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Research article

Lithium price uncertainties due to the development of battery technology under carbon neutrality target

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ABSTRACT

Driven by carbon neutrality target, a faster low-carbon transition will be required in the sectors of electricity and transportation. As a major support for the transition of these sectors, the diffusion of battery technologies in energy storage and electric vehicles will be accelerated. The battery technologies development relies on the price stability of critical materials (nickel, cobalt, lithium), but the price fluctuations caused by potential supply-demand imbalances would become a bottleneck constraining the low-carbon transition and hindering the sustainable application of low-carbon technologies, especially in regions like China where rapid demand expansion intensifies the need for critical material resources (e.g. lithium). Existing researches have paid limited attention to the dynamic changes in metal market, and simplified the influence of supply-demand shifts, as well as internal & external environments, affecting metal prices. Consequently, this study develops a system dynamics model to forecast the metal prices by taking lithium as a case study. The model characterizes the transmission mechanism between market dynamics and lithium prices, starting with supply-demand shifts driven by the carbon neutrality target. The impact of uncertainties (such as carbon-neutral industry demand, production capacity planning, the lithium futures market, import dynamics, and unexpected events) on prices is also investigated. The results suggest that accelerated development of low-carbon technologies could increase average price by approximately 10 % (0.05 million CNY/ton). Among the uncertainties, active futures trading could push prices up by as much as 3.05 million CNY/ton, while substitute import options could reduce prices no less than 0.2 million CNY/ton.

1. Introduction

By 2023, more than 150 countries have proposed carbon-neutral target in response to intensifying global climate change (Energy and Climate Intelligence Unit et al., 2024). Both the power and transportation sectors are critical to achieving low-carbon target, whose reliance on renewable energy would inevitably drive the scaling up of battery technologies in areas of energy storage and electric vehicles (Attílio, 2025; Zhao et al., 2020). As a critical raw material for electric vehicles and energy storage batteries, lithium metal serves as an indispensable resource for achieving carbon neutrality target (Gebhardt et al., 2022; Bandpey et al., 2024). However, the global distribution of lithium resources is highly uneven, with South America holding the majority of high-quality and large lithium reserves (Mineral commodity summaries 2023, 2023). Despite latest exploration revealing a significant increase in China's lithium reserves, the country's lithium resources still suffer from poor endowment, with low concentration and grade, and development has yet to be fully advanced (Liu et al., 2019). This makes the supply of China's lithium resources vulnerable to international factors, with external dependence as high as 75 % (Liu et al., 2019; Tan et al., 2024). The ambition of countries to achieve low-carbon target has further intensified global demand for lithium resources

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(Aguilar Lopez et al., 2023; Manjong et al., 2024), resulting in violent and frequent fluctuations in lithium prices, with spot prices of lithium salts plummeting by over 80 % in recent years (Sun et al., 2022; Zhang et al., 2024). As current domestic supply falls short of meeting the rapidly growing demand for lithium resources in China, the supply-demand gap will continue to expand, exacerbating cost pressures in the new energy industry through the price transmission mechanism, driving up the costs of the low-carbon transition in sectors such as transportation and power, ultimately constraining the achievement of carbon neutrality target. Therefore, it is imperative to elucidate the price formation mechanism of lithium resources and anticipate future price trends.

The mechanism for the lithium metal price change is highly complex (Marañon et al., 2019), requiring a thorough consideration of the multidimensional factors shaping the interaction between demand and supply capacity (Karan et al., 2023; Deng et al., 2021). Specifically, on the demand side, lithium metal demand in China is influenced by domestic production, export trade, and the futures market. Driven by carbon neutrality target, the transition in the transportation and power sectors has intensified demand for battery production, substantially increasing the resource requirements for domestic manufacturing in China (Shojaeddini et al., 2024; Cervantes Barron et al., 2024; Woeste et al., 2024). Regarding export trade, China supplies substantial volumes of compound lithium products to markets such as Japan and South Korea (Tan et al., 2024; Shi et al., 2023). The rapid increase in resource demand has significantly boosted the activity across China and the global lithium futures markets, establishing these markets as critical drivers of demand. While, on the supply side, overall supply capacity is affected by domestic production capacity planning, import dynamics, and unexpected events (Roy et al., 2024). Future production capacity plans for domestic mines will directly influence the supply scale of domestic lithium resources. Import dynamics are often shaped by factors such as mineral protection policies in the country of origin, export regulations, and geopolitical conflicts, which will result in fluctuations in both import volumes and prices. Unforeseen events related to political, natural, and health events may disrupt normal production and logistics operations, even altering the supply structure. The mismatch between supply & demand over time and location creates gaps that affect inventory turnover rates, making traders to derive expected prices based on historical prices, turnover situations, with costs (Sterman, 2000), and ultimately negotiate to determine the final transaction price. Consequently, accurately forecasting lithium prices requires a thorough analysis of the supply and demand factors (domestic production, export trade, futures markets, domestic production capacity planning, import dynamics, and unforeseen events) as mentioned above, along with simulating the process of inventory, consumption, and their interactions.

However, existing research still exhibits limitations in both the selection of influencing factors and the simulation of transmission mechanisms. Current research is often limited to analyzing specific drivers of resource prices (Wang et al., 2023), with a primary focus on supply and demand fluctuations. However, it lacks a comprehensive exploration of specific supply sources (such as domestic and international production capacity planning (Sun et al., 2019) and international policy constraints (Vikstr et al., 2013)) and demand sources (such as low-carbon technology requirements (Zeng et al., 2013) and financial speculation demand (Lasheras et al., 2015)) in depth. This gap has resulted in biases in capturing price fluctuations, particularly in how supply, demand, and inventory jointly influence overall price dynamics. Additionally, insufficiency exists in modeling the nonlinear dynamic interactions and feedback mechanisms of multiple factors within the price system, hindering a comprehensive understanding of the market's long-term dynamics (Huang et al., 2022). More importantly, prior research that didn't consider the impact of much faster low-carbon transition on the metal demand and then the price are not applicable to future lithium metal price forecasts under carbon neutrality target.

To thoroughly address the uncertainties associated with lithium metal prices driven by low-carbon target, this study comprehensively examines a range of influences, which covers specific supply and demand sources, including domestic mining production capacity planning, foreign policies, and geopolitical conflicts on the supply side, as well as emission reduction requirements under carbon-neutrality target, developments in the lithium futures market, and import/export trade on the demand side. A system dynamics (SD) model is constructed to cover the transmission processes of various aspects such as supply, demand, inventory, trading, and other relevant components in the price forming process. This study simulates the price forming mechanism by integrating the aforementioned factors with the aim of capturing the dynamics of price changes. Based on the SD model, this study innovatively explores the impact of industry transition demands on prices under carbon neutrality target, with further exploration of uncertainties such as domestic production capacity in China, speculative trading, foreign imports, and unforeseen events on lithium prices are further investigated.

The structure of this paper is as follows: Section 2 summarizes the exiting research related to price forecasting for critical metals. Section 3 introduces the system dynamics model developed for forecasting the price of lithium metal, describes the parameters and the scenario settings. Section 4 analyzes the results and Section 5 offers conclusion and recommendations.

