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Assessing Risks on China's Natural Gas Supply under Carbon Peaking Policies from Foreign–Domestic Perspectives

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Abstract: China's natural gas supply has been challenged in the past few years by non-traditional risks such as trading conflicts, the COVID-19 pandemic, and the country's own emission policy. To ensure energy security and supply, conducting an up-to-date risk analysis of China's natural gas supply status is crucial. This research utilized the Fuzzy-AHP method to compose a risk index and assessed the key links within China's natural gas supply chain from the import side to the domestic side. The results indicate that (a) for China's gas import, the most influential risks are the correlated dependence risk, international relation risk, and supplier internal stability risk. (b) While the dependence risk and transport risk have decreased sharply in the past decade, the import risk is still China's major concern on natural gas supply. (c) Emissions-peaking and carbon neutrality targets are potential challenges, which the country would possibly face in the near future.

Keywords: natural gas risk; Fuzzy-AHP; natural gas supply of China

Citation: Chen, M.; Li, N.; Mu, H. Assessing Risks on China's Natural Gas Supply under Carbon Peaking Policies from Foreign–Domestic Perspectives. *Energies* **2024**, *17*, 845. https://doi.org/10.3390/en17040845

Academic Editors: Antonio Sánchez-Bayón and Mohamed Elheddad

Received: 4 January 2024
Revised: 6 February 2024
Accepted: 7 February 2024
Published: 10 February 2024

1. Introduction

Natural gas (NG) supply has posed a formidable challenge for China, given the incongruity between the nation's burgeoning demand for NG and its production capabilities in recent years. As China endeavors to improve its energy structure, where coal has been playing a dominant role with more than 50% of the annual total energy consumption [1], NG has been promoted and advocated. From 2000 to 2017, its NG consumption nearly increased tenfold, from 24.7 bcm to 241.3 bcm [2]. It was in the same year when China implemented progressive air quality and coal substitution policies [3,4], and the country needed to supply more NG than ever to meet the aim of these policies. The rocketing NG demand has brought considerable risk to the country's NG supply. Although China was able to expand domestic production from 27.2 bcm to 161.5 bcm by the end of 2018, the country inevitably became one of the largest gas importers [2] and faced similar import problems as many other NG-importing countries. Novel challenges concerning the evolving global geopolitical challenges struck the country in 2020, including the outbreak of the SARS-CoV-2 pandemic and the Russian invasion of Ukraine, when foreign trading relations of the country saw upheavals. Moreover, as China has set carbon-peaking and neutrality targets in 2030 and 2060, respectively [5], the country requires even more NG in substitution for the colossal coal consumption [6], which presents a dilemma with the current unbalanced state of its NG supply.

The supply chain of NG is vulnerable to external factors such as natural calamities, weather conditions, maritime security, and pipeline/container leaks. It is also affected by international markets, as the NG price is connected with crude oil [7]. Moreover, NG trade is subject to the influence of geopolitical dynamics and diplomatic relations, like other energy trades. Given these attributes, various segments of the NG supply chain, including production, liquefaction, regasification, and transportation entail varying degrees of risk [8]. All of these uncertainties surrounding China's NG supply require further and detailed examinations of the NG risks. Through a risk assessment of China's current NG supply chain, we aim to identify vulnerabilities in today's NG supply chain. This will provide policy recommendations not only for China, but also for other NG-importing nations as well.

2. Literature Review

Risk analysis has been a critical topic for energy-importing countries and regions, especially Europe and East Asia. Grais and Zheng [9] used the hierarchical Stackelberg gaming model to analyze the gas transit system after Eastern Europe saw major geopolitical changes, proving that the availability of alternative gas supplies improved the welfare of all stakeholders in the system. Weisser [10] argued that Europe had become dangerously reliant on too few gas sources and too little infrastructure, emphasizing the need for clear proactive policies within EU countries to establish a robust multilateral gas framework. Percebois [11] analyzed the weight of NG in the EU regarding long-term contracts and the impact of geopolitical considerations in the relationships with two major suppliers, Russia and Algeria. Abada and Massol [12] analyzed the impact of uncertain gas supply disruptions in Germany and Bulgaria upon gas retailers using a static Cournot model, suggesting that strategic withdrawal from existing NG storages, alternative short-term imports, and switching to other suppliers may compensate the gas supply disruption. Doukas et al. [13] categorized possible risks against energy security, including conflicts, political instability, terrorism, accidents, weather, and illegal extractions. By using the Fuzzy-AHP method, Pavlović [14] analyzed the supply security of Serbia's NG, suggesting that the top risks were termination of supply with Hungary, termination of Russian gas, and empty gas storage. Krikštolaitis et al. [15] measured the energy security levels of Germany, France, Italy, and Spain between 2006 and 2018 using technical, economic, and socio-political indicators to find that Germany and France have more resilient energy systems than Italy and Spain.

Compared to Europe, Asian countries, especially East Asian countries with a colossal NG demand, have similar troubles from different sources. Geng and Ji [16] used the complex network theory to analyze the international gas trade to find that the markets in North America, Europe, and Asia were not yet integrated, but the degree of integration between the European and Asian markets was relatively strong during 2000–2011. Cabalu and Manuhutu [17] and Cabalu [8] established gas supply security indicators for major Asian gas importers, suggesting that China and Japan had a more stable gas supply than South Korea, Thailand, and Singapore at the time. Manuhutu and Owen [18] analyzed the impact of imported LNG on the market concentration in Shanghai's gas market, showing that Shanghai would remain a supply-constrained gas market that relies upon gas supplies from the western provinces and imported LNG. Vivolda [19] focused on the five largest Asian LNG importers: China, India, Japan, South Korea, and Taiwan and used the HHI index to illustrate their LNG import diversifications to find that China had increased its import diversification through the decade, which brought increased supply security. Dong and Kong [20], Kong et al. [21], Zhang and Bai [22] conducted an analysis on China's NG supply security from various import perspectives, indicating that dependence, suppliers, foreign affairs, and transportation were major risks. Shaikh et al. [23] conducted an ecological network analysis to assess the stability of LNG supplies in Japan, South Korea, Mainland China, Taiwan, and India as well as the overall Asia–Pacific region, indicating that an increased number of LNG suppliers have enhanced the LNG supply stabilities, while China has the highest gas supply security status among Asia–Pacific importers. Lu et al. [24] used network information analysis to find that Chinese NG supply security increased during 2000–2011, while the gas supply source was the most influential factor of gas security. Wang and Xing [25] conducted a risk analysis on China's coupled NG and electricity market using the system dynamics model.

The above-mentioned research results are summarized in Table 1. In brief, both Europe and Asia suffered from a dependence risk and challenges concerning foreign affairs, transportation, weather, etc. More specifically for China, due to the unique geopolitical condition of the country, the NG risks of China appeared on the import side, such as import dependence, diplomatic relations, and transportation. However, as part of the supply chain, risk factors on the domestic side could also influence the country's energy security status, especially when the country is preparing to achieve its emissions-peaking target.

Table 1. Summary of previous research results on natural gas supply risks.

