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Synthesized indicator for evaluating security of strategic minerals in China: A case study of lithium

Na Zhou [a,b], Qiaosheng Wu [a,*], Xiangping Hu [b,**], Yongguang Zhu [a], Hui Su [a], Shuangjiao Xue [a]

[a] School of Economics and Management, China University of Geosciences, No.388 Lumo Road, 430074, Wuhan, China
[b] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Realfagbygget, E4-141, Gløshaugen, Høgskoleringen 5, N-7491, Trondheim, Norway

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ABSTRACT

The transition of the economic growth in China from high-speed to high-quality development provides new challenges to strategic minerals (SMs) security. Under the transition, combined with its development status, but also to maintain global coexistence from the entire industrial chain, we in this paper first expound the security connotation of SMs and take lithium resources as an example to evaluate its security in China. Monte Carlo Simulation (MCS) is used for sensitivity analysis. Results show that the security level of China's lithium resources is rising but fluctuating, and it is closely related to changes in the sub-object of coexistence. Our results illustrate that the proposed synthesized security indicator can effectively evaluate the security status of China's lithium resources. Therefore, it should be possible to be adapted for evaluating the security status of other SMs.

1. Introduction

Global development depends on mineral resources (Bazilian, 2018; Christmann, 2018; Henckens et al., 2016, 2019). Some mineral resources are mainly available in a few countries and regions, and the production and consumption areas can thus be separated by long distances (Henckens et al., 2016). Therefore, the security of mineral resources has become the focus of national game (Ali et al., 2017). The report of the 19th National Congress of the Communist Party of China has put forward a new historical direction for China's development transition, i.e., from high-speed growth in the past to high-quality development (Xi, 2017). Under the economic growth transition and scientific and technological revolution, the supply and demand pattern of China's mineral resources reveals new characteristics (Cheng et al., 2018; Wang, 2018). Also, continuous globalization exposes the inherent attributes of high degrees of integration and interdependence of the world economy (Ali et al., 2017). However, due to the anti-globalization trend, along with technological revolution, global industrial transfer process and climate change issues, the risk of disruption of minerals supply is increasing (Huang, 2019; Yakovleva and Vazquez-Brust, 2018), which leads to a volatile global mining market and challenges to mineral security.

As an essential manifestation of energy security (ES), mineral security presents spatiotemporal characteristics with the further development of ES. The study of ES can be traced back to the First World War (McClure, 1983). The threat of large-scale wars has weakened since the end of the Cold War. The confrontation between countries is essentially a competition for scarce energy, making ES an increasingly crucial part of national or regional security (Klare, 2001). Traditional ES emphasizes on supply stability, that is, a country's ability to acquire resources continuously (Sovacool et al., 2011) at a reasonable price (EC, 2001; IEA, 1985, 2001, 2002; Leung, 2011), focusing on the continuous supply of energy according to demand (Winzer, 2012). As the ecological destruction in the process of energy extraction valued, Blum and Legey (2012), EC (2001) and Von Hippel et al. (2011) introduced sustainable development into ES, highlighting the environmentally friendly nature of ES (Sovacool et al., 2012). In addition to supply and price factors, Nelwan et al. (2017), Sharifuddin (2014) and Wu (2014) believed that ES included technical advances (Ang et al., 2015a,b; Kyriakopoulos and Arabatzis, 2016; Sebitosi, 2008a), energy efficiency improvements (Kemmler and Spreng, 2007; Sebitosi, 2008a), and energy structure (Sovacool et al., 2012). The fourth industrial revolution has spawned a new round of the global industrial competition. Due to the scattered

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[*] Corresponding author. School of Economics and Management, China University of Geosciences, 388 Lumo Road, 430074, Wuhan, China.

[**] Corresponding author. Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Realfagbygget, E4-141, Gløshaugen, Høgskoleringen 5, N-7491, Trondheim, Norway.

E-mail addresses: nazhou@cug.edu.cn (N. Zhou), qshwu@cug.edu.cn (Q. Wu), Xiangping.Hu@ntnu.no (X. Hu), zhuyongguang@cug.edu.cn (Y. Zhu), sh_cug@163.com (H. Su), sylvia9306@163.com (S. Xue).

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Abbreviation

SM	Strategic mineral
MCS	Monte Carlo Simulation
ES	Energy security
EC	European Commission
MNR	Ministry of Natural Resources of the People's Republic of China
GSI	Global supply stability
DES	Domestically economic security
EI	Economic importance
CEI	Coexistence
LiC	Lithium content
BGS	British Geological Survey
LiO	Lithium oxide content
LCE	Lithium carbonate content
HDI	Human development index
PPI	Policy perception index
EPI	Environmental performance index
WGI	World governance index
HHI	Herfindahl-Hirschman index
HS	Harmonized System
Ganfeng Lithium	Ganfeng Lithium Co., Ltd.
Tianqi Lithium	Tianqi Lithium Corporation
CATL	Contemporary Amperex Technology Ltd
SRG	Sinomine Resource Group Co., Ltd.
Tibet Mineral	Tibet Mineral Development Co., Ltd.
Tibet UDI	Tibet Urban Development and Investment Co., Ltd.
NDRC	China's National Development and Reform Commission
LSI	lithium security index
BRI	Belt and Road Initiative

distribution of the mineral resources (Henckens et al., 2016), which are concentrated in only a few countries or regions (Glöser et al., 2015), geopolitics (Hayes and McCullough, 2018; Sharifuddin, 2014; Wu, 2014) and global governance (Ali et al., 2017; Goh and Effendi, 2017; Henckens et al., 2019) are integrated into mineral security.

The list of critical minerals (NARA, 2018) published by the United States (US) in 2018 and the report of the *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* (U.S. Department of Commerce, 2018) indicate that US′ critical minerals depend on foreign suppliers such as China. The US government has taken measures, such as advancing the transformation of critical mineral supply chains, strengthening cooperation with allies, reducing restrictions on domestic development, to promote the production of critical minerals. European Commission (EC) implements the "Horizon 2020" project (EC, 2018), and releases the "EU Raw Materials 2050 Vision and Technology and Innovation Roadmap" (Baumgarten and Vashev, 2017) to ensure reliable access to raw materials such as cobalt, lithium, graphite, and nickel. The approaches of US and EU for ensuring the supply security of critical minerals or raw materials can be summarized as follows: on the one hand, they improve the sustainability of internal resource supply through recycling and reuse; on the other hand, they actively expand raw material resources worldwide. The critical minerals (raw materials) lists issued by US and EU both indicate that their critical minerals have a competitive relationship with China (Blengini et al., 2017), which may increase China's external risks of acquiring overseas resources. China does not release a list of critical minerals but proposes the catalogue of strategic minerals (SMs) for defence security, economic security and the development of strategic emerging industries (MNR, 2016), covering 6 energy minerals, 14 metals and 4 non-metals, shown in Table 1. How to secure SMs is a major realistic issue that China must face.

The rest of the paper is structured as follows. In Section 2, we give the security connotation of SMs. Based on the connotation, in Section 3, lithium is taken as a case for indicators selection and security quantification. Main results and sensitivity analysis are shown in Section 4. Conclusions and policy implications in Section 5 end the paper.

Table 1
Strategic minerals (SMs) catalog in China.

Classification	Minerals
Energy minerals	Oil, natural gas, shale gas, coal, coalbed gas, uranium
Metals	Iron, chromium, copper, aluminum, gold, nickel, tungsten, tin, molybdenum, antimony, cobalt, lithium, rare earth, zirconium
Non-metals	Phosphorus, potassium salts, crystalline graphite, crystalline graphite

Source: MNR (2016).