2. Literature review

For industries such as electric power and transportation, the irreplaceability of raw materials has led to a serious dependence on materials like nickel, cobalt, and lithium, resulting in price fluctuations in raw materials that pose a risk to the development of various industries (Duclos et al., 2010; Elisa et al., 2007; Yulia et al., 2016). There are many literature related to the metal price forecasts. Sverdrup et al. demonstrated that lithium and other metals (e.g., gold, silver, copper, zinc, nickel, etc.) share significant similarities in price mechanisms and market dynamics, with all their prices are driven directly by supply-demand relationships and trading behaviors (Sverdrup et al., 2020). Based on these commonalities, this paper compiles the critical factors involved in existing price forecasting studies of other metals. For example, Kristjanpoller et al. studied the price fluctuations of gold, silver, and copper, while analyzing the impact of financial factors (such as exchange rates, oil prices, and the stock indices of China, the U.S., and the U.K. across different time horizons (Kristjanpoller et al., 2017)) on price. For nickel price fluctuations, Gu et al. primarily considered the roles of various external financial factors, including opening price, closing price, highest price, lowest price, WTI crude oil price, and the U. S. dollar index (Gu et al., 2021). Regarding copper, Liu et al. considered the impact of financial market indicators in terms of the Dow Jones index (Liu et al., 2017); Hu et al. focused on the impact of shocks, including supply, aggregate demand, and specific demand in the international copper market (Hu et al., 2017); while Chen et al. additionally considered the different mechanisms of impact of supply and demand factors (e.g., global production, consumption, and China's imports) beyond the financial factors (Chen et al., 2019). In contrast, existing research on lithium metal prices is relatively limited. Although several studies have explored the drivers of its price fluctuations (Wang et al., 2023), such as geopolitical risks (Olivetti et al., 2017), natural disasters (Sun et al., 2018), demand from the electric vehicle (EV) industry (Zeng et al., 2013), mining supply (Grosjean et al., 2012), etc., the overall research still focuses on the minority of factors and lacks a systematic analysis of the interaction among these factors. Consequently, this study refers to the various factors considered in other metal price forecast research but still found that existing studies on metal price forecasting tend to emphasize financial markets and primary supply & demand. Additionally, they failed to adequately integrate factors such as the futures market, capacity planning, import/export trade, and their interactions across China and the global market. Simultaneously, they did not fully capture or thoroughly examine supply, demand, consumption, inventory, and import/export. As a result, a systematic consideration of all relevant factors and their interactions is urgently needed in lithium price research to reveal the complexity and potential risks of price fluctuations.

Despite the detailed analysis of price drivers in existing studies (Table 1), the inability to capture complex multidimensional nonlinear interactions has driven metal price research to prioritize advanced forecasting models. In the current research on metal price forecasting, Li et al. examined the volatility and future trend of lithium prices based on time series data using Facebook Prophet and artificial neural networks (ANN) (Li et al., 2023a). Copper price forecasting methods primarily use traditional time series models and machine learning methods such as decision trees (Liu et al., 2017), generalized autoregressive conditional heteroskedasticity (GARCH) models (Smith et al., 2003), complex network combined with ANN (Wang et al., 2019), autoregressive integrated moving average (ARIMA) and neural networks models (Lasheras et al., 2015), along with system dynamics models to simulate the linkage between spot and futures markets, inventory changes, and supply control (Zhu et al., 2019). Nickel price forecasting frequently utilizes deep learning methods such as empirical wavelet transform (Gu et al., 2021), long short-term memory (LSTM) (Shao et al., 2019), enhanced multi-kernel LSTM (Shaju et al., 2021), and gated recurrent unit (GRU) networks (Ozdemir et al., 2022). Common methods used in gold price forecasting include convolutional neural networks (CNN) combined with LSTM (Livieris et al., 2020) and bidirectional LSTM (Liang et al., 2022) and other machine learning methods. In addition, hybrid models have been used for forecasting the prices of various metals, including hybrid ANN-GARCH models (Kristjanpoller et al., 2017), improved wavelet-ARIMA models (Kriechbaumer et al., 2014), and hybrid models based on Prophet model with improved complementary ensemble empirical mode (Huang et al., 2022). In essence, the major limitation of traditional methods lies in their heavy reliance on high-quality historical data and their limited interpretability (Risse, 2019). Moreover, they face challenges in simulating the nonlinear dynamic interactions, feedback, and complex dynamic changes within the internal price system (Huang et al., 2022). Building on these insights, system dynamics offers certain advantages in addressing these limitations by integrating multidimensional data and constructing causal relationships along with dynamic feedback loops, so as to provide a more accurate simulation of the interactions (Zhu et al., 2019; Forrester, 1968; Zhou et al., 2022). Simultaneously, the structure of the system dynamics model is intuitive and transparent, which could clearly illustrate the causal relationship between variables and provide better interpretability.

Table 1
Methods comparison.

Metal	Area	Methods	Limitations		
			Focused Factors Selection	Interpretation Challenges	Deficient Interaction Analysis
Lithium	China	Facebook Prophet & ANN (Li et al., 2023a)		✓	✓
Cooper	Global	Decision Trees (Liu et al., 2017)	✓		
		GARCH(Smith et al., 2003)		✓	✓
		Complex Network & ANN (Wang et al., 2019)		✓	
		ARIMA & Neural Networks (Lasheras et al., 2015)		✓	✓
Nickel	LME	EWT & GBDT (Gu et al., 2021)	✓		
		LSTM (Shao et al., 2019)		✓	✓
		LSTM & PSO(Shaju et al., 2021)		✓	✓
		LSTM & GRU (Ozdemir et al., 2022)		✓	✓
Gold	Global	CNN-LSTM (Livieris et al., 2020)		✓	✓
		BiLSTM(Liang et al., 2022)		✓	✓
Multi-metal	Global	ANN-GARCH(Kristjanpoller et al., 2017)	✓		
		Wavelet-ARIMA (Kriechbaumer et al., 2014)		✓	✓
		Hybrid Model (Huang et al., 2022)		✓	
Metal	**Area**	**Methods**	**Contributions**		
Cooper	China	System Dynamics Model (Zhu et al., 2019)	Integration of Multidimensional Factors		
Lithium	China	System Dynamics Model [this paper]	Enhanced Transparency of Model Structures Improved Model Interpretability Explanation of Variable Relationships Simulate System Interaction Mechanisms		

Building on an understanding of the deficiencies and characteristics of the aforementioned methodology, along with a thorough consideration of key driving factors (such as supply, demand, consumption, inventory, and import/export), this study constructs a system dynamics model to capture the formation and dynamic evolution of lithium prices (Sverdrup, 2016). By simulating the resource import (Vikstr et al., 2013; Olivetti et al., 2017; Sun et al., 2018; Sverdrup, 2016; Habib et al., 2016; Bos et al., 2021) and production capacity (Sun et al., 2019; Kushnir et al., 2012) on the supply side, as well as the development of electric vehicles and energy storage (Zeng et al., 2013; Martin et al., 2017; Narins, 2017), speculative behavior in financial markets (Lasheras et al., 2015; Zhu et al., 2019), and the changes in the export trade on the demand side, the model reveals the feedback mechanisms and dynamic transmission processes involved in the formation of lithium prices. The lithium price is finally projected and the uncertainties are also discussed.