Authors	Risk Factors	Methods
Grais and Zheng (1994) [9]	Relationships among suppliers, transporters, and importers	Stackelberg game model
Weisser (2007) [10]	Source dependence, transit dependence, facility dependence, structural risks, natural disaster, political blackmail, terrorism, war, and civil unrest	Qualitative analysis
Percebois (2008) [11]	Long-term contract and geopolitical consideration	Qualitative analysis
Cabalu and Manuhutu (2009) [17]	Cost of gas import, gas intensity, gas consumption per capita, gas share in TPES, domestic gas production–consumption ratio, and geopolitical risk	Weighted index
Cabalu (2010) [8]	Gas intensity, net gas import dependency, domestic gas production–consumption rate, and geopolitical risk	Gas supply security index
Manuhutu and Owen (2010) [18]	Herfindahl–Hirschman Index	Qualitative analysis
Abada and Massol (2011) [12]	Natural gas supply disruption	Static Cournot game model
Doukas et al. (2011) [13]	Conflict, political instability, terrorism, export restriction, accident, weather condition, and monopolistic practice	Qualitative analysis
Vivoda (2014) [19]	Herfindahl–Hirschman Index	Qualitative analysis
Geng and Ji (2014) [16]	Natural gas market integration	Complex network theory
Dong and Kong (2016) [20]	Sea transport distance, pirate attack, political risk, and maritime transportation risks	AHP
Lu et al. (2016) [24]	Supply source, consumption sector, refining, and reserve sectors in a system	Network information analysis
Shaikh et al. (2017) [23]	Diversification, lower dependency, supplier export capacity, minimizing the import cost, transport distance, and political instability associated with each of the foreign natural gas suppliers	MOLP
Praks et al. (2017) [26]	Cost, country risk, shipping risk, and impact of extreme events	MOLP
Kong et al. (2019) [21]	Resource risk, political risk, transport risk, price volatility risk, purchasing power risk, and dependence risk	Weighted index
Zhang and Bai (2020) [22]	Dependence risk, transport risk, price risk, resource risk, financial risk, and international relationship risk	Fuzzy AHP–TOPSIS
Pavlović et al. (2021) [14]	Consumption, termination of supply, empty gas storage, and Herfindahl–Hirschman Index	Fuzzy AHP–HHI
Wang and Xing (2023) [25]	Coupled Natural Gas and Electricity Market	System dynamics

3. Challenges for China's Natural Gas Supply

China's NG consumption originates from three sources: LNG exporters, pipeline gas exporters, and domestic production. As of the year 2020, 28.08% of China's total NG consumption originated from imported LNG, 13.97% from imported pipeline gas, with the rest from domestic gas fields. This supply chain is simplified in Figure 1. As illustrated, several crucial nodes exist on the supply chain. On the import side, they would be the import source, import transportation, and receiving (as well as regasification of the LNG). And on the domestic side, they would be the domestic production, the domestic pipelines, and other auxiliary infrastructures. Based on these key nodes on the supply chain, with additional factors that might interfere the NG supply, the challenges for China's NG supply could be listed and explained as follows:

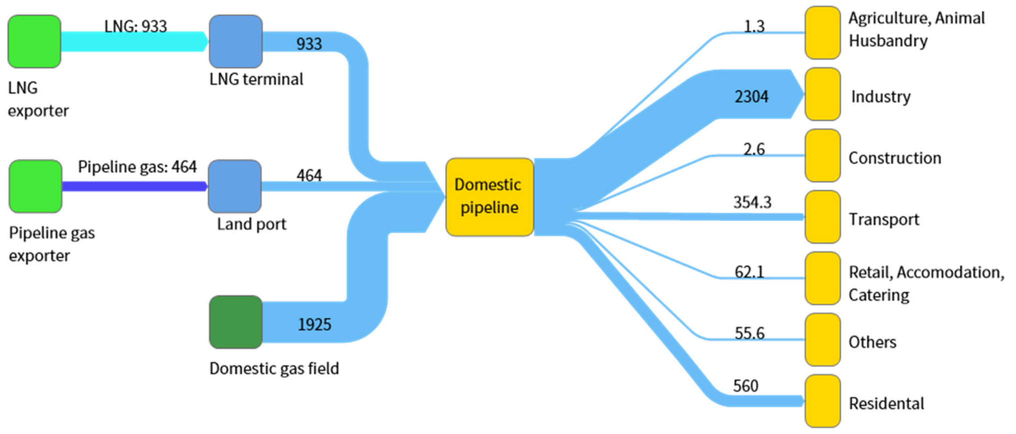

Figure 1. Simplified natural gas supply chain of China. Source: *China Energy Statistical Yearbook* 2021, National Bureau of Statistics of China, China Customs, bp. All numbers are in billion cubic meters (bcm). LNG is converted to gaseous, 1t LNG≈1380m3 NG.

3.1. Imports

Dozens of countries export NG to China, but only a few countries, including Australia, Turkmenistan, Qatar, Malaysia, and Indonesia, have more than 1 bcm of NG exported to China annually, as shown in Figure 2, and could be classified as major suppliers. Similar to petroleum, maritime transport is currently the major NG import channel for China, and the risk criteria of sea-transported oil and gas are usually interchangeable on most occasions, as they have such similar market properties [20]. Sea transportation is considered vulnerable to multiple issues, such as piracy or armed hijacks, rough sea conditions, extreme weather, and sea traffic obstructions (such as the Suez Canal blockage in March 2021) [27]. The Malacca Dilemma was used to describe China's energy imports as being at high risk, as China's unique geographical location requires gas carriers to cruise through multiple straits before unloading the gas to LNG terminals on eastern and southern shorelines [23,28].

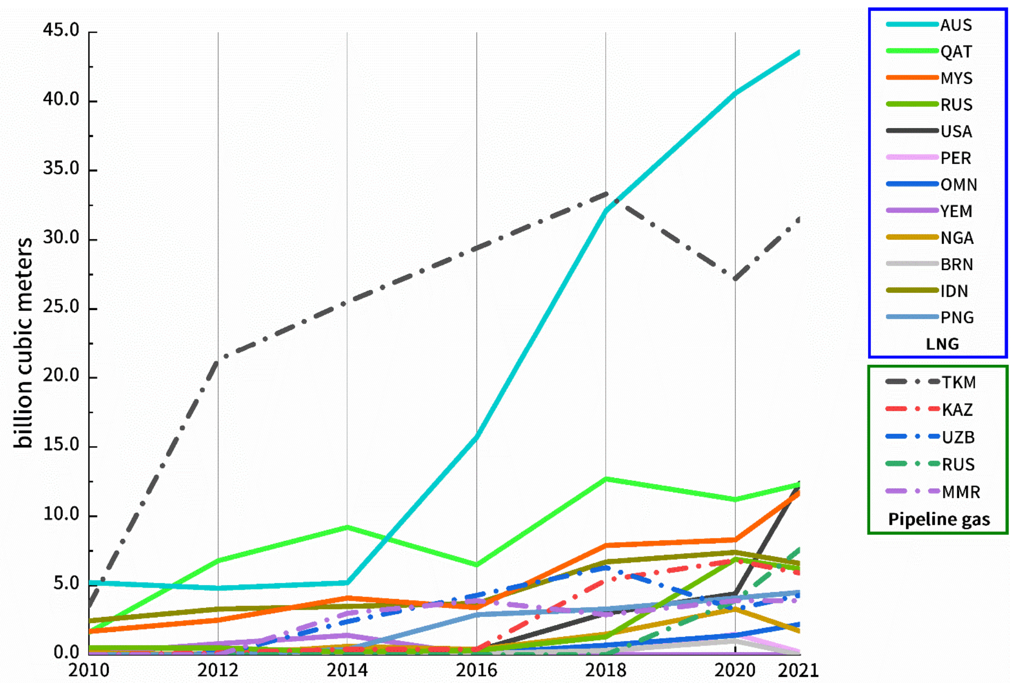

Figure 2. China's natural gas import portfolio in selected years. Source: bp Statistical Review of World Energy 2011–2022. Abbreviations follow ISO 3166-1 alpha-3. Countries with <1 bcm annual average NG export are omitted.