2. Security connotation of strategic minerals

We give the security connotation of China's SMs (Fig. 1), which not only reflects the role of SMs' material basis of national economics (Christmann, 2018; Goh and Effendi, 2017), but also considers the global supply stability (GSI) of SMs (Jasiński et al., 2018; Kamenopoulos and Agioutantis, 2020), and illustrates the synergy of domestic security and global resource governance (Ali et al., 2017; Henckens et al., 2019; Paulick and Nurmi, 2018). GSI of SMs needs to be fully considered from the perspective of global resource distribution (Chuang and Ma, 2013; Yao and Chang, 2014), political, economic, and social conditions of the producing countries (EC, 2014; Graedel et al., 2012), as well as geopolitics (Gemechu et al., 2016; Kamenopoulos and Agioutantis, 2020; Månberger and Johansson, 2019). Domestically economic security (DES) of SMs is similar to the parameter economic importance (EI) used by EC (2010, 2014 and 2017), which defines raw material criticality. For a given candidate material, the parameter EI is related to the terminal application, the value-added of relevant manufacturing sectors, and substitution. However, this approach does not consider the impact of price fluctuations on EI. Drawing on the EU method, when evaluating the DES of China's SMs, we consider not only the stability of domestic production and the resilience of demand, but also the vulnerability of domestic market and import-related market. Global governance is essentially the rise of governance from the domestic level to the international level (Ali et al., 2017; Henckens et al., 2019). From the perspective of global governance, the security of China's SMs is the coexistence (CEI) among various entities from the whole industry chain and global market. Globalization of mineral resource allocation and international mineral resource cooperation, aiming to obtain the international influence of SMs, have become widespread concerns around the world. The so-called international influence of resources is to measure a country's ability to affect the international resource structure from international price influence of SMs to industrial back-end advantages (Daw, 2017).

3. Outlook of lithium, methodology and data for lithium security

To further understand the security connotation of China's SMs, we use lithium as an example to evaluate its security. Lithium has characteristics of lightweight, corrosion resistance, high-temperature resistance and impact resistance. So it is widely used in chemical, pharmaceutical, nuclear industry, aerospace, machinery manufacturing and other fields (Jaskula, 2010). At the same time, lithium has excellent electrical conductivity, providing a stable and reliable power supply for modern electronic equipment, especially for new energy vehicles (IEA,

Fig. 1. Security connotation of China's strategic minerals (SMs). The number in brackets in each rectangle is the number of sub-indicators associated with that dimension.

2017; Majeau-Bettez et al., 2011; Zackrisson et al., 2010). With the rapid development of lithium-related emerging industries such as new energy vehicles, China's lithium resource gap is increasing, and the challenges of lithium security are gradually deepening (Zeng and Li, 2013).

3.1. *Outlook of lithium*

From the extraction to the manufacture of downstream products, the life cycle of lithium can be divided into the upstream lithium ore, downstream end products, and intermediate products between upstream and downstream (Fig. 2). Observed from the upstream, global lithium resources are mainly in salt lake brines and solid lithium ores, which are mainly spodumene, lepidolite, and petalite (Hao et al., 2017; Lu et al., 2017; Sun et al., 2017, 2018). According to USGS (2020), 80 million tons of lithium content (LiC) resources have been proven globally. Bolivia, Argentina and Chile are the major salt lake brine lithium resource countries. Australia and Canada are countries with great spodumene resources. China, with 4.5 million LiC resources, accounts for 5.9% of the world' total, and it is the fifth-largest lithium country in the world. 85% of lithium resources are contained in brines, mainly distributed in Qinghai (58%) and Tibet (33%), and ore lithium resources account for the remaining 15%, mainly distributed in Sichuan (57%) and Jiangxi (33%) (Sun et al., 2019).

Main intermediate products from the lithium industry chain are lithium carbonate, lithium hydroxide, lithium chloride, and lithium-containing compounds, and these intermediate products are further processed and manufactured to final products. Among them, lithium carbonate is the world's most extensive lithium product in terms of output and trade volume (Martin et al., 2017).

There are many products in the downstream lithium market, of which 35% of lithium is used as battery. Lithium is widely used in ceramics, lubricants, refrigerants and other fields (BGS, 2016). Lithium is also a critical raw material for medicine and polymers.

In the global value chain, one country is continuously importing and exporting lithium-containing products with other countries at all life cycle stages. Considering the completeness of the data, we choose the

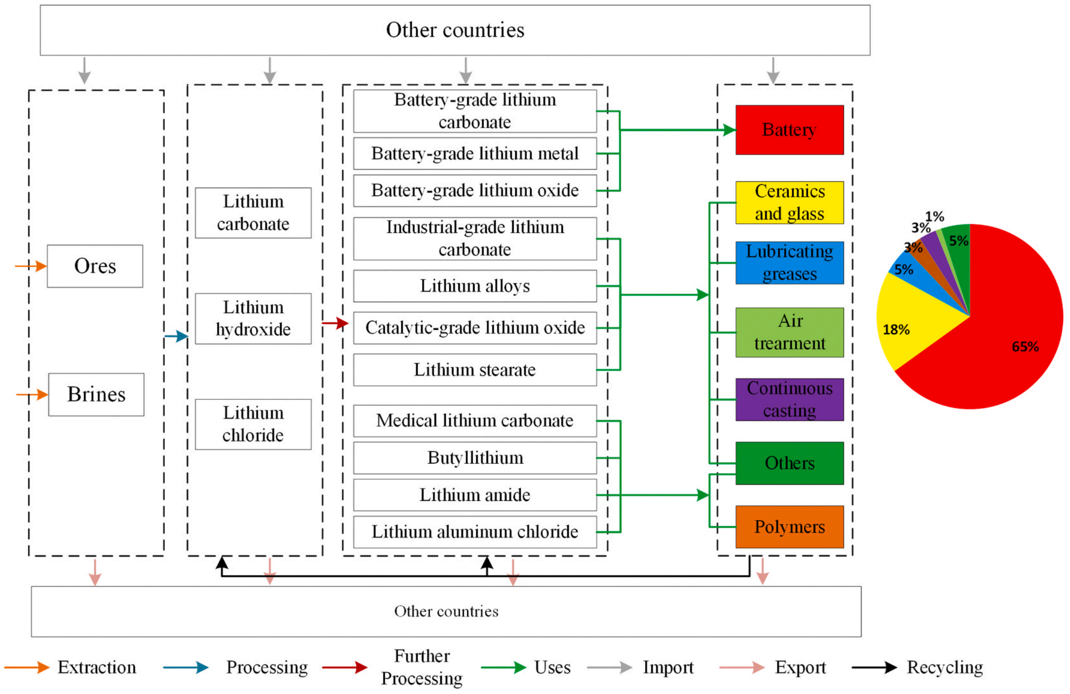

Fig. 2. Lithium life cycle industry chain. The pie chart is global end-use lithium consumption (USGS, 2020). Different colors represent terminal lithium products, and colored arrows indicate major processes in lithium life cycle. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

United Nations Commodity Trade Database (UN Comtrade) as the source of global trade data for lithium-containing products. Limited to the number of commodities included in this dataset, we identify a list of lithium-containing products covered in this study (see Table 2). However, lithium products are often measured by different units, such as LiC, lithium oxide content (LiO), and lithium carbonate content (LCE), and we need to unify them for further evaluation. Based on Sun et al. (2017) and BGS (2016), we set lithium related commodity conversion coefficients (shown in Table 2) to convert, and all the lithium-containing product data used is measured as LiC.

3.2. Indicators selection for lithium security

Achzet and Helbig (2013) analyzed 15 representative documents of critical minerals and summarized the general process of supply risk assessment. Firstly, select indicators and find specific quantitative indicators for each risk. Secondly, calculate the supply risk using a weighted average method. Finally, summarize risk values into corresponding target values in a linear or matrix form. We draw on similar ideas to build an evaluation index system and compute the security level.