3. Lithium price forecasting model

This study employs a system dynamics approach to simulate how various factors, including industry production, import/export trade, and financial market transactions, contribute to price volatility by influencing changes in supply and demand for lithium, thereby facilitating accurate predictions of future price trends. Following the system dynamics modeling method (Fig. 1), the study first needs to construct a causal loop diagram based on the feedback relationships among each factor. Then, the stock-flow diagram should be established based on real data and mathematical principles. Subsequently, the study should utilize real data to validate the model simulation results and determine the final model. Finally, the uncertainty of future lithium resource prices will be predicted and analyzed based on future demand and supply scales. Based on the research framework, this study first defines four key modules in the simulation model: inventory, price, demand, and supply. The simulation system is then developed through historical data fitting,

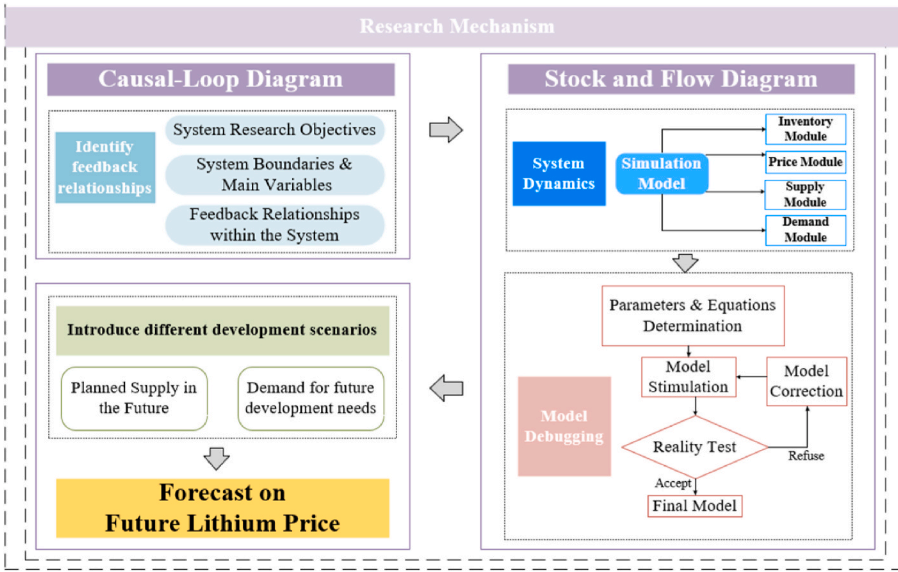

Fig. 1. Framework for model development.

and finally, the price is forecasted by combining the uncertainties in industrial demand for carbon neutralization, capacity planning, lithium futures market dynamics, changes in the import situation, and unexpected events. The modeling process mainly involves clarifying system goals and boundaries, hypothesizing feedback mechanisms and constructing causal relationships, as well as quantitatively analyzing the combined modules to establish stock-flow relationships.

3.1. System boundary analysis

This paper primarily studies the overall lithium-based products market. Among them, lithium carbonate and lithium hydroxide as two core lithium salt products in the lithium industry chain, play a crucial role both in the upstream and downstream industries (Maxwell, 2015; Sterba et al., 2019). Due to their close proximity in both application fields and market prices, and the dominant position of lithium carbonate in the lithium salt market (Wang et al., 2023; Grosjean et al., 2012), this paper takes lithium carbonate as the target for model construction. The system is established based on fluctuations in the lithium carbonate market price, encompassing factors such as historical consumption, inventory, costs, supply, import, export, and market trading rules that contribute to the formation of transaction prices so as to perform the simulation system.

The system variables mainly fall into two categories: the exogenous variables and the endogenous variables. Exogenous variables include imports of lithium carbonate from major production and processing regions (such as Chile and Argentina, etc.) to China, exports from China to countries (such as Japan and South Korea, etc.), domestic mining supply, domestic production demand, speculative demand in financial markets, the CIF (Cost, Insurance, and Freight) price of battery-grade lithium carbonate in Asia, and the domestic ex-factory prices of lithium carbonate in China. Endogenous variables contain inventory, inventory turnover rate, indicative price, expected price, minimum price, etc. However, due to the lack of reliable data for some factors, available data is used as a substitute for these elements. For instance, adjustments in export policies of origin countries are represented by export data.

3.2. Causal loop relationships

The feedback mechanism is the core of the entire system operation, with the causal loop diagram also serving as an important tool to characterize the feedback mechanism of the system. The causal loop diagram contains all the system variables, which are connected by the causal chains to illustrate the hypotheses on the causal relationships within the system. This study takes price as the core focus and identifies the system variables involved in the entire process of price formation from three main aspects: supply, demand, and inventory. This model integrates the relevant factors involved in price formation by utilizing the feedback relationships of each part, thereby forming a causal loop diagram. The feedback relationships in the diagram could be categorized into positive and negative feedback loops. A positive feedback loop generally refers to the increase of a variable or an attribute, setting off a series of reactions that then lead to further increases of the variable or the attribute, ultimately forming a self-reinforcing cycle. Conversely, a negative feedback loop reduces the variable or attribute (Sterman, 2000).

The price of lithium carbonate is influenced by various factors, such as economic development, demand for carbon-neutral industry, supply of China's domestic resources, and international situations. Based on the price formation mechanism, the market price and the causal relationships of its influencing factors are analyzed as follows:

On the demand side, China's overall demand mainly consists of domestic production demand, foreign trade demand, and speculative demand. Domestic production demand in China primarily derives from the need for raw materials for battery production, which is positively correlated with battery production. As the demand for batteries increases, the demand for raw materials also rises. Foreign trade demand mainly comes from export markets such as Japan, South Korea, Canada, etc., where an increase in international trade demand directly drives up total demand, and vice versa. Speculative demand arises from lithium carbonate speculative activity after the establishment of the futures market, which is positively correlated with the open interest.

On the supply side, the scale of supply is influenced by both China and foreign supply sources. Domestic supply sources in China are constrained by domestic mining capacity, which mainly includes domestic mining policy, infrastructure, technology levels, emission requirements, as well as the capacity planning and execution ability of specific mining companies. These supply-influencing factors can be directly represented by China's domestic lithium carbonate production. Foreign supply sources are susceptible to factors such as mineral protection policies of origin countries, export restrictions, together with geopolitical conflicts, etc., whose impacts are directly reflected in the volume of imports.

Inventory lithium carbonate is a gap created by a mismatch between supply and demand, and there is a feedback relationship between inventories and prices (Brissaud et al., 2010). When the price rises, this may indicate a tight inventory, leading to sharp price fluctuations; conversely, price fluctuations tend to be more moderate. In actual trading, traders determine the expected price based on the historical price of lithium carbonate, inventory turnover dynamics with various types of costs. Through the trading process, traders negotiate on the basis of the expected price to finalize the trading price.

By mapping the interconnections among economic, policy, and industry factors that influence lithium carbonate price formation, this study reveals the internal feedback and correlations within the price system and ultimately constructs the causal loop relationship of lithium carbonate price (Fig. 2) (Zhu et al., 2019).