As Figure 2 illustrates, pipelines are used to deliver greater amounts of NG to China compared to the amounts imported via the sea. Existing import pipelines are the Central Asia–China line, Myanmar–China line, and the newly built Russia–China East line, as shown in Figure 3 [29,30]. The transportation via pipelines relieved traditional NG import risks, and in this respect, the Myanmar line relieved China's maritime LNG import pressure [31] for its geographical location ahead of the Malacca Straits, which could avoid sea transport risks from the surrounding area. However, a new problem arose as soon as the Central Asia line was built: dependence risk [22,32]. Turkmenistan, as the major supplier of the Central Asia line, remained China's top NG supplier from 2010 to 2017 [2]. If a country relies too heavily on a single source, its energy security could be easily affected by certain extreme conditions [33,34], as the European countries experienced in 2022. When the Ukrainian war erupted, the Kremlin limited the NG flow to Europe as retaliation after Russia–Europe relations deteriorated, knowing that European countries heavily relied on Russia's pipeline gas [35]. As a result, Europe suffered from frequent NG market fluctuations, energy shortages, and further inflations [36]. As for China, although Russia agreed to the Power of Siberia 2, a second NG pipeline that reaches Northeast China through Mongolia [37], and proposed a third line to Xinjiang (as shown in Figure 3), while the NG flows through Sino–Russo pipeline manifolded in 2022 [38], China needs to observe its potential dependence risk, despite its close relationship with Russia. In addition, the problems associated with the Nord Stream in September 2022 have highlighted the risks of transporting NG via long distance pipelines.

Figure 3. Import, domestic, and proposed major natural gas pipelines of China. Source: [39].

The internal stability of exporting countries and their diplomatic relationships with importers have also been identified as a major risk previously [22,32]. Over the past two decades, regime changes, terrorism, and consequential regional conflicts have caused internal instabilities and energy market fluctuations [40–42]. China had relatively peaceful trading experiences with most partners since joining the World Trade Organization [43,44]. Nevertheless, the US–China trading conflict, which began during Trump's presidency, and the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic outbreak in 2019, have emphasized the trading risks and have necessitated that these be examined from different perspectives. Frequent trading sanctions and political criticism have caused significant damage to international trading relations [45–47] and could have negative effects on energy trading.

3.2. Domestic Resources

Although China is one of the largest energy producers in the world, its energy resources are unbalanced in terms of both variety and geographical distribution. Only 3.1% of the world's NG reserves are found in China (ranking 7th in the world), and the proven NG gas reserves cover a mere 8.4 trillion m^3 [2]. China's gas resources are mainly discovered within three basins in its southwestern and northwestern regions: the Tarim Basin in Xinjiang, the Ordos Basin in Nei Mongol, and the Sichuan Basin, as well as in off-shore fields in surrounding waters [48]. The West–East pipeline was designed and constructed to transport the unevenly distributed resource to developed eastern coastal regions. On the other hand, LNG terminals are located on the eastern and western coasts, but have higher uncertainties brought by sea transports and imports. The long-distance gas transport within the country also has a considerable risk concerning the safety of the pipeline and gas facilities. Research has also focused on exploring the natural gas hydrates in Chinese waters; however, large-scale exploitation is not instantly feasible [49–51].

Following the interruption in the supply of NG in the winter of 2017, China took various measures to increase its NG production capabilities. However, the limitations of insufficient NG resources are insurmountable [52,53]. As illustrated in Figure 4, the gap between domestic production and demand has continued to grow, especially after 2015, when NG dependence rapidly grew toward 50%. China was obliged to obtain the largest amount of gas from international markets, which resulted in further import risks.

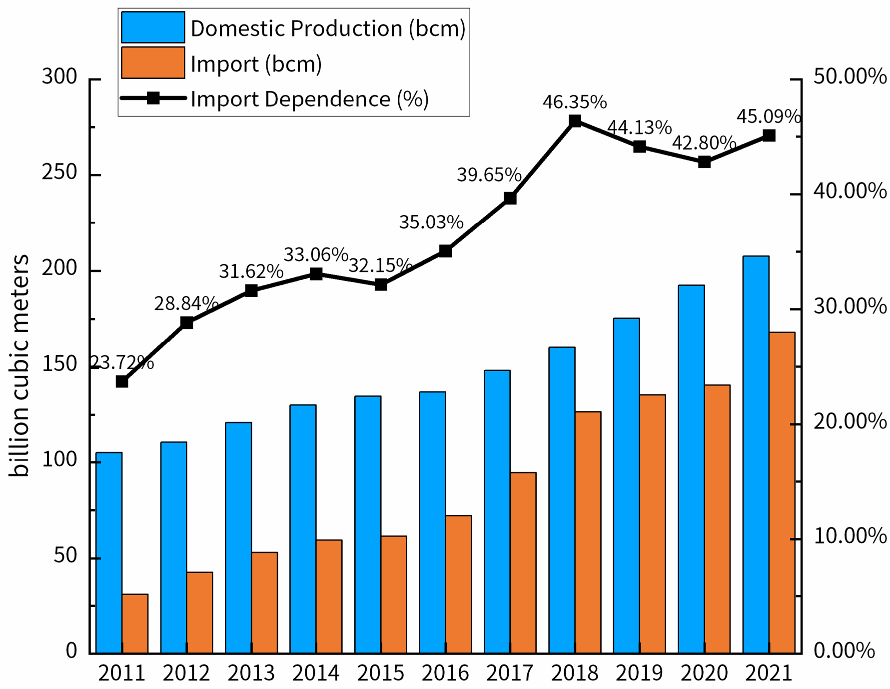

Figure 4. China's natural gas supply portfolio over the past decade. Source: China Natural Gas Development Report, 2015–2022; National Bureau of Statistics of China; CEIC.

3.3. Markets, Disruptions, Policies, and Other Uncertainties

In the past, when Japan and South Korea were the dominant players in the Asian gas market, China had a more peripheral role, and the impact of the external NG market was considered to be one of the most significant issues when considering China's NG risks [20]. However, when China surpassed South Korea to become the second largest gas importer in east Asia since 2017, China's role in the Asian and global NG markets became more influential [54].