Based on the security connotation of SMs, we construct the lithium security index system with 3 sub-objects, 7 dimensions and 20 indexes. Definitions and references of the indexes are shown in Table 3. GSI aims to evaluate the combined effects of global reserves, the stability of resource-producing countries and geopolitical environment related to lithium security. Three specific indicators quantify the stability of resource-producing countries and geopolitical indicators. DES reflects the role of lithium in supporting the sustainable development of national economy, from supply stability, demand resilience, and market vulnerability. CEI indicates the degree of integration of domestic and foreign markets. As pointed out by Daw (2017), the existing risk assessment only considers a single mineral product market but ignores international material processing. We use international raw material conversion indicator constructed by Daw (2017) as measures with domestic market openness and overseas market shares to quantify coexistence.

Here we describe quantitative methods for each indicator. Considering the availability of data, the study period of China's lithium security is from 2010 to 2018.

(1) **GSI/GSI1** Supply potential

Reserve-to-production ratio is used to measure global lithium availability. Data of global lithium reserves are from USGS (2020). National-level lithium production data comes from USGS (2020) except the US because USGS does not disclose it. Instead, the US lithium production data used in this article is from Daw (2017) and Statista (2020). For each year, lithium output of each country is aggregated to global lithium production data (see Table 4). GSI1 is a positive indicator.

(2) **GSI2** Social stability

Social-economic development of a lithium-producing country affects the global supply of lithium resources. Human Development Index (HDI), published by the United Nations Development Programme (UNDP, 2020), is a widely accepted standard to measure the socio-economic development of countries since 1990. We compute the social stability level of global lithium supply based on the lithium production shares of primary lithium producing countries and their HDIs (see Table 5), shown in Equation (1).

$$GSI2 = \sum HDI_i \times \frac{P_i}{P} \tag{1}$$

where P_i and HDI_i are the lithium production and the Human Development Index in the lithium-producing country i, respectively. P is a global lithium production (see Table 4). GSI2 is a positive indicator.

Table 2
List of lithium-containing products and the conversion factor of relevant units.

Commodity code	Commodity	Convert to Lithium content	
		Multiply by:	Unit
282520	Lithium oxide and hydroxide	0.165	t LiC/t
283691	Lithium carbonates	0.188	t LiC/t
850650	Cells and batteries; primary, lithium		
850760	Electric accumulators; lithium-ion, including separators, whether or not rectangular (including square)		

Source: BGS (2016) and Sun et al. (2017).

(3) **GSI3** Maturity of mining policy

In addition to geological and economic factors, mining policy adopted by lithium producing country is an essential factor affecting the global supply (Fraser Institute, 2018). We select the policy perception index (PPI) released by Fraser Institute (2018) to quantify the maturity of global mining policy (see Table 6). The Equation for calculating the indicator is as follows:

$$GSI3 = \sum PPI_i \times \frac{P_i}{P} \tag{2}$$

where PPI_i is the policy perception index of country i. A higher value of GSI3 indicates better lithium security.

(4) **GSI4** Environmental performance

The Environmental Performance Index (EPI) published by Yale University is used to measure environment governance in lithium-producing countries based on Equation (3).

$$GSI4 = \sum_i EPI_i \times \frac{P_i}{P} \tag{3}$$

The EPI is a positive indicator, and an immense value indicates a better environmental situation in the resource country. Therefore, GSI4 is a positive indicator (see Table 7).

(5) **GSI5** Global governance

Taking the global share of lithium production as the weight, six indicators, which are voice and responsibility, political stability and non-existence of violence, government efficiency, regulatory quality, the legal system, and corruption control of global governance, indexed by the World Bank are used to compute the global governance indicator, shown in Equation (4).

$$GSI5 = \sum WGI_{i,n} \times \frac{P_i}{P} (n = 1, 2, \ldots, 6) \tag{4}$$

where $WGI_{i,n}$ is the world governance index of the n_{th} year of lithium-producing country i. Table 8 gives the global governance index of the major lithium-producing countries. GSI5 is a positive indicator.

(6) **GSI6** Global supply concentration

Herfindahl-Hirschman Index (HHI) is used to calculate the degree of global supply concentration of lithium, shown in Equation (5). GSI6 is a negative indicator.

$$GSI6 = \sum \left(\frac{P_i}{P}\right)^2 \tag{5}$$

(7) **GSI7** Balance between production and consumption

Table 3
Indicators for lithium security.

Sub-objects	Dimensions	Indicators	Code	Theoretical direction*	References
Global supply stability (GSI)	Reserve availability	Supply potential	GSI1	+	Chuang and Ma (2013), Feygin and Satkin (2004), Sharifuddin (2014), Wu et al. (2012) and Yao and Chang (2014)
	Stability of lithium-producing countries	Social stability	GSI2	+	Wang and Liu (2015) and Zhou et al. (2020)
		Maturity of mining policy	GSI3	+	EC (2010)
		Environmental performance	GSI4	+	EC (2010)
	Geopolitical factors	Global governance	GSI5	+	EC (2010), Graedel et al. (2012) and Rosenau-Tornow et al. (2009)
		Global supply concentration	GSI6	–	EC (2010), Graedel et al. (2012) and Rosenau-Tornow et al. (2009)
		The balance between production and consumption	GSI7	+	Chuang and Ma (2013), Sharifuddin (2014), Vivoda (2010) and Yao and Chang (2014)
Domestically economic security (DES)	Supply stability	Domestic supply potential	DES1	+	Chuang and Ma (2013), Feygin and Satkin (2004), Sharifuddin (2014), Wu et al. (2012) and Yao and Chang (2014)
		The proportion of China's reserve to the world	DES2	+	Chuang and Ma (2013), Feygin and Satkin (2004), Sharifuddin (2014), Wu et al. (2012) and Yao and Chang (2014)
		The proportion of China's production to the world	DES3	+	Chuang and Ma (2013), Feygin and Satkin (2004), Sharifuddin (2014), Wu et al. (2012) and Yao and Chang (2014)
		Substitution	DES4	+	EC (2010)
		Recycling	DES5	+	EC (2010) and NRC (2008)
	Demand resilience	Apparent consumption increase rate	DES6	–	Chuang and Ma (2013), Sharifuddin (2014), Vivoda (2010) and Yao and Chang (2014)
		The balance between domestic production and consumption	DES7	+	Chuang and Ma (2013), Sharifuddin (2014), Vivoda (2010) and Yao and Chang (2014)
	Market vulnerability	Price volatility	DES8	–	Duclos et al. (2010)
		Net import dependence	DES9	–	Ang et al. (2015), Chuang and Ma (2013), Feygin and Satkin (2004), Wu et al. (2012) and Yao and Chang (2014)
		Import concentration	DES10	–	EC (2010), Graedel et al. (2012) and Rosenau-Tornow et al. (2009)
Coexistence (CEI)		Domestic market openness	CEI1	+	Gulley et al. (2019)
		Overseas ownership	CEI2	+	Gulley et al. (2019)
		International material transformation	CEI3	+	Daw (2017)

Note: * is the link between the theoretical evolution of each indicator and the Li security. The sign "+" is for a positive indicator. The higher value of it illustrates better lithium security. While"-" is for a negative indicator whose impact on Li security is negative with a higher value.

Table 4
Global lithium production and reserves (Unit: tons of LiC).