The main feedback loops revolving around the price fluctuations of lithium carbonate are as follows:

(1) Empirical studies demonstrate that the futures market and the spot market display a significant nonlinear cointegration relationship in the long term, with prices tending to converge, which adjusts dynamically according to changes in market conditions (Li et al., 2023b; Gil-Alana et al., 2020; Ameur et al., 2022). Due to the correlation between the futures and spot markets, the prices of both futures and spot contracts tend to follow the same trend. If the price of lithium carbonate futures rises, the corresponding spot price will also increase; conversely, if the futures price decreases, the spot price will follow, forming a positive feedback loop. i.e., **Futures price → + Spot price → + Futures price**

(2) Empirical studies also indicate that there is a significant interaction between futures prices and spot prices, with both realizing dynamic linkages through the price discovery mechanism: futures prices provide information for the spot market, while fluctuations in spot prices also react to the futures market, resulting in a bidirectional feedback mechanism. In addition, as a buffer mechanism to regulate the balance between supply & demand, inventories have a significant effect of adjusting the dynamic relationship between futures & spot prices indirectly by influencing the supply & demand expectations of market participants (Miljkovic et al., 2020). As the increase in lithium carbonate futures prices might trigger an increase in speculative demand and foreign trade demand, it would lead to a reduction in inventories and a subsequent decline in spot prices. This would further trigger a reduction in futures prices due to the linkage between the futures and spot markets, constituting a typical negative feedback loop. i.e., **Futures price → + Demand → - Inventory → - Spot price → - Futures price**

(3) An increasing lithium carbonate futures prices may stimulate an increasing demand in speculation, etc., leading to a reduction in inventories, which in turn could influence the futures market by increasing the convenience yield (the additional benefit of holding a certain spot commodity), ultimately causing a fall in the future's price. i.e., **Futures price → + Demand → - Inventory → - Futures price.**

3.3. Stock-flow relationships

Taking into account the price causality diagram of lithium carbonate, the real-world situation, and the data availability, this paper establishes a price simulation model with four major modules: inventory, price, supply, and demand. Then, further characterizing the evolution process of the stock-flow relationship concerning lithium carbonate. Starting from the supply chain of lithium carbonate products, the total supply of lithium carbonate is mainly composed of domestic mining in China and foreign imports (Zhang et al., 2025). On the other hand, along with the financialization of metals, speculative behavior of market participants exerts a significant influence on the price of lithium carbonate. This leads to total demand for lithium carbonates not only covering battery production demand in China and foreign export trade, but also incorporating speculative demand in the futures market (Zhu et al., 2019). Due to the fact that producers typically transfer costs to consumers, prices in the market for lithium carbonate are generally influenced jointly by inventory turnover rates and costs (Sterman, 2000). For the purpose of modeling the price formation mechanism in the market, this study first derives inventory levels through supply-demand equilibrium, and then simulating the price negotiation process through historical prices, inventory turnover rates, and cost factors, ultimately yielding the stock-flow dynamics of lithium carbonate prices in the domestic market in China, as depicted in Fig. 3:

3.4. Parameters and scenario setting

This section will explain the selection and specific settings of the data for key parameters, followed by a description of the settings for various scenarios, including both conventional and unconventional development scenarios.

3.4.1. Parameter settings and data sources

The model simulates the price variation between 2011 and 2023 with a time step of 1 month. The data used for model construction are compiled from China Customs, Asia Metal Website, Benchmark, company annual reports, and company announcements. This study uses monthly frequency data to fit the configuration needs of the time-step parameters for the system simulation model. The main variables and related parameter settings are shown in Table 2, which are mainly based on the fitting and testing results, as well as the literature (Zhu et al., 2019; Zhou et al., 2022).

3.4.2. Scenario setting

This study constructs a two-tier scenario analysis framework of "technology evolution - risk transmission". Within this framework, the conventional scenario focuses on the endogenous trajectory of low-carbon technologies under the carbon neutrality targets, which

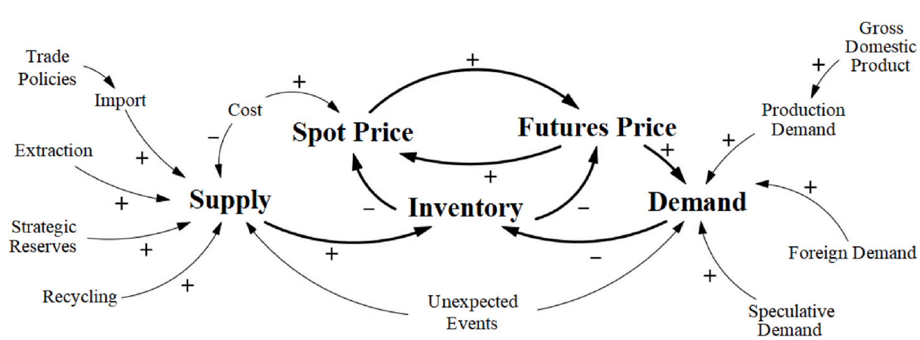

Fig. 2. Casual loop relationships.

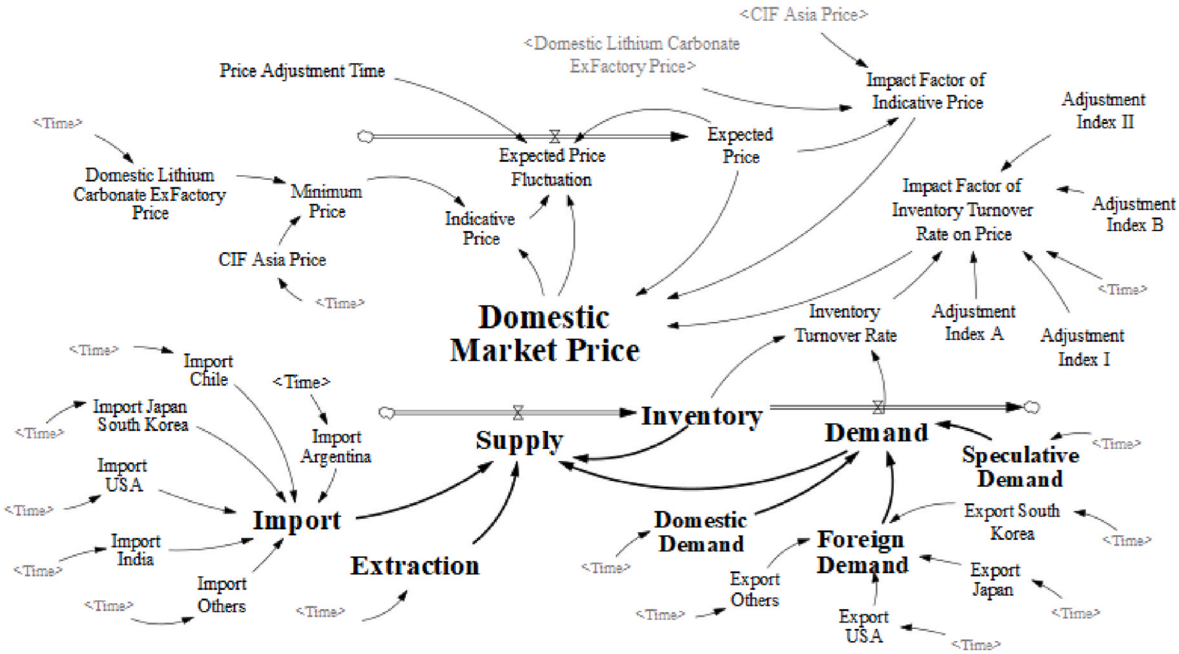

Fig. 3. Stock-flow relationships.

specifies the diffusion rate of low-carbon technologies in terms of electric vehicles and energy storage installations. The unconventional scenario is based on the technological evolution, which incorporates four-dimensional exogenous perturbations related to the development of China's mineral resources, the evolution of financial markets, the changes of trade patterns, and the vulnerability of the system, which forms a dynamic stress-monitoring system. In the following sections, the parameter settings and the nesting logic of multi-dimensional scenarios under this framework will be elaborated systematically.

(1)The conventional scenario (Table 3): It considers only the effects of varying development speeds associated with low-carbon technologies. Based on the national energy technology model (C^{3}IAM/NET) (Wei et al., 2020; Zhao et al., 2021), the development speed of low-carbon technologies such as electric vehicles and energy storage under carbon neutrality target was set to high, medium, and low scenarios (specific parameter settings are shown in Table 3) so as to further forecast the price of lithium carbonate in the next decade. Under the high-speed development of low-carbon technologies, the demand for lithium-ion batteries is expected to grow at an average annual rate of 13.7 %; under medium-speed development, the growth rate is around 13.5 %; and under low-speed development, the growth rate is around 13.1 %. The supply baseline is referred to Bin Lu et al. (2017) for the lithium salt supply forecast in China.