There have been a few domestic NG disruptions over the past decade. In November 2009, Norther Central China experienced heavy rain and snow, which caused a moderate gas supply disruption in related provinces [55] and concerns regarding NG supply disruption increased thereafter. In winter 2017, an unprecedented disruption occurred due to strict coal consumption limitations in the Beijing–Tianjin–Hebei economic belt cities. Under the air quality control policies, coal combustion was strictly prohibited in such regions, and NG was used for heat generation purposes [3,4]. The impact of this disruption spread to neighboring countries, and the cost of Asian market LNG reached a new high that was almost three times higher than normal prices [56]. Four years later in winter 2021, a further moderate disruption occurred in Northeast Asian countries due to concurrent problems that included abnormally high coal prices, heavy rain, coal control, and emission reduction policies, and many regions in China suffered from power shortages [57]. As Northeast Asian countries were expecting a colder than average winter, the increased demand for NG once again resulted in high LNG prices [58]. It is acknowledged that the impact of climate-associated disruptions is often stochastic and difficult to forecast, which poses unpredictable risks to China's NG supply.

China plans to reach the peak of its carbon emissions prior to 2030 and to further reach carbon neutrality by 2060. According to China's "Reaching carbon emission peak before 2030" plan, coal consumption needs to be cut to reach the 2030 target. NG is thus the ideal substitute for coal to generate power and heat, and this brings both potentials and risks owing to large NG energy consumption demands [59]. However, to further reach carbon neutrality in 2060, it is possible that NG cutting policies may be applied after 2030 for less neutralizing efforts, which could lead to both redundant NG supplies and storage infrastructure [6,60,61].

3.4. Infrastructure Failures

Long-distance domestic pipelines are required in China because of the unbalanced NG resources and demands. The West–East gas pipeline project (with a length of more than 4200 km) was built to transport both domestic and imported NG from Central Asia to Beijing, Shanghai, Zhejiang, Guangdong, and Fujian. However, the long-distance underground steel pipes and their affiliated structures are vulnerable to corrosion, natural disasters, and third-party faults [62,63].

4. Fuzzy-AHP Methods

The popular Multiple Criteria Decision Making (MCDM) approaches used to assess risk include the Analytic Hierarchy Process (AHP), the Analytic Network Process (ANP), Elimination and Choice Expressing Reality (ELECTRE), the Technique of Order Preference by Similarity to the Ideal Solution (TOPSIS), and the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) [34]. When evaluating international risks, it is generally preferable to use a public risk index, such as the International Country Risk Guide (ICRG), as such an index provides a balanced review of the different aspects of international trading. However, geopolitics evolved faster between 2021 and 2022 than any index could promptly respond to. In addition, some of the rankings are difficult to quantify. Therefore, it is preferable in the current research to use the hierarchy method.

4.1. Construction of Hierarchy

In many cases, the presence of complex criteria contradictions and ambiguous situations in the hierarchy model could impact the result of the decision-making process [64]. As the number of criteria involved in the hierarchy increase, evaluators could be confused, leading to difficulties in clearly comparing some proposals due to ambiguity. In order to improve the hierarchy results, the fuzzy set theory was merged into the MCDM process by van Laarhoven and Pedrycz [65], where decisions could be made during the pairwise comparison process with the presence of uncertainty. Buckley [66] later refined this approach by calculating the weights after the fuzzy numbers using the geometric means. Based on the original AHP method, the Fuzzy-AHP approach has been tested and proven by multiple researchers as a method with improved accuracy and efficiency [67].

Before conducting the fuzzy AHP, a hierarchy model was set up to define the decision problem. The hierarchical model used to assess the security of China's NG supply is illustrated in Figure 5. In this model, the top level defines the overall goal of this assessment, which is to determine the risk status of China's NG supply. The second level identifies the specific risk indicators in each stage.

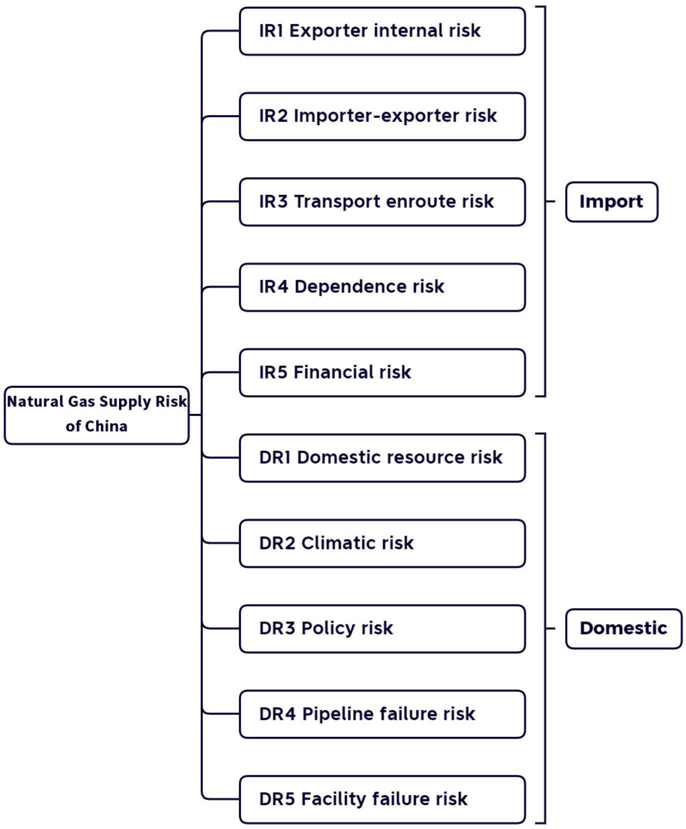

Figure 5. Hierarchy model of the current research.

In the current research, we invited five experts familiar with China's energy sector who have experience in related fields of research. Their affiliations and research interests are listed in Table 2. The evaluators were tasked with performing pairwise comparisons between each of the listed criteria in Table 3 and rating the importance based on the original nine-point Saaty scale of 1 to 9, where 1 stands for equal importance (two activities contribute equally to the objective) and 9 stands for absolute importance (the evidence favoring one activity over another is of the highest possible order of affirmation). The results from the five evaluators are collected and formalized in Appendix A.

Table 2. List of evaluators.

No.	Name	Affiliation	Research Interests
1	Prof. Zhang M.	China University of Mining and Technology	Energy economics
2	Prof. Sun C.L.	Chinese Academy of Sciences	Energy market, petrochemical industry
3	Prof. Ning Y.D.	Dalian University of Technology	Geopolitics, energy security
4	Prof. Li L.X.	China University of Geosciences	Energy modeling, risk analysis
5	Assoc. Prof. Li J.D.	China University of Petroleum	Carbon footprint, risk analysis

Table 3. List of China's natural gas supply risk criteria.