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018
United states	640	470	600	870	1200	1040	1380	1630	600
Argentina	2950	2950	2700	2500	3200	3600	5800	5700	6400
Australia	9260	12500	12800	12700	13300	14100	14000	40000	58800
Brazil	160	320	150	400	160	200	200	200	300
Chile	10510	12900	13200	11200	11500	10500	14300	14200	17000
China	3950	4140	4500	4700	2300	2000	2300	6800	7100
Portugal	800	820	560	570	300	200	400	800	800
Namibia	0	0	0	0	0	0	0	0	500
Zimbabwe	470	470	1060	1000	900	900	1000	800	1600
Canada	0	0	0	0	0	0	0	0	2400
World production	28740	34570	35570	33940	32860	32540	39380	70130	95500
World reserves	13000000	13000000	13000000	13500000	14000000	14000000	16000000	14000000	17000000
GIS1	452.331	376.049	365.477	397.761	426.050	430.240	406.298	199.629	178.011

Source: Compiled by the authors and based on Daw (2017), Statista (2020) and USGS (2020).

The ratio of global lithium production to consumption is used to express the global lithium balance. When the ratio is greater than 1, the global supply is excessive; otherwise, the supply is insufficient (see Table 9). Global lithium consumption data is from USGS (2020). GSI7 is a positive indicator.

(8) **DES/DES1** Domestic supply potential

China's lithium reserve-to-production ratio measures domestic resource supply potential. The higher the ratio, the higher the degree of supply security. China's lithium resource reserves and production data come from USGS (2020).

(9) **DES2** Proportion of China's reserve to the world

We use the ratio of Chinese lithium reserve to global reserve to quantify this indicator. DES2 is a positive indicator.

(10) **DES3** Proportion of China's lithium production to the world

Table 5
HDI for lithium-producing countries.

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018
United states	0.911	0.914	0.916	0.914	0.915	0.917	0.919	0.919	0.920
Argentina	0.818	0.823	0.823	0.824	0.825	0.828	0.828	0.832	0.830
Australia	0.926	0.928	0.932	0.926	0.929	0.933	0.935	0.937	0.938
Brazil	0.726	0.730	0.734	0.752	0.755	0.755	0.757	0.760	0.761
Chile	0.800	0.812	0.818	0.830	0.834	0.839	0.843	0.845	0.847
China	0.702	0.711	0.719	0.727	0.735	0.742	0.749	0.753	0.758
Portugal	0.822	0.827	0.829	0.837	0.840	0.843	0.846	0.848	0.850
Namibia	0.588	0.601	0.612	0.622	0.631	0.637	0.639	0.643	0.645
Zimbabwe	0.472	0.490	0.516	0.527	0.537	0.544	0.549	0.553	0.563
Canada	0.895	0.899	0.906	0.910	0.914	0.917	0.920	0.921	0.922

Source: Compiled by the authors and based on UNDP (2020).

Table 6
PPI for lithium-producing countries.

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018
United states	57.60	66.23	65.83	83.16	79.50	83.18	81.70	79.25	88.42
Argentina	32.44	31.28	44.28	50.35	49.66	39.12	52.14	58.08	55.78
Australia	63.98	69.02	66.08	83.89	80.37	80.25	80.52	73.97	82.98
Brazil	43.20	43.29	38.19	63.65	59.17	56.57	64.97	55.66	64.43
Chile	81.32	75.30	67.67	85.89	83.16	83.50	78.68	80.55	88.61
China	30.90	43.08	28.51	52.30	42.73	46.22	59.71	37.46	49.39
Portugal	0.00	0.00	0.00	85.48	91.78	89.56	90.30	87.01	93.50
Namibia	57.90	51.58	63.67	81.52	84.44	80.70	77.77	71.11	80.71
Zimbabwe	22.35	21.77	13.44	17.71	13.68	24.67	18.06	29.54	47.68
Canada	72.70	76.10	71.80	85.10	84.70	82.78	86.01	81.26	88.00

Source: Compiled by the authors and based on Fraser Institute (2018)

Table 7
Environmental performance index (EPI) for major lithium-producing countries.

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018
United states	63.48	58.08	56.59	59.95	67.52	77.05	84.72	85.10	71.19
Argentina	61.05	63.53	56.48	48.84	49.55	63.55	79.84	83.42	59.30
Australia	65.66	50.99	56.61	70.02	82.40	88.62	87.22	80.42	74.12
Brazil	63.41	67.12	60.90	53.33	52.97	64.74	78.90	82.02	60.70
Chile	73.34	57.52	55.34	61.31	69.93	76.26	77.67	72.10	57.49
China	49.00	48.34	42.24	39.14	43.00	53.32	65.10	68.89	50.74
Portugal	72.98	58.47	57.64	65.19	75.80	84.62	88.63	85.25	71.91
Namibia	59.28	58.46	50.68	43.30	43.71	55.96	70.84	75.85	58.46
Zimbabwe	47.82	53.56	52.76	49.92	49.54	54.25	59.25	57.86	43.41
Canada	55.60	54.71	58.41	65.09	73.14	80.71	85.06	83.21	72.18

Source: The data of EPI for the year 2010, 2012, 2014, 2016 and 2018 is obtained from SEDAC (2020). Furthermore, the data between the year (which is 2011, 2013, 2015 and 2017) are calculated using cubic spline interpolation (Gülüm et al., 2019; Shao and Zhang, 2020).

Table 8
WGI for lithium-producing countries.

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018
United states	1.25	1.26	1.28	1.23	1.23	1.25	1.25	1.27	1.24
Argentina	-0.27	-0.21	-0.32	-0.34	-0.39	-0.31	-0.05	0.01	0.01
Australia	1.60	1.62	1.61	1.58	1.61	1.55	1.57	1.54	1.58
Brazil	0.13	0.11	0.06	0.00	-0.03	-0.13	-0.14	-0.20	-0.24
Chile	1.22	1.19	1.20	1.19	1.18	1.08	1.01	0.94	1.01
China	-0.58	-0.56	-0.56	-0.56	-0.48	-0.46	-0.43	-0.33	-0.31
Portugal	0.95	0.93	0.95	0.98	0.96	1.06	1.03	1.10	1.07
Namibia	0.31	0.30	0.36	0.37	0.28	0.33	0.34	0.29	0.30
Zimbabwe	-1.56	-1.48	-1.41	-1.36	-1.32	-1.20	-1.22	-1.22	-1.19
Canada	1.61	1.61	1.62	1.61	1.65	1.66	1.68	1.67	1.59

Source: Compiled by the authors and based on World Bank (2019).

The ratio of Chinese lithium production to global production is used to quantify this indicator. DES3 is a positive indicator.

(11) **DES4** Substitution

Silevers et al. (2012) defined the substitution of critical minerals as the potential of the SMs to be replaced by other resources in the terminal sector. The higher the possibility of substitution, the more secure lithium is for China. Referring to Silevers et al. (2012), we define the possibility of Li substitution in Equation (6).

$$Substitution = 1 - Difficulty \tag{6}$$

Table 9
World lithium balance (Unit: tons of LiC).

Indicators	2010	2011	2012	2013	2014	2015	2016	2017	2018
World production	28740	34570	35570	33940	32860	32540	39380	70130	95500
World consumption	24732	24732	26587	28182	31000	49400	36700	39700	49100
GSI7	1.16	1.40	1.34	1.20	1.06	0.66	1.07	1.77	1.95

Source: Compiled by the authors and based on USGS (2020).

where *Difficulty* measures the inconvenience of replacing Li. Silevers et al. (2012) divided the difficulty of substitution into 4 levels: 0 means no additional replacement cost; 0.3 means low replacement cost; 0.7 represents higher replacement cost or more significant performance loss; 1 means the substitution cannot be completed. Due to the unique characteristics of lithium, there are few substitutes for lithium, and almost all lithium substitutes will lead to a decline in product performance. Therefore, we set the difficulty of Li substitutability to 0.7, and the substitution of Li is 0.3.