(2) The unconventional scenario (Table 4): Lithium carbonate prices are profoundly affected by unconventional events such as China's domestic mining production plans, futures market development, changes in foreign import policies, and unforeseen events (e.g., suspension of production and work due to pandemics). Therefore, the unconventional scenario builds upon the conventional scenario by incorporating the impacts of unconventional events. This study establishes four unconventional scenarios: (a) production capacity adjustment scenario, (b) futures market adjustment scenario, (c) import dynamics adjustment scenario, and (d) unexpected event scenario to assess the impact of uncertain events on lithium carbonate prices under the carbon neutrality context. This paper forecasts the price trend of lithium carbonate under high, medium, and low carbon technology development assumptions (consistent with the assumptions of the conventional scenarios) for each unconventional scenario and compares the results with those of the conventional scenarios to quantify the effects of these unconventional events.

(a)Production Capacity Adjustment Scenario: Given the current excess lithium carbonate inventory in China, low refining and manufacturing start-up rate, as well as the shutdown and rectification caused by environmental inspections, etc., the future domestic production capacity may suffer from reduction or even complete suspension of supply. Therefore, two cases with production cuts of 20 % and 50 % are set on the basis of the existing capacity situation and the assumption of the conventional development rate that serves as the unconventional scenario under the influence of the domestic production planning in China.

(b) Futures Market Adjustment Scenario: With the gradual improvement of the China's lithium futures market, the increasing activity and scale of financial trading have exerted a considerable impact on lithium carbonate prices. The prediction of future market trends and speculative purchases from investors could rapidly drive prices up or down. Therefore, this paper sets up two cases of active trading and depressed trading to simulate unconventional scenarios under the influence of financial speculation. The depressed trading case is based on the average open interest of lithium carbonate futures (0.004 million tons) at the Bohai Commodity Exchange in China from 2013 to 2016, and the active trading case is based on the average open interest (0.18 million tons) at the Guangzhou Futures Exchange in China, from 2023 to 2024.

(c) Import Dynamics Adjustment Scenario: Policy adjustments such as production cuts and taxes in lithium carbonate-producing countries abroad could alter the import situation (both volume and cost of imports) of lithium carbonate by affecting supply chain flows. This paper sets up a substitution case in which imports from Argentina are increased by 8.5 times to replace Chile as the largest lithium supplier for China, and a disruption case in which all foreign imports are disrupted.

(d) Unexpected Event Scenario: Unforeseen contingencies, such as natural disasters, or health crises, could lead to production disruptions or logistical impediments, further exacerbating market

Table 2
Main variables and calculation process.

No.	Variables	Unit	Calculation Formula/Source
1	CIF Asia Price	CNY/Kg	CIF Asia Price CIF Asia Price (Lithium Carbonate)
2	Supply	Kg	Import + Extraction
3	Import and Export	Kg	Import and Export Statistics (Time)
4	Domestic Market Price	CNY/Kg	Expected Price*Impact Factor of Inventory Turnover Rate on Price*Impact Factor of Indicative Price
5	Domestic Ex-Factory Price	CNY/Kg	Lithium Carbonate Ex-Factory Price in China (Time)
6	Domestic Demand	Kg	Domestic Consumption Volume (Time)
7	Foreign Demand	Kg	Export_Japan + Export_South Korea + Export_USA + Export_Others
8	Inventory	Kg	Supply - Demand
9	Inventory Turnover Rate		Inventory/Demand
10	Impact Factor of Inventory Turnover Rate on Price		For time <129, Adjustment Index A * Inventory Turnover Rate + Adjustment Index I For time ≥129, Adjustment Index B * Inventory Turnover Rate + Adjustment Index II
11	Impact Factor of Indicative Price		1+(0.5*(CIF Asia Price + Domestic Lithium Carbonate Ex-Factory Price)/ Expected Price −1)
12	Extraction	Kg	Domestic Production Volume in China (Time)
13	Speculative Demand	Kg	End-of-Month Lithium Carbonate Open Interest (Time)
14	Indicative Price	CNY/Kg	MAX (Domestic Market Price, Minimum Price)
15	Minimum Price	CNY/Kg	MIN (CIF Asia Price, Domestic Lithium Carbonate Ex-Factory Price)
16	Demand	Kg	Domestic Demand + Foreign Demand + Speculative Demand
17	Expected Price	CNY/Kg	Expected Price Fluctuation + Expected Price
18	Expected Price Fluctuation	CNY/Kg	(Indicative Price - Domestic Market Price *0.5- Expected Price *0.5) * Price Adjustment Time
19	Price Adjustment Time	Second	0.5
20	Adjustment Index A		0.02
21	Adjustment Index B		−0.13
22	Adjustment Index I		1.46
23	Adjustment Index II		1.08

Note: Adjustment coefficients are obtained from regression fittings.

Table 3
Parameter settings for lithium carbonate supply and demand in the conventional scenario.

Time	Domestic Supply (10^4t)	Domestic Demand (10^4t)			Reference
		High-Speed	Medium-Speed	Low-Speed	
2025	52	52	51	50	Yi-Ming Wei (Wei et al., 2020; Zhao et al., 2021)
2030	73	111	109	106	Bin Lu (Lu et al., 2017)
2035	85	187	181	176	

uncertainty and price volatility. Since natural disasters and the health crises will lead to the downsizing of domestic production lines in China, this paper assumes that the contingency will lead to a large-scale suspension of production (80 %), or even a complete shutdown (100 %).

4. Results analysis

This section will provide an in-depth discussion of lithium carbonate price fluctuations under both conventional and unconventional

Table 4
Scenario combination settings.

Scenario Type	Unconventional Impact Factors	Case 1	Case 2
Conventional	None	None	None
Unconventional	Production Plan	20 % Reduction	50 % Reduction
	Futures Market	Active Trading	Depressed Trading
	Import Dynamics	Supply Substitution	Supply Disruption
	Unexpected Events	Large-Scale Suspension	Complete Suspension

scenarios. Firstly, this section will demonstrate the accuracy of the model fitting by comparing the actual data with the simulation results, and then validate the reliability of the model. Under the conventional scenario, this section will analyze the basic price trend based on the different development circumstances of low-carbon technologies in the context of carbon-neutral development. Then, analyses of price evolution under unconventional scenarios will be conducted.

4.1. Model accuracy

This study examines the validity of the model through historical testing, i.e., comparing the difference between the simulated values of the model and the actual values (Zhu et al., 2019). By comparing the model' fitting results with actual prices, it can be observed that the simulation system closely aligns with the overall real price trends (Fig. 4). Except for the 2014–2017 and 2020–2022 periods, the relative errors of the remaining years are all below 10 %. For the periods with large errors, the first period was due to missing data and the second period was during the epidemic. Since the model is established according to the normal market operation law, which may lead to large errors in the simulation results with missing data and unexpected situations. Excluding unusual circumstances, the overall trend predicted by the model aligns closely with actual outcomes, demonstrating a satisfactory model fit. Therefore, it can be considered that the simulation results of the model reflect real-world conditions effectively.