Criteria	Description
IR1 Exporter internal risk	Exporter's own stability status, including political, economic, military, social, and diplomatic stabilities. An exporter with a stable political and social environment is generally perceived as less risky.
IR2 Importer–exporter risk	International relations between importers and exporters. Deteriorated or downgraded relations between countries can introduce risks to the trading environment.
IR3 Transport enroute risk	Enroute risks of NG transport, including transport distance, pirate and hijack risks, maritime traffic status, regional conflicts and confrontations, and extreme weather.
IR4 Dependence risk	The importer's degree of dependence on exporters, which reflects the risks associated with the monopoly control of gas exporters over the importer's gas imports.
IR5 Financial risk	Fluctuation of NG price, especially LNG price, which involves complexed global spot trades and futures trades. The pipeline NG price is usually determined in mid- or long-term contracts and has less frequent price fluctuations.
DR1 Domestic resource risk	NG resource depletion and exhaustion risks.
DR2 Climatic risk	Higher summer temperatures and lower winter temperatures result in larger NG demand, while bursts of adverse weather (such as wide-range freezing rain or snow in winter) could cause an abrupt increase in NG demand or even NG supply disruption.
DR3 Policy risk	The role of NG in China's energy sector is unclear under the current emissions-peaking policy, and when emission peaks are reached, the role of NG is also unclear. With respect to meeting carbon neutrality goals, extracted NG could be excluded as a non-carbon-neutral fuel.
DR4 Pipeline failure risk	Most of China's domestic underground pipelines are made of steel and are at risk from corrosion, earthquakes, excavation accidents, and other pipeline failures.
DR5 Facility failure risk	Risk of failures associated with NG supply facilities, including LNG terminals, NG gate stations, and NG storage facilities.

4.2. Evaluation of Fuzzy Pairwise Comparison

Assuming n evaluators assessed m criteria, the $m \times m$ matrix for each evaluator $k \in [1, n]$ could be denoted as

$$\tilde{A}^k = \begin{bmatrix} 1 & a_{12}^k & \cdots & a_{1m}^k \\ a_{21}^k & 1 & \cdots & a_{2m}^k \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}^k & a_{m2}^k & \cdots & 1 \end{bmatrix} \quad (1)$$

Each coefficient scales from 1 to 9, which corresponds to the kth evaluator and the importance of criterion i in relation with criterion j. a_{ij}^k is the comparison by expert k of the two criteria i and j, and $a_{ij}^k = 1/a_{ji}^k$ [68].

To aggregate the judgments from n evaluators [66], the minimum, maximum, and geometrical mean values of n opinions were calculated to form the fuzzy comparison matrix $\tilde{M}$:

$$\tilde{M} = \tilde{m}_{ij} = \begin{bmatrix} 1,1,1 & l_{12}, g_{12}, u_{12} & \cdots & l_{1m}, g_{1m}, u_{1m} \\ l_{21}, g_{21}, u_{21} & 1,1,1 & \cdots & l_{2m}, g_{2m}, u_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ l_{m1}, g_{m1}, u_{m1} & l_{m2}, g_{m2}, u_{m2} & \cdots & 1,1,1 \end{bmatrix} \quad (2)$$

where

l_{ij} is the minimum value of n opinions, $l_{ij} = min a_{ij}^k$;

g_{ij} is the geometrical mean of n opinions, $g_{ij} = \sqrt[n]{\prod_{k=1}^{n} a_{ij}^k}$;

u_{ij} is the maximum value of n opinions, $u_{ij} = max a_{ij}^k$;

$l_{ij}, g_{ij}, u_{ij} \in [1/9, 9]$; $i, j = 1, \ldots, m$; $k = 1, \ldots, n$.

Defuzzification of the matrix could be conducted by adding two additional parameters; the Unstable conditions index α and the Expert judgment pessimism index μ were used, where $0 \leq \alpha \leq 1, \alpha + \mu = 1$. We set α to 0.5 by default. The defuzzified pairwise comparison matrix could be denoted as

$$D_{\alpha,\mu}\left(\widetilde{m}_{ij}\right) = \left[\mu \cdot f_{\alpha}\left(l_{ij}\right) + (1-\mu) \cdot f_{\alpha}\left(u_{ij}\right)\right], 0 \leq \alpha, \mu \leq 1, i < j \quad (3)$$

$$D_{\alpha,\mu}\left(\widetilde{m}_{ij}\right) = \frac{1}{D_{\alpha,\mu}\left(\widetilde{m}_{ij}\right)}, 0 \leq \alpha, \mu \leq 1, i > j \quad (4)$$

where

$$f_{\alpha}\left(l_{ij}\right) = \alpha\left(g_{ij} - l_{ij}\right) + l_{ij} \quad (5)$$

$$f_{\alpha}\left(u_{ij}\right) = u_{ij} - \alpha\left(u_{ij} - m_{ij}\right) \quad (6)$$

After defuzzification, the consistency of the evaluators' opinions could be inspected by calculating the consistency ratio (*CR*) using the consistency index (*CI*) and the eigen value λ_{max} of the defuzzified pairwise comparison matrix $D_{\alpha,\mu}\left(\widetilde{m}_{ij}\right)$:

$$CI = \frac{\lambda_{max} - m}{m - 1} \quad (7)$$

$$CR = \frac{CI}{RI} \quad (8)$$

where *RI* is the random index in Table 4. A consistency ratio below 0.1 was accepted in most cases.

Table 4. Random index values.

Number of Criteria (*m*)	1	2	3	4	5	6	7	8	9	10	11
Random Index (*RI*)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51

The criteria weightings were eventually ranked from 1 to m based on m components of the eigenvector of the pairwise comparison matrix $D_{\alpha,\mu}\left(\widetilde{m}_{ij}\right)$.

The processing of the matrices could be found in [69]. By processing the original matrix in Appendix A, the Fuzzy pairwise matrix could be composed as in Table 5 and the defuzzified matrix in Table 6.

Table 5. Fuzzy pairwise matrix.

(1,1,1)	(0.5,1.783,3)	(1,1.741,2)	(0.333,0.977,2)	(4,5.073,7)	(1,2.408,3)	(2,2.352,3)	(4,4.782,5)	(5,6.153,7)
(0.333,0.561,2)	(1,1,1)	(0.5,1,4)	(0.5,0.871,1)	(5,5.785,6)	(2,2,2)	(2,2.551,3)	(4,4.573,5)	(5,5.378,6)
(0.5,0.574,1)	(0.25,2)	(1,1,1)	(0.5,0.758,1)	(4,4.959,6)	(4,4.573,5)	(1,1.644,3)	(3,3.519,5)	(4,4,4)
(1,1.516,2)	(2,3.104,4)	(1,2.169,4)	(2,2.551,3)	(6,7.108,9)	(6,6,6)	(3,4.076,5)	(7,7.975,9)	(6,6.971,8)
(0.5,1.024,3)	(1,1.149,2)	(1,1.32,2)	(1,1,1)	(6,6.382,7)	(2,2.352,3)	(1,1.783,3)	(4,5.144,6)	(4,5.335,6)
(0.143,0.26,0.667)	(0.2,0.524,0.667)	(0.2,0.266,0.667)	(0.143,0.36,0.667)	(1,1,1)	(0.333,0.461,0.5)	(0.2,0.242,0.333)	(2,2.702,4)	(1,1.32,2)
(0.333,0.415,1)	(0.5,0.5,0.5)	(0.2,0.219,0.25)	(0.333,0.425,0.5)	(2,2.169,3)	(1,1,1)	(0.5,1,2)	(0.5,1.465,3)	(2,2.766,3)
(0.333,0.425,0.5)	(0.333,0.392,0.5)	(0.333,0.608,1)	(0.333,0.561,1)	(3,4.129,5)	(0.5,1,2)	(1,1,1)	(4,4.373,5)	(2,3.981,5)
(0.2,0.209,0.25)	(0.2,0.219,0.25)	(0.2,0.284,0.333)	(0.2,0.339,0.667)	(0.25,0.37,0.5)	(0.333,0.683,2)	(0.2,0.229,0.25)	(1,1,1)	(0.333,0.922,2)
(0.143,0.283,0.667)	(0.2,0.324,0.667)	(0.25,0.25,0.25)	(0.2,0.431,0.667)	(0.5,0.758,1)	(0.333,0.361,0.5)	(0.2,0.251,0.5)	(0.5,1.084,3)	(1,1,1)

Table 6. Defuzzified matrix.