(12) **DES5** Recycling

Most of the used lithium-ion batteries in China are treated as ordinary waste, and the recycled are designed to recover cobalt and nickel (Hao et al., 2017). As the lithium price rises and China's waste management improves, the recycling rate of lithium is expected to increase. We quantify this indicator based on UNEP (2011), which says the average end-of-life functional recycling rate of lithium is less than 1%. DES5 is a positive indicator.

(13) **DES6** Apparent consumption increase rate

Based on Daw (2017) and Gulley et al. (2018), we can obtain China's apparent consumption of lithium using Equations (7) and (8).

$$AC = P_D + M_N + \Delta S \tag{7}$$

$$DES6 = \frac{(AC_n - AC_{n-1})}{AC_{n-1}} \tag{8}$$

where P_D is China's lithium production, M_N is the net lithium imports, and ΔS is China's lithium stocks, while stock changes are assumed to 0. China's lithium production data comes from USGS (2020). Data on lithium imports and exports are derived from UN Comtrade. DES6 is a negative indicator.

(14) **DES7** Balance between domestic production and consumption

This indicator is complementary and can be computed by subtracting apparent lithium consumption from China's lithium ore and refined lithium production.

(15) **DES8** Price volatility

The domestic lithium spot price in China comes from Qianzhan Dataset (2020), including two products, lithium carbonates (Li_2CO_3) and lithium hydroxide (LiOH), which are compatible with products mentioned on Table 2. To measure the domestic annual change in lithium price in China, we first calculate the average prices of the above mentioned two products from 2009 to 2018, as shown in Fig. 3. Then we use the average price of the two prices as the domestic lithium price in each year and get the indicator DES8 by Equation (9).

$$DES8 = \frac{(p_n - p_{n-1})}{p_{n-1}} \tag{9}$$

where p_n is the lithium price of the domestic market in the n_{th} year. DES8 is a negative indicator.

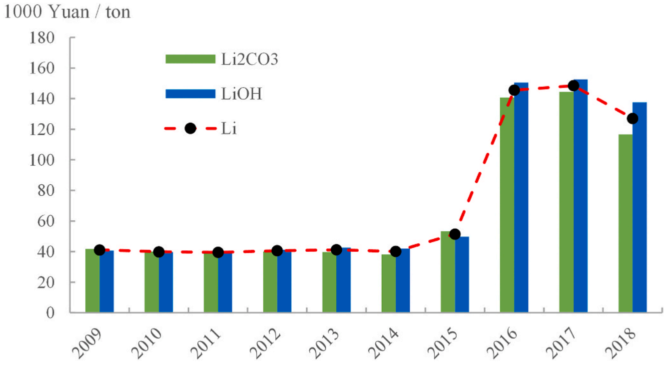

Fig. 3. China's annual lithium price and its composition from 2009 to 2018. The green and blue bar graphs are the annual prices of Li_2CO_3 and LiOH, respectively, calculated by the authors based on the Chinese lithium daily price data from Qianzhan Dataset (2020). The red dotted line with black dots is the annual price of the Chinese lithium market. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

China's domestic lithium price since 2009 can be divided into three phases based on the year 2015 and the year 2017. Before 2015, the price of lithium in China was around 40,000 yuan/ton, with relatively small price fluctuations. With the rapid development of the new energy vehicles industry since 2015, the price of lithium was rising to a peak in 2017 (148478.5 yuan/ton). As a large number of new lithium mines and lithium salt processing enterprises began to build and gradually put into operation in 2018 (SRC, 2018), the industry gradually showed an oversupply (Roskill, 2020), and lithium prices fell. From the perspective of lithium price composition, the price of lithium carbonate was higher than that of lithium hydroxide in the early years. However, with the high probability of ternary lithium battery development towards high nickel ternary battery, the source of lithium will inevitably shift from lithium carbonate to lithium hydroxide monohydrate (Wu et al., 2020), resulting in the prices of lithium hydroxide increased significantly.

(16) **DES9** Net import dependence

The ratio of net imports to apparent consumption in each year indicates the net import dependence. DES9 is a negative indicator.

(17) **DES10** Import concentration

Commodities with the Harmonized System (HS) codes of 282520 and 283691 in the UN Comtrade are used as imported lithium intermediate products, and the concentration of imports is measured using the HHI index. This indicator can be computed as follows:

$$DES10 = \sum \left(\frac{Q_{i,l}}{Q_o}\right)^2 \tag{10}$$

where $Q_{i,l}$ is the quantity of lithium intermediate products l imported by China from country i, and Q_o is the total quantity of lithium intermediate products l imported by China. DES10 is a negative indicator.

(18) **CEI/CEI1** Domestic market openness

Global lithium compounds and lithium metal industry are markets with high barriers and are dominated by a small number of manufacturers (Ganfeng Lithium, 2018). At present, the major listed lithium ore companies in China are Ganfeng Lithium Co., Ltd. (Ganfeng Lithium), Tianqi Lithium Corporation (Tianqi Lithium), Contemporary Amperex Technology Ltd (CATL), Sinomine Resource Group Co., Ltd. (SRG), Tibet Mineral Development Co., Ltd. (Tibet Mineral), Tibet Urban Development and Investment Co., Ltd. (Tibet UDI). The main lithium mine projects in China and their holding companies are shown in Table 10. As shown in Table 10, China's lithium projects are mainly concentrated in salt lakes on the Qinghai-Tibet Plateau (Liu et al., 2017) and are controlled by Chinese companies. Foreign investment has not yet obtained the rights to develop lithium mines in China. Therefore, we quantitatively evaluate the degree of foreign development of China's lithium resource based on the foreign investment guidance policy related to lithium issued by China's National Development and Reform Commission (NDRC, 2007, 2015, 2017; MOFCOM, 2011), and encouraging development is recorded as 1, while restricting is recorded as 0. Before the 2017 edition of the *Guidelines for Foreign Investment Industries* (NDRC, 2007; 2015; MOFCOM, 2011), lithium mining and processing were foreign-invested restricted industries. Therefore, the indicator is recorded as 0 before 2017, and 1 after that to illustrate better lithium security.

(19) **CEI2** Overseas ownership

We check annual reports of listed Chinese lithium companies and pick out the overseas ownership share of the Chinese companies in specific lithium projects (Shown in Table 11) to calculate China's overseas lithium equity since 2010. We then accumulate the current overseas reverses of Chinese companies in each year and calculate its ratio to global reserves as China's overseas lithium rights to measure the degree of overseas market development. The Equation is as follows:

$$CEI2 = \frac{\sum S_m \times R_m}{R} \tag{11}$$

where S_m is the ownership share of a Chinese enterprise in the development of a foreign mine, R_m is the reserves of the mine, and R is the global lithium reserves. CEI2 is a positive indicator.

(20) **CEI3** International material transformation

This indicator takes the entire life cycle of global lithium conversion process into consideration. It assumes that the export of high value-added downstream products can effectively resist the risk of upstream raw materials (Daw, 2017). Drawing on Daw (2017), we quantify the indicator as:

$$CEI3 = \frac{\sum_a X_a - M_a}{\sum_a X_a + M_a}, \quad a = 1, 2 \tag{12}$$

where $a = 1$,2 represent the international trade links of the upstream lithium intermediates and the downstream lithium-containing products respectively. X_a and M_a is China's export and import value for a product, respectively. According to Equation (12), the range of *CEI3* is [-1, 1]. CEI3 is a positive indicator.