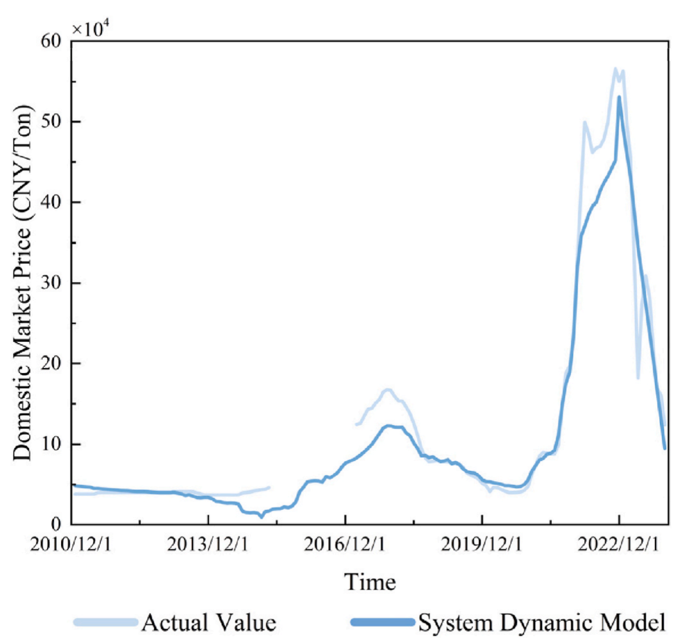

Fig. 4. Historical data fitting. Note: Actual observed data from May 2015 to February 2017 is missing.

4.2. Analysis of conventional scenario results

The study of the conventional scenario reveals that, under the background of carbon neutrality, the impact of the three different development speeds of lithium-ion batteries on lithium prices follows a similar trend of decline followed by a rebound, with a bottoming out point around 2027 (Fig. 5). This initial decline of the price is mainly due to the overcapacity in lithium salt enterprises and the prolonged mismatch between supply-demand cycles. Under the high, medium, and low development speed of low carbon technology, the corresponding lithium carbonate price is in the range of 0.39–0.85 million CNY/ton, 0.37–0.75 million CNY/ton, and 0.32–0.65 million CNY/ton, respectively. Overall, an increase in development speed results in an approximate 10 % increase in the average price (around 0.05 million CNY/ton).

Compared with the low-speed scenario, prices in the high-speed development scenario are approximately 0.2 million CNY/ton higher, and in the medium-speed scenario, the prices are around 0.1 million CNY/ton higher, suggesting that the increased pace of lithium-ion battery development has a cumulative upward pressure on prices over the long term. Strong market demand, technological advances, production efficiency improvements, and optimistic market expectations for lithium-ion batteries collectively contribute to the price increase. Additionally, compared to the price level in 2023, the overall price fluctuation from 2023 to 2035 widens with higher development speeds: under the high-speed development scenario, prices increase by 0.158 million CNY/ton (23.0 %); under the medium-speed scenario, the prices rise by 0.071 million CNY/ton (10.3 %); and under the low-speed scenario, the prices drop by 0.031 million CNY/ton (−4.5 %). This indicates that faster development in lithium-ion batteries industry not only leads to stronger recovery of market demand but also accelerates technological advancements, ultimately resulting in a more rapid price rebound.

4.3. Analysis of unconventional scenario results

The unconventional scenario mainly focuses on the impact of capacity plans, futures markets, import dynamics, and unforeseen events on lithium carbonate prices. By comparing the price trends under these scenarios with those of the conventional scenario (baseline level), the study quantifies the effects of various influencing factors on price fluctuations.

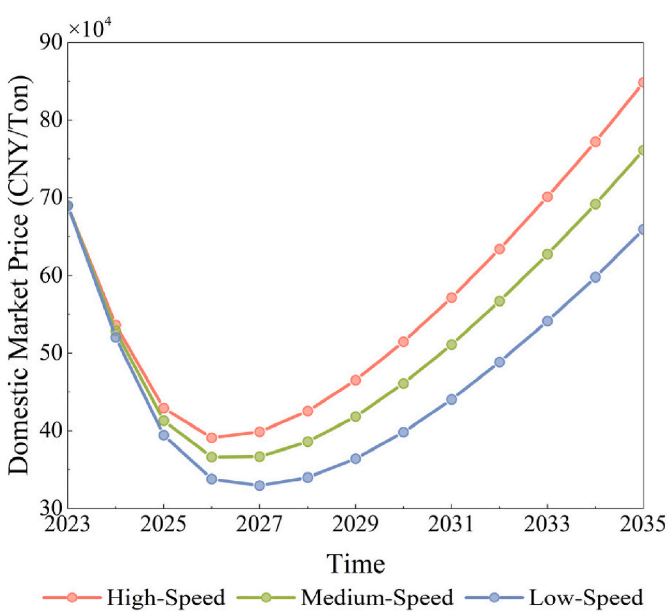

Fig. 5. Lithium carbonate price trend under the conventional scenario.

4.3.1. Impact of production capacity planning

Fig. 6 illustrates the impact of different low-carbon technology development rates and production reduction plans on lithium carbonate prices. Overall, market demand and supply levels are the main drivers of price volatility, with significant increases in prices driven by production cuts. Before 2027, an overall oversupply leads to price declines; however, by 2027, as inventory gets depleted, prices are expected to rise again. Compared to 2023, for the 20 % production reduction, the overall increase over 2023–2035 under high, medium, and low development speed is shown to be 0.445 million CNY/ton (64.4 %), 0.366 million CNY/ton (53.0 %), and 0.274 million CNY/ton (39.7 %), which is relatively moderate compared to the baseline level. Whereas, at 50 % production reduction, prices increased by 0.874 million CNY/ton (126.6 %), 0.808 million CNY/ton (117.0 %), and 0.73 million CNY/ton (105.8 %) under high, medium, and low development speed, with significant increases compared to the baseline, especially drastic in the high development scenario. This price trend confirms the linkage mechanism between futures and spot prices: reductions in supply will lead to a decrease in inventory, which will then drive an increase in futures prices. Coupled with the interdependence between the futures and spot markets, changes in the futures market will be transmitted to the spot market, thereby causing an increase in spot prices. During the current stage of overstocking, the inhibitory effect of the production contraction on prices is weakened by the inventory buffer, which leads to the convergence impact of varying intensity of production cuts. As inventory is exhausted year by year, the long-term production capacity reduction caused by environmental protection or capacity withdrawal works together with rigid demand, resulting in significant enhancement of price sensitivity and reaction strength. Furthermore, differences in the magnitude of production cuts will be translated directly into divergences in price increase intensity.

4.3.2. Impact of the futures market

With the increasing maturity of the futures market, speculative trading has had a significant impact on lithium carbonate prices. Fig. 7 illustrates the price variation patterns of lithium carbonate under different low-carbon technology development speeds and speculative trading conditions. Compared to 2023, the overall price increases during 2023–2035 show that price hikes under all three development speeds are notably driven by the degree of market activity. Under the case of depressed trading, prices under the high-speed, medium-speed, and low-speed development increased by 0.343 million CNY/ton (49.7 %), 0.264 million CNY/ton (38.2 %), and 0.17 million CNY/ton (24.7 %),

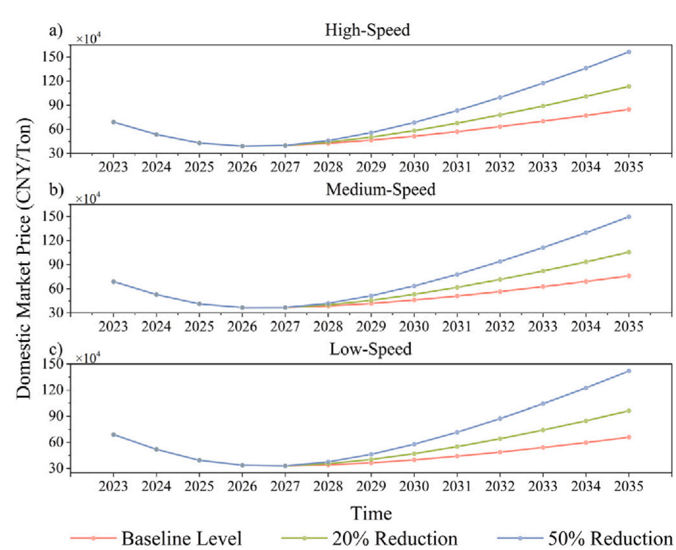

Fig. 6. Lithium carbonate price trend of unconventional scenario: Impact of production planning.