CR = 0.008									
1	1.766	1.621	0.705	1.072	5.287	2.204	2.426	4.641	6.077
0.566	1	1.625	0.349	0.810	5.643	2.000	2.525	4.537	5.439
0.617	0.615	1	0.543	0.754	4.980	4.537	1.822	3.760	4.000
1.419	2.869	1.842	1	2.525	7.304	6.000	4.038	7.987	6.986
0.933	1.234	1.326	0.396	1	6.441	2.426	1.891	5.072	5.167
0.189	0.177	0.201	0.137	0.155	1	0.439	0.254	2.851	1.410
0.454	0.500	0.220	0.167	0.412	2.279	1	1.125	1.608	2.633
0.412	0.396	0.549	0.248	0.529	3.930	0.889	1	4.437	3.741
0.215	0.220	0.266	0.125	0.197	0.351	0.622	0.225	1	1.044
0.165	0.184	0.250	0.143	0.194	0.709	0.380	0.267	0.957	1

5. Results and Discussions

The normalized weights are ranked in Figure 6. This illustrates the current situation of China's gas supply chain where the risks on the import side were significantly greater than those on the downstream domestic side. The dependence risk was found to be the most challenging link of all, followed by the exporter internal risk, financial risk, and international risk, while the climate and policy risks were slightly less risky. Domestic resource and failure risks were considered to be the least risky parts within China's NG supply chain.

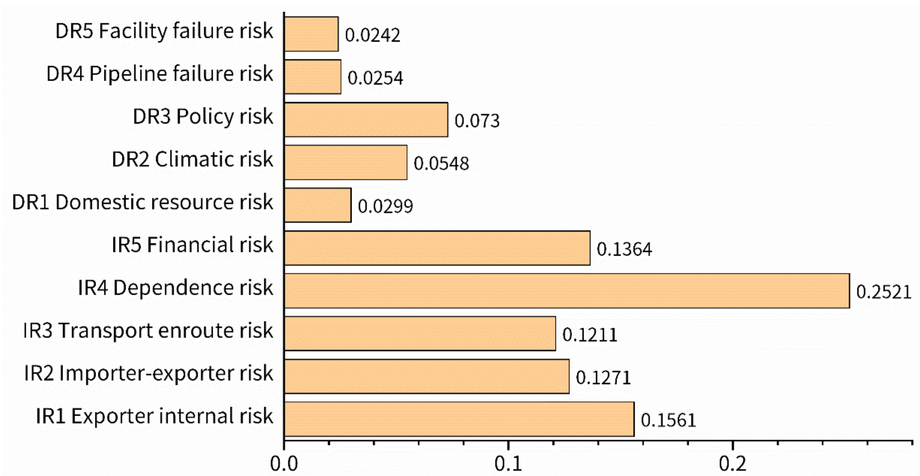

Figure 6. Normalized final weights.

5.1. Imports

The risk of dependence has been China's primary NG import risk for several years [20,21], and efforts have been made by the Chinese government to decrease this risk. Typically, this risk can be solved by either cutting the demand for NG, increasing domestic production, or finding stable suppliers as substitutes [54]. For China, the first two methods are most likely unavailable because of the colossal demand for NG and the limited domestic reserves. As previously shown in Figure 2, China has been shifting its NG dependency eastward, primarily relying on geopolitically and politically friendly regions such as Central Asia, Oceania (at the time), and, more recently, neighboring Russia to meet its NG demands. Prior to the Russia–Ukraine war, bilateral trade including energy between Russia and China had made steady but sluggish progress. The Power of Siberia 1 was introduced early in 2009, but was not constructed until 2014. As one of the consequences of the war, Russia has been rerouting its energy export strategies to Asian countries, including China, under the sanctions from Europe and the United States. The agreement of the Power of Siberia 2 through Mongolia to China was signed by all three countries in 2021, while the Russian Duma further ratified to supply China through its eastern border in

Jixi, Heilongjiang with the existing Sakhalin–Khabarovsk–Vladivostok gas pipeline in May 2023, whose annual supply was expected to be 10 bcm [70]. Compared with a previous gas risk analysis on China, with such geopolitically close and friendly suppliers and one of the largest NG exporters being pushed toward China, the risks of dependence or disruption in international relations and problems with transport have been simultaneously reduced.

While the risk of dependence has been mitigated with China's efforts to establish strong connections with geopolitically friendly suppliers, it is crucial to recognize that certain critical conditions could potentially increase this risk. An example is the disruption in international relations, similar to what transpired between Russia and Europe in 2022. Europe, heavily dependent on Russian gas with a pre-conflict rate of 40% [71], has been grappling with severe energy issues due to the strained Russia–EU relations [72,73].

From China's perspective, the country generally maintains a mild foreign policy stance and fosters positive bilateral relations with various nations, especially its trading partners. The terms used by the Ministry of Foreign Affairs of China to describe these relationships, as outlined in Table 7, reflect China's subjective attitude toward its trading partners. The country has actively worked toward establishing and reinforcing cooperative relations with most of its trading partners, particularly with gas suppliers [74,75].

Table 7. China's cooperative relations with foreign countries through the ages. Gas suppliers are marked in bold.

Country	Partnership of Friendship and Cooperation	Strategic Cooperation Partnership	Comprehensive Strategic Cooperation Partnership	Strategic Partnership	Comprehensive Strategic Partnership
Russia		1996	2011		2019
Khazakstan	1993	2005		2011	2019
Turkmenstan		2013		2018	2023
Uzbekistan	2005			2012	2016
Kyrgyzstan				2013	2017
Tajikistan	2007			2013	2017
Malaysia	1999	2004			2013
Indonesia		2005			2013
India		2005			
Phillipines		2005			2018
Japan	1998	2008			
South Korea	1998	2008			
Qatar	1988			2014	
Oman				2018	
Saudi Arabia		2008		2016	
UAE		2012		2018	
Germany		2010			
Australia					2014
USA [76]					

China's diplomatic approach has been characterized by the frequent promotion of cooperation with Central Asian countries since the mid-2010s. As the demand for NG imports continued to rise, diplomatic meetings and agreements with these countries became more frequent after 2015. These efforts have resulted in the elevation of relations to the highest level of China's cooperative partnership with these nations.

However, despite the cooperative relations, diplomatic issue still affect the country's NG imports. With respect to territorial-related disputes, China's firm attitude has resulted in diplomatic tensions that have affected maritime transport, for example, the conflict between China and Japan over the Diaoyu Islands (1980s–present) and China and the Philippines over the South China Sea (2016). These disputes have also resulted in unrelated issues, such as the conflict with Australia in 2020. Although the problems with Australia have a limited influence on Australian gas imports, as shown in Figure 1, tense relationships with China's southern neighbors and suppliers have caused an unhealthy gas import environment and associated risks for China.