3.3. Lithium security evaluation in China

The raw data of each indicator is shown in Supplementary Table S1. Each indicator is measured in inconsistent units, so it is impossible to compare directly (Song et al., 2019). Besides, some indicators with higher values reveal better Li security, such as GSI1, GSI2, DES5, while other indicators with smaller value mean better Li security, such as GSI6, DES6, DES8, DES9, DES10. In order to overcome this issue, we first perform dimensionless processing on the original indicators with Equation (13) and Equation (14) for positive indicators and negative indicators, respectively. After the processing, all the indicators are in the interval [0,1]. This procedure ensures that higher values of indicators indicate better security (see Table 12).

Table 10
China's major lithium project and its holding company.

Holding company	Name of mining area	Acquisition date	Equity ratio	Place	Resource category	Reserves*	Grade**	Current status
Ganfeng Lithium	Ningdu Heyuan	2016	100%	Jiangxi	Spodumene	10(1)	0.0103	Put into production
Ganfeng Lithium	Fenghuangtai Area, Mangya Executive Committee of Qinghai Province	2019	70%	Qinghai	Brine	–(2)	–(2)	Prospecting right
Shenghe Lithium(4)	Zola mine	2008	100%	Sichuan	Spodumene	63	0.013	Mining rights
Tibet Mineral, Tianqi Lithium	Zabuye Salt Lake	2004	100%	Tibet	Brine	183(5)	0.42–1.61(5)	Mining rights
Guoan Lithium	Xitaijinaier Salt Lake	2017	100%	Qinghai	Magnesium sulfate subtype	268	0.22%	Mining rights
Qinghai Dongtaijinaier Lithium Resources Co., Ltd.	Dongtaijinaier Salt Lake		100%	Qinghai	High magnesium-lithium ratio	60	0.6%	Mining rights
Lanke lithium	Chaerhan Salt Lake	2007	100%	Qinghai	Brine	700	0.01%	Mining rights
Qinghai Chaidamu Xinghua Lithium Salt Co., Ltd. (6)	Dahaidan Salt Lake	2017	100%	Qinghai	Brine	–(3)	–(3)	Put into production
Five metals Salt Lake Co., Ltd.	Yiliping Salt Lake	2009	100%	Qinghai	Brine	–(3)	–(3)	Put into production

* In 10000 tons LCE.

** In Lio average grade (Mg/l).

[1] Measured according to Chinese national standards.

[2] Obtaining prospecting rights, no exploration has been conducted, and no lithium resource reserves data are available.

[3] Undisclosed resources and grade data.

[4] Shenghe Lithium is a wholly-owned subsidiary of Tianqi Lithium. The mining right of the Zola spodumene mine has not yet been put into use as a reserve lithium mine asset.

[5] Source from Nie et al. (2010).

[6] Source from Qinghai Province (2017).

Table 11
Chinese company’s overseas lithium shares.

Chinese Enterprises	Overseas mines/ companies	Acquisition date	Equity ratio	Country	Lithium resources (10,000 tons LCE)	Grade (average grade of lithium oxide)/ concentration (mg/L)
Ganfeng Lithium (1)	Mount Marion	2015	43.1%	Australia	270(2)	0.0127
	Pilgangoora	2017	4.3%	Australia	708(2)	0.0127
	Mariana	2014	82.75%	Argentina	190(3)	306
	Cauchari-Olaroz	2017	3.75%	Argentina	1180(3)	585
	Avalonia	2012	55%	Ireland	_(4)	_(4)
Tianqi Lithium (5)	Greenbushes	2014	51%	Australia	878	0.021
	Atacama Salt Lake	2018	25.87%	Chile	220	_(6)
	Atacama Salt Lake	2016	2.1%	Chile		
CATL (7)	North American Lithium	2018	48.44%	Canada	23	_(4)
SRG (8)	Prospect Resources Limited(PSC)	2018	8.41%	Zimbabwe	1883(9)	0.0131

[1] Data from Ganfeng Lithium (2019).
[2] Measured according to the JORC standard.
[3] Measured according to the CIM guidelines (NI43-101).
[4] The project is currently in the early stages of exploration, and no lithium resource reserves data are available.
[5] Data from Tianqi Lithium (2019).
[6] No data.
[7] Data from CATL (2019).
[8] Data from SRG (2019).
[9] PSC owns 70% of the Zimbabwe Arcadia lithium project. According to the financial report released by PSC on December 31, 2017, Arcadia’s recoverable and pre-minable stone reserves are 26.9 million tons, which means that PSC has 18.83 million tons of resources.

Table 12
Standardized data of China’s lithium security indicators and results under baseline weighting scenario.

Indicators	2010	2011	2012	2013	2014	2015	2016	2017	2018
GSI1	1.000	0.722	0.683	0.801	0.904	0.919	0.832	0.079	0.000
GSI2	0.000	0.203	0.202	0.267	0.502	0.612	0.558	0.904	1.000
GSI3	0.105	0.228	0.000	0.829	0.752	0.718	0.709	0.583	1.000
GSI4	0.430	0.015	0.000	0.226	0.616	0.911	1.000	0.895	0.512
GSI5	0.000	0.285	0.142	0.018	0.445	0.303	0.109	0.638	1.000
GSI6	1.000	0.846	0.860	0.958	0.779	0.734	0.893	0.254	0.000
GSI7	0.391	0.574	0.528	0.424	0.312	0.000	0.322	0.861	1.000
GSI	**0.418**	**0.410**	**0.345**	**0.503**	**0.616**	**0.600**	**0.632**	**0.602**	**0.645**
DES1	0.516	0.488	0.443	0.420	0.859	1.000	0.859	0.015	0.000
DES2	1.000	1.000	1.000	0.954	0.807	0.807	0.671	0.059	0.000
DES3	0.993	0.772	0.856	1.000	0.150	0.043	0.000	0.487	0.322
DES4	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300
DES5	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
DES6	0.553	0.736	0.352	0.651	1.000	0.913	0.025	0.000	0.916
DES7	0.502	0.611	0.226	0.187	0.320	0.512	0.058	0.000	1.000
DES8	0.942	0.931	0.913	0.920	0.940	0.783	0.000	0.917	1.000
DES9	1.000	0.832	0.762	0.808	0.272	0.000	0.042	0.449	0.229
DES10	0.579	0.096	0.000	0.526	0.882	0.571	0.919	0.989	1.000
DES	**0.639**	**0.578**	**0.486**	**0.577**	**0.554**	**0.494**	**0.288**	**0.323**	**0.478**
CEI1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000
CEI2	0.000	0.000	0.000	0.000	0.503	0.602	0.528	1.000	0.969
CEI3	0.000	0.122	0.409	0.572	0.658	0.812	0.869	0.899	1.000
CEI	**0.000**	**0.041**	**0.136**	**0.191**	**0.387**	**0.471**	**0.466**	**0.966**	**0.990**
LSI	**0.353**	**0.343**	**0.323**	**0.424**	**0.519**	**0.522**	**0.462**	**0.630**	**0.704**

$$x'_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})}, 1 \le i \le n \tag{13}$$

$$x'_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})}, 1 \le i \le n \tag{14}$$

Where x'_{ij} is the indicator after dimensionless processing, *i* is for the year *i*, and *j* is the indicator *j*. $max(x_{ij})$ and $min(x_{ij})$ are the maximum value and minimum value of the indicator *j*. Taken indicator GSI1 and GSI6, for example, which is a positive and a negative indicator, respectively. For GSI1, $max(x_{ij})$ is 452.331 for the year 2010, and $min(x_{ij})$ is 178.01 for the year 2018 (see Table S1). The standardized GSI1 is in row 2 of Table 12 using Equation (13). Similar to GSI1, $max(x_{ij})$ and $min(x_{ij})$ of GSI6 are 0.422 and 0.269 respectively. After standardization by Equation (14), the value of GSI6 illustrates in row 7 of Table 12.