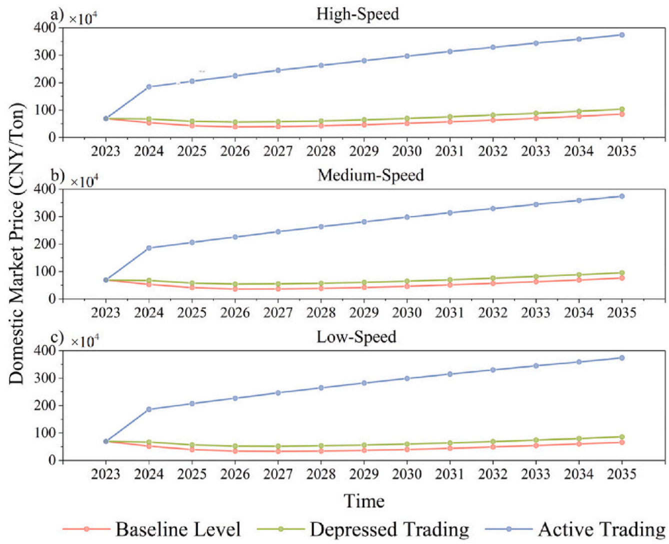

Fig. 7. Lithium carbonate price trend under unconventional scenario: Impact of the futures market.

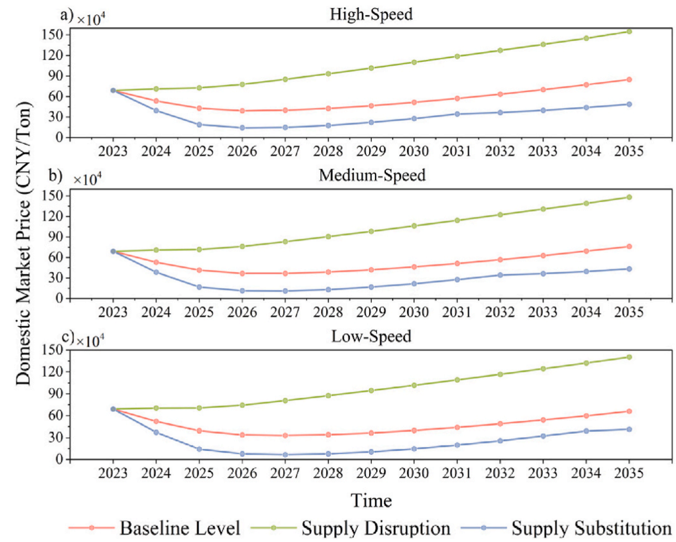

Fig. 8. Lithium carbonate price trend under unconventional scenario: Impact of import dynamics.

respectively, reflecting a moderate increase from the baseline level. However, under the active trading case, the impacts across the three development speeds are almost the same, with prices rising by 3.05 million CNY/ton (442.1 %), 3.049 million CNY/ton (441.9 %), and 3.048 million CNY/ton (441.7 %), which represents even more drastic increases compared to the baseline level, showing the sharp amplification effect on prices caused by highly active speculative trading. The above-mentioned changes reflect the following feedback mechanism: when the futures market activities are relatively active, the futures prices will rise, which also stimulates the expansion of demand. This process both exhausts inventory and drives spot prices higher, thereby triggering another round of increases in futures prices. However, when trading activities are relatively sluggish, this interdependent effect becomes less significant, resulting in a weaker amplifying effect on prices. Speculative trading boosts the price of lithium carbonate regardless of whether the market is in a market phase with active market trading or diminished market participation and weak market liquidity. As market expectations increase, liquidity injections, policy incentives and other factors incentivize speculative trading, lithium price increases more substantial, making speculative demand a crucial driver of dramatic price volatility and price bubbles in markets with high demand for lithium batteries.

4.3.3. *Impact of import dynamics*

Due to the heavy reliance on foreign imports of lithium resources, changes in the import situation on the price are also very obvious. Fig. 8 demonstrates the pattern of price changes for lithium carbonate under the combined influence of different low-carbon technology development speeds and import dynamics. Compared to 2023, the overall increase over the 2023–2035 period shows that prices under the full disruption scenario increase by 0.859 million CNY/ton (124.5 %), 0.792 million CNY/ton (114.8 %), and 0.715 million CNY/ton (103.6 %) for the high, medium, and low development scenarios, respectively. The price increase caused by complete supply disruption is much higher than the baseline level, particularly in the high-speed development scenario. In contrast, when alternative supply exists, the prices under high, medium, and low speed development drop by 0.203 million CNY/ton (−29.4 %), 0.258 million CNY/ton (−37.4 %), and 0.276 million CNY/ton (−40.0 %) separately, demonstrating that substitution of supply is able to suppress price rises effectively, or even lead to reductions. When compared with the baseline level, the alternative supply reduces the price significantly. These phenomena clearly illustrate the operating mechanism of import sources in ensuring supply stability. When imports face disruptions, reduced supply would result in declining inventories, which may drive up prices. On the contrary, when substitute imports take effect, supply will be secured and inventory stability will be maintained, which effectively mitigates price fluctuations. This further reflects the impact of supply stability on prices, as a complete disruption of import channels due to policy restrictions (e.g., export bans), geopolitical conflicts (e.g., political unrest in the origin country) or natural disasters (e.g., shutdowns of foreign lithium mines) would trigger a significant increase in prices, especially in the context of a high-speed development scenario. Conversely, single-country supply risks could be hedged through the development of alternative sources of supply, thereby curbing price increases or even facilitating price reductions.