Furthermore, the leakage and failure of Nord Streams 1 and 2 in September 2022 highlight the safety risks associated with international gas pipelines. Although all of China's gas pipelines are land-based, which are seldom affected by natural disasters [77], the unpredictable risks of sabotage need to be considered. Such risks are then further connected with provider stability.

The stability of gas exporters is an important factor in China's gas supply safety. A politically unstable country with social unrest will result in NG trade problems. Minor to moderate internal political instability has occurred with a few of China's gas suppliers, most recently in Myanmar (February 2021), Kazakhstan (January 2022), and Uzbekistan (July 2022). We are no experts in international politics, but the energy trade and infrastructure in the above countries appears to have been unaffected to date. Although experts have different opinions about these risks, they are generally ranked below those of other import risks.

Since 2022, the international LNG market has experienced more frequent fluctuations compared to previous periods. The reasons for the fluctuation are multifaceted and involve complex factors such as geopolitics, currency dynamics, supplier conditions, and demand variations and are beyond our capability, but these factors are involved in China's NG imports. Despite China's long-term pipeline contracts not being directly linked to global market fluctuations, the impact on the country's NG supply is still significant. While the proportion of NG supplied through these long-term contracts is substantial, the overall percentage of NG supplied to China is relatively low. Consequently, the price of domestic gas in China remains susceptible to the fluctuations in the global market. China's International Energy Exchange in Shanghai has yet to enter the global mainstream. As a result, China is compelled to accept and navigate the challenges posed by global market fluctuations, as these fluctuations can have a direct impact on the pricing and availability of natural gas within the country.

To summarize, the primary risk for China's natural gas (NG) imports is the risk of dependence, ranking as the top concern. While other related risks such as international risks, exporter internal risks, and transport risks have diminished to varying degrees, they should not be overlooked. China's status as a net importer and its limited pricing power in the natural gas market emphasize the importance of the country's ability to navigate and withstand fluctuations in the global gas market.

5.2. Domestic

China aims to reach peak carbon emissions by 2030, but to fulfil this target, the fossil fuels used in its domestic electricity and heat generation sectors must be substituted with clean NG and renewable energy. China took initial action in 2017, when urban heating suppliers and rural users in Beijing, Tianjin, and 26 surrounding cities and affiliated regions were ordered to use NG instead of coal prior to winter, with the aim of reaching the "Air pollution control plan" targets made in 2013. Although the air quality in the area was indeed improved, China's domestic NG market suffered from severe supply issues, rocketing prices, and public unease. We consider that China's policymakers learned from this incident, as the NG supply fluctuation in 2020 and the subsequent power shortage in late 2021 were handled adequately. According to the publicly released carbon-peaking policies of China's 34 provincial administrative divisions (including four municipalities), most provinces simply mentioned NG as the substitution in the industry and transport sectors. Only Tianjin, Shanghai, Anhui, Shandong, and Henan set specific targets for NG supply or consumption, while only Guangdong, Henan, and Hainan planned to build gas-fired power plants. This indicates that due to the consequences of the 2017 incident, the uncertainty of China's NG supply and unclear future policies have an obvious influence over provinces, which are the executors of the carbon-peaking policy. Due to unaffordable prices, unstable and prioritized supply, and "campaign-style" temporary policies, provincial governments were unwilling to spend much effort on extending NG supplies and consumptions, but are rather eyeing renewable energy and nuclear power or even carbon capture, utilization, and storage facilities.

In addition to policy uncertainties, the role of NG in the future energy sector of any country is unclear. The use of NG is undoubtedly the best choice for cutting coal use, because it emits low levels of pollution but provides good heating value. However, emission neutrality targets require cutting emissions that cannot be captured both naturally and artificially, and NG is a carbon-based fuel. Nevertheless, the transition from coal to NG could take a few decades, and for short- or mid-term strategies, the expansion of China's NG demand and supply could continue, although moderate risks exist in association with long-term carbon neutrality strategies.

Domestic infrastructure includes pipelines and NG facilities, and the NG facilities further consist of LNG terminals, NG storage facilities, pressurizing stations, and gate stations. According to domestic statistics, the top causes of leakage from China's domestic pipelines are accidental damage during excavation (~50%), pipeline theft (~20%), natural causes including corrosion (~20%), and other reasons (<10%) [78,79]. For major pipelines, most researchers have rated China's domestic trunk pipelines with an acceptable risk level, because quality control during the manufacturing and installation of China's NG pipelines are considered superior to those in North America and Europe. With respect to the LNG terminals, a fire caused by maloperation during construction started in the Beihai LNG terminal within Tieshan Port, Beihai, Guangxi Province in November 2020 and resulted in seven deaths and direct losses worth CNY 20 million. However, compared to crude oil facilities and pipelines where several severe accidents have occurred in the past few decades (Qingdao oil pipeline in 2013 and PetroChina Dalian oil pipeline and tank in 2010), LNG pipelines and facilities have lower accident rates. Nevertheless, with the growth in China's NG market and the increasing numbers of LNG terminals and NG storage facilities, the number of accidents could increase; therefore, extreme precautions should be taken.

China's has 8.4 trillion m^3 of proven NG reserves, which have grown sixfold since 2000 [2]. Although China has a low share of the global NG reserves, most evaluators believe that the risk of NG reserve depletion can be neglected. In addition to the growing amount of proven reserves and potentially undisclosed reserves, China has considerable methane hydrate reserves that could relieve pressure on its NG resources [51], and the associated exploitation technologies are increasingly being developed over time.

In summary, China's domestic NG risks are influenced by emission policies, uncertainties in NG use and demand trends, and potential accidents in pipelines and facilities. While challenges exist, the country's significant reserves and ongoing technological advancements provide a foundation for navigating these uncertainties in the pursuit of a sustainable energy future.

6. Conclusions

As many importing countries from Europe and Asia, China is now experiencing natural gas supply challenges consisting of multiple risks. In this study, we identified 10 risk factors based on an analysis of China's natural gas supply chain status from both domestic and import perspectives, including import channels, global natural gas market, domestic production and transportation, and China's carbon-peaking and neutralization plans. We then conducted a risk analysis using the Fuzzy-AHP method. The following conclusions were obtained from the model results:

The import side presents the greatest challenge to China's NG supply, and the weighting of the risks is significantly greater than those on the domestic supply side. Regarding the import factors, the risks of dependence, transport, international relations, markets, and gas supplier internal stability rank from the highest to lowest. On the domestic side, emission policies and climate are the major risks, while domestic resources, infrastructure, and terminal users have a limited influence on China's overall natural gas supply risks.

China's natural gas risk level has risen over the past decade owing to the country's increasing reliance on imports. Several methods can be used to reduce risks. First, China should obtain its NG imports from various countries with different geopolitical interests, so that the country's gas supply is not bound to a single entity, while dependence and political risks should be avoided as far as possible. Secondly, the sustainable diplomatic policies regarding present major gas suppliers and international pipeline operators will be continued following the country's "Five Principles of Peaceful Coexistence", to avoid the risk brought by international incidents. To decrease internal supply risks, stronger infrastructure needs to be constructed (including developed pipeline networks and abundant NG storage facilities), but the extent of construction should be properly controlled to avoid the potential redundancy of such infrastructure while becoming carbon neutral. In this respect, a stepwise transition from the use of these facilities from NG to hydrogen could be considered.