To evaluate the security of lithium in China, we set a base weighting scenario refereed to Song et al. (2019). Under this scenario, three sub-objects of lithium security are given the same weight, namely 1/3, 1/3, and 1/3, to emphases the same importance to China’s lithium security. Similarly, indicators in each sub-object are given the same weight. Therefore, lithium security index (LSI) in China is calculated by Equation (15):

$$LSI = \frac{GSI + DES + CEI}{3} \tag{15}$$

4. Results and sensitivity analysis

4.1. Main results

The results for three sub-objects for LSI and LSI from 2010 to 2018 are shown in Fig. 4a and Table 12 (see rows 9, 20, 24, and 25,

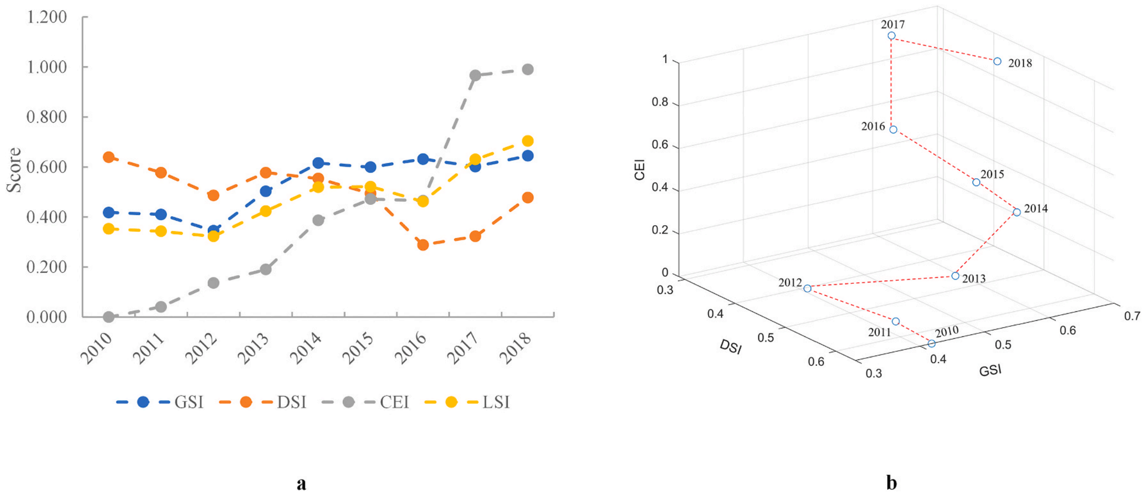

Fig. 4. The scores of China's lithium security index (LSI), global supply stability (GSI), domestically economic security (DES) and coexistence (CEI) and from 2010 to 2018 (a) and its changes (b).

respectively). Among the sub-objects, the most massive improvement observed is in CEI. It increased from 0.000 in 2010 to 0.990 in 2018 steadily. Over the period 2010 to 2013, the increase of CEI was due to the increase of indicator CEI3, revealing the enhancement of China's export of downstream-lithium products during this period. Since 2014, the overseas lithium resources owned by Chinese enterprises were put into production, which increased the rights of China's overseas lithium resources (illustrated by indicator CEI2). The further growth of CEI after 2017 was mainly due to the implementation of the opening policy in China's domestic lithium market (CEI3).

DES decreased from 0.639 in 2010 to 0.288 in 2016 and then increased to 0.478 in 2018. The change of DES was mainly affected by the indicators DES3, DES7, DES9 and DES10. Before 2016, the fluctuated decrease in DES3, DES7, DES9 and DES10 resulted in a decrease in DES. Since 2017, the improvement of the above four indicators increased DES. This shows the key to improving China's domestic security of lithium is to increase the production capacity of domestic lithium resources on the one hand and to continuously optimize the market structure by reducing the excessive concentration of foreign resources on the other hand.

GSI was 0.418 in 2010 and decreased to 0.345 in 2012 and then increased to 0.645 in 2018. The decline in GSI from 2010 to 2012 was attributed to the drop in global lithium supply potential (GSI1), and environmental performance related to resource countries (GSI4). While the increase of GSI from 2013 to 2018 was affected not only by the improvement in indicators GSI1 and GSI4, but also by the increment in GSI2 and GSI5. The change shows that the vital role of geopolitical factors to GSI of lithium resources, and that environmental regulations and social stability of resource countries are important factors affecting the GSI of lithium resources.

The performance of China's LSI in three sub-objects is shown in Fig. 4b. As illustrated in Fig. 4a, China's LSI exposes an upward trend under the joint action of the three sub-objects, increasing from 0.353 in 2010 to 0.704 in 2018. Compared with the other two sub-objects, the value of DES is lower, which indicates that the improvement of domestic lithium security should be further strengthened. As shown in Fig. 4a and b, China's LSI grew significantly since 2016, mainly due to the significant growth of CEI, and this showed the positive effect on China's LSI by opening the domestic market and integrating into the international lithium market.

4.2. Sensitivity analysis

We consider three alternative weighting scenarios using Monte Carlo Simulation (MCS) method (Lal et al., 2019; Tokdemir et al., 2019), and all sub-objects are no longer set as same weights. The maximum weights in scenario 1, scenario 2 and scenario 3 are assigned to GSI, DES and CEI, respectively. For example, DES has a higher weight relative to GSI and CEI in scenario 2 to emphasize the role of domestic supply stability in lithium security, which is consistent with the focus on supply availability in energy security evaluation (Ang et al., 2015a,b; Song et al., 2019; Yao and Chang, 2014). The theoretical basis of the MCS is the law of large numbers, which describes the results of a considerable number of repeated trials by generating a random variable with a known probability distribution. We use Equation (16) to generate weights under the abovementioned scenarios.

$$LSI=\sum_{m} w_m \times I_m \left(\sum_{m} w_m = 1, m = GSI, DES, CEI\right) \tag{16}$$

Where $w_{GSI} \geq w_{DES}$ and $w_{GSI} \geq w_{CEI}$ in scenario 1. In scenario 2 we assume $w_{DES} \geq w_{GSI}$ and $w_{DES} \geq w_{CEI}$, while $w_{CEI} \geq w_{GSI}$ and $w_{CEI} \geq w_{DES}$in scenario 3. The assumed distribution law for w_m is a standard uniform distribution. Namely, all values have an equal chance of occurring within the interval [0, 1]. And then, we rescale them to fulfil the constraint that the sum of the weights is equal to 1. Based on the above method, we conduct 10000 iterations randomly (Li et al., 2014; Nassar et al., 2012) for each scenario, and compare them with the result under the base scenario to test the sensitivity (shown in Fig. 5).

To show the changes of LSI under different scenarios more clearly, according to the eight-scale energy security rating program proposed and applied by Ang et al. (2015a, b) and Song et al. (2019), we provide a rating scheme applicable to the LSI security thresholds, as shown in Table 13.

Fig. 5 shows that although the value of LSI changes in each scenario every year, all scenarios show a common trend, that is, the grade of LSI has risen from "Fair" in 2010 (except "Fair^{+}" in scenario 2) to "Good^{+}" in 2018 (except in Scenario 3, it is "Excellent"). It indicates that the changing trend of LSI is not sensitive to the weighting and that the current evaluation index system can effectively estimate the lithium security in China and has the potential to be extended to estimate the security of other SMs in China.