4.3.4. *Impact of unexpected events*

Under the unconventional scenario, unexpected events also have a significant impact on the lithium carbonate price as well. Fig. 9 demonstrates the price variation patterns of lithium carbonate under the combined influence of different low-carbon technology development

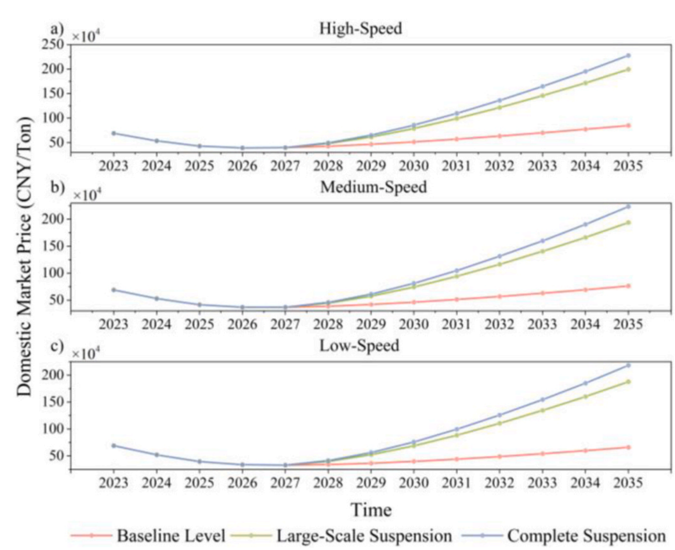

Fig. 9. Lithium carbonate price trend under unconventional scenario: Impact of unexpected events.

speeds and unexpected events. Compared to 2023, the overall price increases during the 2023–2035 period show that under the large-scale production halt case, the price under high, medium and low speed development increases by 1.303 million CNY/ton (188.8 %),1.249 million CNY/ton (181.1 %), and 1.187 million CNY/ton (172.0 %), which is significantly higher than the baseline level. The increase in prices is particularly violent under high-speed development, highlighting its strong push on prices. Under the complete shutdown scenario, the prices under the high, medium, and low rates of development increased by 1.589 million CNY/ton (230.3 %), 1.544 million CNY/ton (223.7 %), and 1.491 million CNY/ton (216.1 %), representing a further increase in the rate of price increase, which is more dramatic compared with the baseline level. The above changes reflect the following feedback mechanism: unexpected events triggered a severe shock to supply, i.e., a sudden reduction in supply, which led to a rapid depletion of inventories, resulting in sharp price increases in both the futures and spot markets. Markets respond to supply fluctuations with a high degree of sensitivity, as sudden-onset natural disasters or widespread infectious diseases could trigger large-scale or complete closures, which could push the price up significantly. The magnitude of price increases is influenced by the extent of supply chain disruptions; greater disruptions will lead to more significant price hikes.

4.4. *Summary of results*

During 2023–2035, the impact of various factors on lithium carbonate prices shows significant variation compared to 2023 under the unconventional scenario. Fluctuations in the futures market have the most pronounced effect, particularly under the high-speed development scenario, where it could rise prices by as much as 442.1 %. Subsequently, a general supply disruption of imports could also lead to significant increases in prices. Adjustments in production plans primarily manifest in the high-speed development scenario. Notably, the substitute supply case under import conditions yields a different outcome compared to other factors—under the high, medium, and low development scenarios, substitute supply leads to price reductions of 29.4 %, 37.4 %, and 40.0 %, respectively, demonstrating that the alternative supply mechanism is able to effectively alleviate upward price pressures under special circumstances and play a unique role of market regulation.

5. Conclusions and policy implications

As a core material for battery technology, the price fluctuations of lithium have profound implications for the promotion of technological development and the low-carbon transition process. Considering the complexity and dynamics of the lithium price formation mechanism, predicting its trend is of great significance for achieving the low-carbon transition. To better understand this impact, this study constructs a system dynamics model guided by carbon neutrality target, incorporating dynamic changes of factors such as low-carbon technology development, production capacity planning, futures market, import dynamics, and unexpected events to simulate the price formation process of lithium. The results reveal that developing low-carbon technologies causes periodic fluctuations and convergence patterns in lithium prices. Prior to 2027, the market will generally experience price reductions due to the overcapacity and mismatch between supply-demand of lithium salts, and then recover steadily, finally reaching a new peak in 2035. As the speed of low-carbon technology development accelerates, the demand for lithium is rising rapidly on the one hand, resulting in a 10 % increase in the average lithium price (about 0.05 million CNY/ton); on the other hand, the price rises more sharply under the high-speed development, with an increase of about 0.158 million CNY/ton (23 %) in 2035 compared to 2023.

Accounting for the effects of production capacity planning, the futures market, import conditions, and unexpected events, lithium prices exhibit notable fluctuations under different development scenarios, with the cumulative effects of these factors exerting a lasting impact on prices. From 2023 to 2035, the production cut plan shows that a 50 % reduction results in an additional price increase of approximately 0.43 million CNY/ton (98 %) compared to a 20 % reduction, demonstrating that the magnitude of price increases far outpaces the scale of supply cuts. In the futures market, high trading activity leads to an additional price increase of around 2.71 million CNY/ton (797 %) compared to low activity, suggesting that price volatility tends to increase significantly as the market becomes more active in speculative trading. Regarding import conditions, a complete supply disruption results in an additional price increase of around 1.06 million CNY/ton (530 %) compared to the substitution scenario, indicating that import dependence significantly exacerbates the market price volatility while diversified supply-chains serve as an irreplaceable stabilizer in dampening the price. In the case of unexpected events, a complete shutdown in production drives an additional price increase of around 0.29 million CNY/ton (22 %) compared to large-scale suspension. The severity of supply-chain disruptions shows a significant positive correlation with price growth, with the effect of this correlation being more dramatic in a market environment of high demand.

Based on the complexity of the price formation mechanism of lithium carbonate and its driving factors, together with the results of this paper, the government and enterprises are recommended to take measures in advance by taking actions in the areas of technological development, resource expansion, market regulation, and emergency response to ensure price stability. First, in terms of implementing the mining production capacity in China, tax incentives and financial subsidies should be provided to encourage enterprises to expand their production scale and support technological research & development so as to improve production efficiency and reduce production costs. The government should also enhance infrastructure to ensure smooth production and transportation for capacity expansion. Then, in the area of resource development, with an increasingly uncertain import outlook and tightening export policies in South American countries, it is essential to support foreign resource development, diversify lithium import channels, and reduce reliance on single-source supplies. Domestic enterprises in China should also be encouraged to explore overseas resource markets to ensure import stability in the long term. Next, with regard to market regulation, the government should monitor the market readily and intervene promptly to curb speculative activities, prevent price manipulation, so as to stabilize market prices effectively. Finally, for contingency response, the government should formulate a detailed contingency response plan and establish a national strategic reserve to ensure stable market supply during critical moments.

Table 5
Lithium carbonate price increase under unconventional scenarios (Variation).

Development Speed	Baseline Level	Production Planning		Futures Market		Import Dynamics		Unexpected Events	
	Variation 10^4 CNY/ton	20 % Reduction	50 % Reduction	Depressed Trading	Active Trading	Disrupted Imports	Substitute Imports	Large-Scale Suspension	Complete Shutdown
High	15.8	44.5	87.4	34.3	305.0	85.9	−20.3	130.3	158.9
Medium	7.1	36.6	80.8	26.4	304.9	79.2	−25.8	124.9	154.4
Low	−3.1	27.4	73.0	17.0	304.8	71.5	−27.6	118.7	149.1

Table 6
Lithium carbonate price increase under unconventional scenarios (Percentage).

Development Speed	Baseline Level	Production Planning		Futures Market		Import Dynamics		Unexpected Events	
	Percentage %	20 % Reduction	50 % Reduction	Depressed Trading	Active Trading	Disrupted Imports	Substitute Imports	Large-Scale Suspension	Complete Shutdown
High	23.0	64.4	126.6	49.7	442.1	124.5	−29.4	188.8	230.3
Medium	10.3	53.0	117.0	38.2	441.9	114.8	−37.4	181.1	223.7
Low	−4.5	39.7	105.8	24.7	441.7	103.6	−40.0	172.0	216.1

Note: Changes and percentages in Tables 5 and 6 are overall changes in prices between 2023 and 2035 compared to 2023.

CRediT authorship contribution statement

Jian-Yu Wu: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Biying Yu:** Writing – original draft, Validation, Supervision, Funding acquisition, Conceptualization. **Gan Wang:** Software, Methodology. **Yi-Ming Wei:** Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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