, 71st, and 48th in resilience, respectively. All municipalities were above the average level, not only for resilience but for CV, CE and CI. Beijing ranked first in CI and CV.
- The minimum, median, and maximum resilience results corresponded to Rikaze, Yingkou, and Weifang, respectively. Detailed comparisons of these three cities are shown in Figures 5 and 6. The numbered acronyms on the left in Figure 6 correspond to the indices in Figure 3. The levels of the three cities’ CV varied little. Rikaze had an obvious advantage in energy vulnerability, but its city vulnerability was due mainly to a large number of civil protection units in the city, such as historic sites,
temples, and repositories of ancient books, pictographs, and other cultural relics. Its city competitiveness (index Fl 13-20), including the city’s external connectivity, software and hardware environment, knowledge and information development level, and infrastructure construction, was in a disadvantageous position as well. These data were obtained from the Yearbook of China’s Cities sponsored by the Sustainable City Committee of the China Research Society of Urban Development. According to the editor, the evaluation indices mainly reflected the competitiveness of cities in transforming from quantitative growth to qualitative sustainable development. To improve the resilience of Rikaze, this sustainable competitiveness should be comprehensively considered. Additionally, the reliability of the power supply can be improved, and the line loss rate of power enterprises can be reduced. Electricity conservation could be further advocated and executed, and new energy vehicles and enhanced transportation accessibility could be promoted. In terms of energy diversity, the use of natural gas and heat supply also lagged. However, this is related to the local climate and residents’ habits and customs, which are difficult to change in the short term and require long-term adjustment and planning.

![Figure 5. Comparison of the three cities’ R/CV/CE/CI results.](image)

- For Yingkou, the main means of improving resilience would include promoting and practicing electricity conservation; improving the management of State Grid Liaoning Power Co., Ltd., among the major power grid companies in the country; and improving the diversity of power generation. With the current Huaneng Yingkou Thermal Power plant as the dominant plant, the city could develop microgrid projects, distributed energy systems, etc., to develop capacity other than thermal power generation.
- As the comparison of financial feasibility was based on provincial data, Weifang’s advantages in both the fixed assets and current assets of the energy industry benefit from Shandong’s advantages among provinces, as do the decommissioning of thermal power units and the achievement of energy savings. In addition, according to the China Electric Power Industry Annual Development Report, State Grid Shandong Power Co., Ltd., has relatively better comprehensive management on the supply side in its industry, so cities in Shandong also scored high on this series of indices. This implies that financial and managerial resilience can be improved at the provincial level.

### 3.4. Regression Analysis

Since the resilience of UESs is a critical issue in the current energy transition toward the 3060 targets, it is interesting to understand the relation among a city’s energy system resilience, carbon dioxide emissions (megaton) and GDP ($10^{10}$ RMB).

By the weighted least squares method ($weight = 1/resid^2$), the following binary nonlinear regression equation is obtained, and the model fits the evaluation results well.
Figure 6. Comparison of cities with minimum/median/maximum resilience results.

$$\text{RESILIENCE}_i = -0.049111 + 0.177735 \text{CO}_2 E_i^{0.204} + 0.045861 \ln \text{GDP}_i + e_i$$  \hspace{1cm} (9)

$$t = (705.8698 ***) (749.1603 ***) (484.5519 ***)$$

R squared = 0.9999, n = 309

where *** means at 1% significant level. The empirical results showed a positive correlation between resilience and carbon dioxide emissions, suggesting that there should be a balance among loss of resilience, reduction in carbon dioxide emissions, and increase in GDP. For an example, in Yingkou, a reduction in carbon dioxide emissions of one million tons would sacrifice resilience by 0.0073 and drop the city 12 places in the ranking, and an increase in GDP of 22,949.87 million RMB would enhance resilience to maintain the original position. Therefore, in the process of achieving the 3060 targets, to ensure the safety and sustainability of a city and allow its resilience to fluctuate within reasonable limits, how to appropriately...
allocate the carbon dioxide emission reduction quota to each city is critical. Based on the evaluation framework of this study, the options for both reducing emissions and enhancing resilience vary from city to city. Generally, feasible alternatives include advancing the financial feasibility of the energy sector, promoting, and practicing energy conservation, and improving the management of power enterprises.

4. Conclusions

With the ambitious 3060 targets, China is looking forward to an unprecedented energy transition. As a core part of energy transition and sustainability, resilience must be given serious attention, especially when extreme events have occurred more frequently in recent years.