According to the result of this risk analysis, we put forward a few policy recommendations to further reduce risks. Firstly, China should continue fortifying bilateral relations with its gas suppliers, especially with Eurasian countries that have the potential to provide stable, contracted supplies of NG through land pipelines, through its global infrastructure development strategy, the Belt and Road Initiative. The measures within this initiative could offer a template for international trades and relations, as the policy focuses on trading and cooperation, but ignores some previous ideology and diplomatic disputes, which decrease risks concerning foreign affairs to a more appropriate extent. China should also establish a viable future energy market to minimize the effects of global currency and energy market fluctuations. This could help eliminate the risk concerning markets. Furthermore, to decrease domestic challenges, future NG emission plans should be far-sighted to avoid a sudden unforeseen demand for natural gas and excessive unrequired constructed infrastructure. The safe operation of natural gas pipelines, facilities, and LNG terminals should also be strengthened. Afterall, the most important measure is to strengthen China's natural gas storage system. Only when the natural gas storage can handle normal supply interruptions as well as seasonal fluctuations, can the country grasp the energy security within its own hands.

This risk analysis could be further improved using a dynamic risk evaluation. As for now, annual reports and scientific research updates would lag behind the global trends and the evolution of international relations, markets, and incidents. During the writing of this paper, we needed to instantly react to geopolitical changes and those in the global NG market to avoid presenting irrelevant and out-of-date information. By analyzing the frequency and relativity of real-time feeds from global social media and news, it is possible to acquire instant information about changes in the NG supply, and related timely measures can be taken to prevent and cope with potential challenges and threats. In future studies, we aim to use an AI-based real-time risk analysis based on the filtering and processing of information from social media relating to climate and political events and to conduct a dynamic NG risk analysis. Furthermore, a comparative analysis of risk mitigation strategies implemented by other countries facing similar challenges could also offer valuable insights for refining China's approach to securing its natural gas supply.

Author Contributions: Conceptualization, M.C., H.M. and N.L.; methodology, M.C.; software, M.C.; formal analysis and data curation, M.C.; writing—original draft, M.C.; writing—review and editing, M.C.; funding acquisition, H.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (51976020) and the National Natural Science Foundation of China (71603039).

Data Availability Statement: The data used in the current study are available in the British Petroleum Statistical Review and other public resources.

Acknowledgments: We would like to thank the editor and anonymous referees for their constructive suggestions and valuable comments on the earlier draft of this paper, Based on these, we improved the content.

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

Appendix A. Opinions of 5 Evaluators

Evaluator 1							**(CR = 0.04763)**			
	IR1	IR2	IR3	IR4	IR5	DR1	DR2	DR3	DR4	DR5
IR1	1	3	2	1/2	2	6	3	3	5	6
IR2	1/3	1	1/2	1/3	1	6	2	3	5	5
IR3	1/2	2	1	1/4	1	5	4	2	4	4
IR4	2	3	4	1	3	8	6	5	8	7
IR5	1/2	1	1	1/3	1	7	2	3	5	6
DR1	2/3	2/3	1/5	1/8	1/7	1	1/3	1/5	2	1
DR2	1/3	1/2	1/4	2/3	1/2	3	1	2	3	3
DR3	1/3	1/3	1/2	1/5	1/3	5	1/2	1	5	5
DR4	1/5	1/5	1/4	1/8	1/5	1/2	1/3	1/5	1	1/2
DR5	2/3	1/5	1/4	1/7	2/3	1	1/3	1/5	2	1
Evaluator 2							**(CR = 0.06597)**			
	IR1	IR2	IR3	IR4	IR5	DR1	DR2	DR3	DR4	DR5
IR1	1	2	2	1	1/3	5	3	2	5	7
IR2	1/2	1	1/2	1/4	1	6	2	2	4	5
IR3	1/2	2	1	1	1	5	4	1	3	4
IR4	1	4	1	1	2	7	6	3	8	7
IR5	3	1	1	1/2	1	6	3	1	6	5
DR1	1/5	2/3	1/5	1/7	2/3	1	1/2	1/4	3	2
DR2	1/3	1/2	1/4	2/3	1/3	2	1	1/2	1/2	3
DR3	1/2	1/2	1	1/3	1	4	2	1	4	2
DR4	1/5	1/4	1/3	1/8	2/3	1/3	2	1/4	1	2
DR5	1/7	1/5	1/4	1/7	1/5	1/2	1/3	1/2	1/2	1
Evaluator 3							**(CR = 0.06259)**			
	IR1	IR2	IR3	IR4	IR5	DR1	DR2	DR3	DR4	DR5
IR1	1	1/2	2	1/2	2	4	1	2	4	6
IR2	2	1	4	1/2	1/2	6	2	3	5	5
IR3	1/2	1/4	1	1/4	1	4	5	2	3	4
IR4	2	2	4	1	3	6	6	5	7	6
IR5	1/2	2	1	1/3	1	6	2	2	6	6
DR1	1/4	2/3	1/4	2/3	2/3	1	1/2	1/3	2	1
DR2	1	1/2	1/5	2/3	1/2	2	1	2	3	3
DR3	1/2	1/3	1/2	1/5	1/2	3	1/2	1	4	5
DR4	1/4	1/5	1/3	1/7	2/3	1/2	1/3	1/4	1	1
DR5	2/3	1/5	1/4	2/3	2/3	1	1/3	1/5	1	1
Evaluator 4							**(CR = 0.07193)**			
	IR1	IR2	IR3	IR4	IR5	DR1	DR2	DR3	DR4	DR5
IR1	1	2	1	1	1/3	4	3	2	5	5
IR2	1/2	1	2	1/4	1	5	2	2	4	6
IR3	1	1/2	1	1	1/2	6	5	1	3	4
IR4	1	4	1	1	2	6	6	3	9	8
IR5	3	1	2	1/2	1	6	3	1	5	4
DR1	1/4	1/5	2/3	2/3	2/3	1	1/2	1/4	4	2
DR2	1/3	1/2	1/5	2/3	1/3	2	1	1/2	1/2	2
DR3	1/2	1/2	1	1/3	1	4	2	1	5	4
DR4	1/5	1/4	1/3	1/9	1/5	1/4	2	1/5	1	2
DR5	1/5	2/3	1/4	1/8	1/4	1/2	1/2	1/4	1/2	1

Evaluator 5						(CR = 0.05582)				
	IR1	IR2	IR3	IR4	IR5	DR1	DR2	DR3	DR4	DR5
IR1	1	3	2	1/2	2	7	3	3	5	7
IR2	1/3	1	1/2	1/3	1	6	2	3	5	6
IR3	1/2	2	1	1/3	1/2	5	5	3	5	4
IR4	2	3	3	1	3	9	6	5	8	7
IR5	1/2	1	2	1/3	1	7	2	3	4	6
DR1	1/7	2/3	1/5	1/9	1/7	1	1/2	1/5	3	1
DR2	1/3	1/2	1/5	2/3	1/2	2	1	1	3	3
DR3	1/3	1/3	1/3	1/5	1/3	5	1	1	4	5
DR4	1/5	1/5	1/5	1/8	1/4	1/3	1/3	1/4	1	1/3
DR5	1/7	2/3	1/4	1/7	2/3	1	1/3	1/5	3	1

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