Furthermore, we compare the changes in LSI values under three additional scenarios (see Fig. 5 and Table S2). The grade of LSI in scenario 3 changed from "Fair" in 2010 to "Excellent" in 2018 with the most significant improvement, and the error band range of scenario 3 was smaller than the other two additional scenarios, indicating that the improvement of CEI had a stable and improving effect on LSI. The value

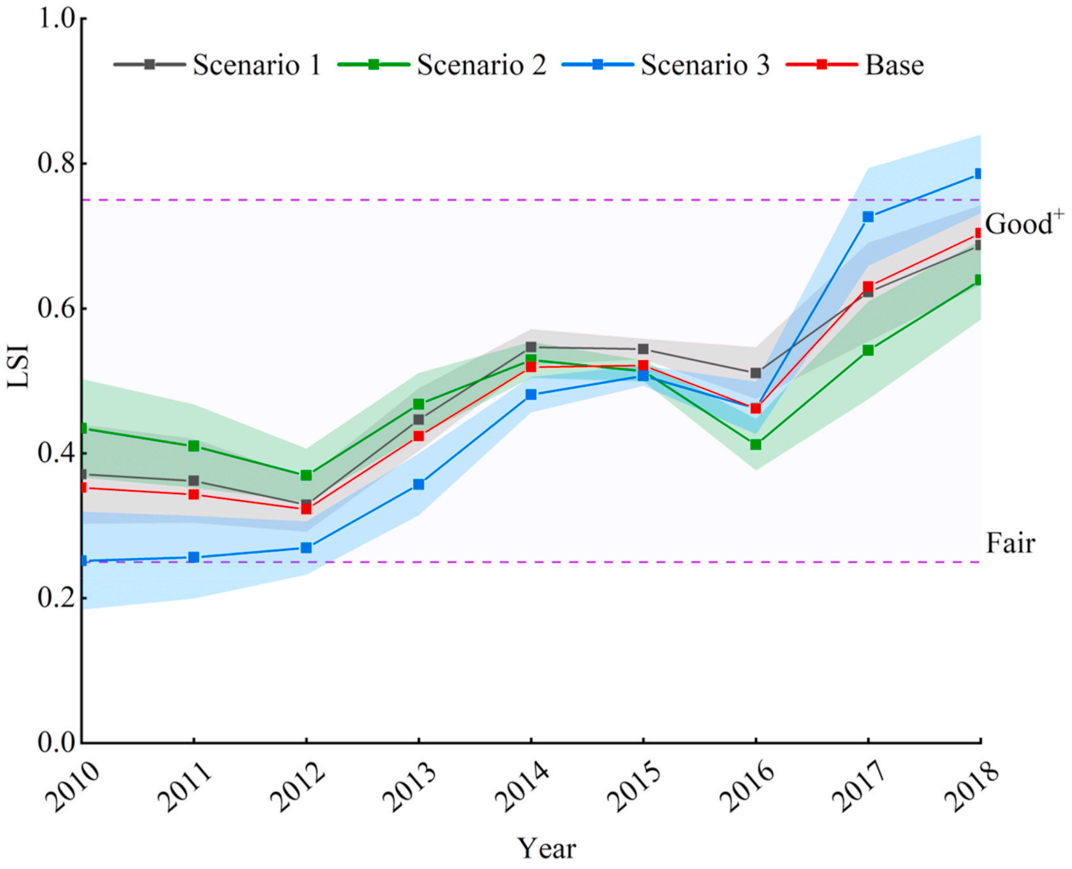

Fig. 5. Lithium security index (LSI) under different scenarios. The colorful solid lines with blocks are the average value of LSI after 10000 iterations under each additional scenario, and dark grey is for scenario 1, green for scenario 2, blue for scenario 3 and red for the base scenario. For the first three scenarios, bands with the same color as solid lines are error bands with one standard error. The two purple dashed lines are the lower boundary of rating "Fair" (0.25) and the upper limit of rating "Good+" (0.75), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of LSI in scenario 2 was with a higher growth rate than the base scenario before 2014. However, the increase of LSI value under this scenario was lower than that of the base scenario from 2015, showing that the increase in DES had a significant effect on the improvement of LSI in the short term. Long-term reliance on DES alone was not the strongest for LSI. The absolute increase of LSI value in scenario 1 was lower than Scenario 3, but higher than Scenario 2, and has the smallest difference from the base scenario, illustrating the positive effect of the stability of global lithium supply on China's lithium security.

Table 13

The thresholds of lithium security. The eight-scale granularity of energy security given by Ang et al. (2015a, b) is in the first column, which divides the value of energy security within the interval [0.4] into eight equal parts. Based on the idea, we give the thresholds for each level of lithium security.

Range of energy security	Thresholds of LSI	Grade
[0, 0.5)	[0, 0.125)	Poor
[0.5, 1)	[0.125, 0.25)	Poor$^+$
[1, 1.5)	[0.25, 0.375)	Fair
[1.5, 2)	[0.375, 0.5)	Fair$^+$
[2, 2.5)	[0.5, 0.625)	Good
[2.5, 3)	[0.625, 0.75)	Good$^+$
[3, 3.5)	[0.75, 0.875)	Excellent
[3.5, 4)	[0.875, 1)	Excellent$^+$

5. Conclusions and policy implications

5.1. Conclusions

From the perspective of global resource governance and considering China's economic transition requirements, we define the security connotation of SMs, and further select lithium as an example to evaluate its security. The study finds that: firstly, China SMs security aims to coordinate national and global securities to realize global governance and sustainable development of SMs. Secondly, the security framework of SMs should consider three sub-objects: the global resource supply stability, domestically economic security, and coexistence of various players in the global industrial chain. Thirdly, the security level of China's lithium resources is rising, and it is closely related to changes in the sub-object of coexistence.

Sensitivity analysis with additional weighting scenarios produced by MCS is used to test the validity of the lithium security evaluation framework, and the results show that the temporal trend of the lithium security in China is consistent. Therefore, it illustrates that the current security framework can effectively estimate the security of China's lithium resources and has the potential to be adapted to evaluate the security of other SMs and this remains for our future research.

5.2. Policy implications

Based on the above results, we put forward policy recommendations for improving China's lithium security.

Firstly, China need to actively integrate into the global lithium industrial chain to improve discursive power on lithium resources. We find that global coexistence is of significance for improving lithium security in China. China has increased its advantage in the global lithium industrial chain by opening up domestic markets, obtaining overseas ownership and promoting exports of downstream products, manifested in the rapid rise of LSI in 2016. To further improve the security of lithium, the Chinese government should encourage domestic enterprises to increase their control over global lithium resources based on the Belt and Road Initiative (BRI), such as through the reorganization of assets or the exchange of projects to increase the development of overseas high-quality lithium resources.

Secondly, China should strengthen the layout of the domestic lithium industry to enhance the economic security of domestic lithium resources. Compared with the other two sub-objects, DES shows a downward trend during the study period. The decline in DES in 2016 led to a drop of LSI, illustrating that DES is the cause of fluctuations in LSI. The fluctuations of indicators DES3, DES7, DES9 and DES10 affect the level of DES. Therefore, China should focus on improving domestic lithium security to optimize domestic resource layout and to improve the balance of supply and demand. China should, on the one hand, reinforce unified planning of the domestic lithium industry from the development of strategic emerging industries to optimize resource allocation; on the other hand, cultivate large enterprises to integrate upstream and downstream operations through the use of supporting policies in taxations, subsidies and loans.

Finally, China has more room to firm regional cooperation aiming to increase the global lithium supply sustainability. The stability of the global lithium supply has improved significantly during the study period. There is little room for improvement in the potential of global resource supply. Therefore, the stable supply of global lithium resources needs to focus on minimizing risks related to the lithium-producing countries and the risk of global governance in the future. Relying on the steady advancement of the BRI, China can lower regional market risk, transportation risk and concentration of import sources through regional cooperation. At the same time, BRI is also an effective means to improve regional cooperation and achieve global governance.

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Declarations of competing interest

None.

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Appendix A. Supplementary data

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