To this end, this paper implemented a nationwide comprehensive assessment of the resilience of UESs in China. The results showed that the current capabilities of Chinese UESs to handle exogenous extreme events are very uneven, and that cities in the eastern region generally have higher resilience than those in other regions. The minimum, median, and maximum UESR results corresponded to Rikaze, Yingkou, and Weifang, respectively. Regression analysis of 309 cities’ resilience evaluation results showed a positive correlation among UESR, carbon dioxide emissions, and GDP. When the details of this evaluation are combined and the differences lucubrated at the urban/provincial levels, each city should develop a tailored plan to reduce carbon emissions, ensure reasonable changes in UESR, and flexibly utilize economic instruments.

The aim of this study was to establish a benchmark to understand the complicated correlations and challenges of energy transition. The findings of this study may assist municipal and provincial decision makers with unique insights for enhancing overall UESR. Moreover, continual assessments of the UESR of these cities in future years could offer policy makers much more valuable information on energy transition and urban development.

The proposed indicators mainly suit China’s current reality, and different, specific indices should be adopted when the assessments are applied to cities in other countries. The results do not contain value or other judgments.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14042077/s1, Table S1: Resilience evaluation results of 309 Chinese cities, Table S2: CI data and results of 309 Chinese cities, Table S3: CE data and results of 309 Chinese cities, Table S4: CV data and results of 309 Chinese cities.

Author Contributions: Conceptualization, Z.W. and R.W.; methodology, Z.W. and Q.S.; software, Z.W.; validation, Z.W., C.M. and Q.S.; investigation, Z.W. and Z.C.; resources, Q.S.; data curation, Z.W. and Z.C.; writing—original draft preparation, Z.W.; writing—review and editing, Z.W.; supervision, R.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data sources included scholarly publications, trade organization publications, research reports produced by governmental departments and educational organizations, and, when possible, direct contact with experts in related fields. In detail, the CI data sources included governmental yearbooks and bulletins at the city/provincial/country levels, the academic research results of transportation accessibility in [40], and the China Urban Construction Statistical Yearbook. The CE data sources included governmental yearbooks and bulletins at the city/provincial/country levels; the business inquiry platform www.tianyancha.com (accessed on 22 May 2021); the official website of the Ministry of Industry and Information Technology of the People’s Republic of China, https://www.miit.gov.cn/ (accessed on 1 February 2022); the official website of the National Development and Reform Commission of the People’s Republic of China, https://www.ndrc.gov.cn/ (accessed on 1 February 2022); and the China Urban Construction Statistical Yearbook, China Electric Power Yearbook, China Electric Power Statistical Yearbook, State Grid Yearbook, China Electric...

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

**Appendix A**

Table A1. Aggregated index selection for CE (note: ✓ indicates compliance with the selection principle and X indicates noncompliance; selection principles: systematism (S), unity (U), feasibility (F), objectivity (O), and representation (R)).

<table>
<thead>
<tr>
<th>No.</th>
<th>Primary Index</th>
<th>Ref.</th>
<th>S</th>
<th>U</th>
<th>F</th>
<th>O</th>
<th>R</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Energy feedstock</td>
<td>[52]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Deleted</td>
</tr>
<tr>
<td>2</td>
<td>Energy not supplied</td>
<td>[53]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Deleted</td>
</tr>
<tr>
<td>3</td>
<td>Energy storage</td>
<td>[54]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Retained</td>
</tr>
<tr>
<td>4</td>
<td>Hydrophobic coating on equipment</td>
<td>[55]</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Deleted</td>
</tr>
<tr>
<td>5</td>
<td>Key replacement equipment stockpile</td>
<td>[55]</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Deleted</td>
</tr>
<tr>
<td>6</td>
<td>Redundant power lines</td>
<td>[55]</td>
<td>✓</td>
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<td>Fuel nodes with the most links are the most interconnected and serve as hubs</td>
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<td>Response to equipment outages—degree to which the system is able to continue to reliably operate in the event of equipment downtime</td>
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<td>Adaptive capacity—degree to which the system is capable of self-organization for recovery of system performance levels</td>
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<td>Absorptive capacity—degree to which a system can automatically absorb the impacts of perturbations and minimize consequences with little effort</td>
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<td>Community response to mitigate impact, e.g., demand curtailment</td>
<td>[124, 126, 128]</td>
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<td>Recovery crew managing incremental recovery with available equipment</td>
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This work was supported by the Shandong University Seed Fund Program for a Ph.D. dissertation. The authors declare no conflict of interest.
Table A1. Cont.

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<td>Smart microgrids fed by microturbines and solar panels (photovoltaics, building integrated photovoltaics) and storage facilities Building-integrated photovoltaic/thermal for recovery of heat loss form photovoltaics and building integrated photovoltaics</td>
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Conflicts of Interest: The authors declare no conflict of interest.
Table A2. Aggregated index selection for CI.

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References


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