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Securing the supply of clean energy metals to achieve carbon reduction: a review

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Abstract

Climate change is a major threat to the world. The cause for this global challenge is directly linked to greenhouse gas (GHG) emissions. In order to mitigate climate change, major policies such as reducing GHG emissions are required. Many countries have proposed carbon emission reduction targets at the national strategic level. A crucial issue in achieving the target is low-carbon energy transition, which requires a large amount of clean energy metals as supporting materials. This paper summarizes the latest research results of existing literature on the supply of clean energy metals in achieving the goal of carbon reduction, including the definitions, demand changes, supply capacity assessment, supply risk evolution, supply guarantee and policy system, *etc*. We point out that further research should be conducted in the following three directions in the future: firstly, strengthen research on the impact of trade and geopolitics on the supply of clean energy metals; secondly, further evaluate the effectiveness of minerals security policies in various countries; finally, broaden the analysis of the clean energy metals supply to encompass the entire industrial chain perspective.

Keywords: Carbon reduction, clean energy metals, metal supply, supply guarantee policy, geopolitical risks

INTRODUCTION

With the rapid development of economy and continuous progress of science and technology, human beings now enjoy unprecedented levels of convenience. However, this progress has also brought about a negative impact on climate and environment. Climate change is one of the major challenges of our time. Ongoing climate change has been demonstrated to impact the risk of disasters, human well-being, and terrestrial ecosystems. In the future, how to control GHG emissions will be a key issue in managing climate change. In this context, reducing carbon emissions seems to have become a consensus among countries, with relevant laws, governance plans, strategic plans and so on.

There are slight differences in the understanding of achieving carbon reduction among different countries. China aims to peak its emissions by 2030 and achieve carbon neutrality by 2060. Australia has committed to reducing carbon emissions by at least 26% by 2030. Germany has clearly explicitly outlined plans to incrementally increase the proportion of renewable energy in its total electricity consumption, targeting a level exceeding 80% by 2050. We can see that low-carbon energy transition (Hereafter referred to as energy transition) is the ultimate task for countries to achieve their carbon reduction goals, and each country is willing to reduce carbon emissions to a certain quantitative level at a certain point in time. In order to achieve the goal of carbon reduction, low-carbon energy and low-carbon fossil fuels have become the top priority, and achieving these technologies requires large amounts of metals as the foundation[1]. Therefore, the research objective of this article is to summarize and sort out the supply of clean energy metals within the context of carbon reduction goals, and its latest research results, grasp the current demand, safety situation, and countermeasures of key metals as a whole, and propose effective response suggestions.

Shao and Zhang, Shao *et al.* defined the metals related to clean energy technology as clean energy metals[2,3]. On the one hand, we sort out the metals related to wind energy, hydropower, solar power generation, electric vehicles and energy storage, nuclear energy, biomass energy, geothermal energy, power grid and hydrogen technology from the perspective of the innovation of low-carbon energy technology. On the other hand, we summarize the metals related to low-carbon traditional energy sources such as natural gas and coal from the perspective of the low-carbon technology of fossil fuels. For coal, measures such as efficient combustion technology, flue gas desulfurization and denitrification, fuel conversion, coal gasification and clean coal technology, carbon capture and storage, and energy efficiency improvement can be used to achieve a low-carbon coal system. We combine the research of Shao and Zhang, Shao *et al.*, and other scholars, comprehensively consider the metals used in low-carbon energy technology and the low-carbon process of fossil energy, and further define clean energy metals[2,3].

Secondly, this paper analyzes the future demand and availability of clean energy metals for achieving carbon reduction. In this section, we analyzed existing literature on methods for predicting the demand for clean energy metals. Due to the high uncertainty in the future demand for clean energy metals, we have divided the existing relevant literature into uncertainty in climate policy and environmental protection, and uncertainty in industry development. We have summarized the scenarios set in the literature for these uncertainties. Corresponding to the future demand for clean energy metals, the supply capacity of clean energy metals in the process of achieving carbon reduction is also very important. This article summarizes the analysis methods for the availability of clean energy metals and the influencing factors of clean energy metals availability from five perspectives: geology, economy, technology, environment, and emergencies.

Thirdly, due to the uneven distribution of metals, domestic supply may not necessarily meet one's own needs. Therefore, when achieving carbon reduction, there are risks in the supply of clean energy metals. Based on this, this paper analyzes relevant literature on the supply risks of clean energy metals and summarizes the evolution of the evaluation system for metals supply risks. In recent years, due to trade protectionism and resource nationalism, the supply of clean energy metals has become increasingly serious due to trade risks and geopolitical risks. Therefore, this article focuses on summarizing the impact of trade and geopolitical risks on supply risks of clean energy metals in the existing literature.

Finally, in order to ensure the stable supply of clean energy metals in each country, a series of policies have been proposed, which are an important cornerstone for ensuring the security of clean energy metals supply. This paper combs the policies of the United States, the European Union, China, Japan and other countries on clean energy metal-related industries, and summarizes the evolution trend of policy content and supply guarantee measures.

This paper has the following contributions: Firstly, as an important support for achieving carbon reduction, we have considered the potential challenges of carbon reduction from the perspectives of clean energy metal supply, demand, and policies. Secondly, we have considered the impact of international trade and geopolitical factors on the supply of clean energy metals, which is an important source of uncertainty in the supply of clean energy metals. Finally, we reviewed the security policies for clean energy metals and found a lack of research on the evaluation of policy effectiveness.

DEFINITION OF CLEAN ENERGY METALS FOR ACHIEVING CARBON REDUCTION

In order to achieve carbon reduction, reducing carbon emissions in the energy industry has become the most important issue. Generally speaking, the energy sector can achieve the goal of reducing carbon emissions through two paths: low-carbon energy technology innovation (Wind energy, Hydro energy, Solar power, Electric vehicles and energy storage, Nuclear energy, Biomass energy, Geothermal energy, Power grid, Hydrogen energy) and low-carbon fossil fuels (Natural gas, Coal). Both low-carbon energy technology innovation and fossil energy low-carbon require a large amount of metals as support[1]. Graedel[4] believes that accompanying metals are becoming increasingly important for many carbon-free energy technologies.

Given the important supporting role of metals in clean energy technology, as shown in Figure 1, Grandell *et al.* defined metals that are crucial and scarce for green energy technology as energy metals[5], while Shao and Zhang, Shao *et al.* defined metals related to clean energy technology as clean energy metals[2,3]. In recent years, low-carbon energy technology and fossil energy low-carbon technology have further developed. Based on existing research, Table 1 summarizes the relevant metals used under these two energy transition paths.

From Table 1, it can be seen that there is a bidirectional coupling relationship between clean energy metals and energy transition, which is generally characterized by the diversity and similarity of critical metals that low-carbon energy relies on[8,9]. On the one hand, there is a "one to many" demand relationship, which means that the implementation of a low-carbon technology often relies on the use of multiple critical metals. On the other hand, there is a "many to one" consumption relationship, which means that multiple low-carbon technologies may simultaneously rely on the consumption of a critical metal.

THE EVOLUTION LAW OF THE DEMAND FOR CLEAN ENERGY METALS TO REALIZE CARBON REDUCTION

Prediction method for clean energy metals demand

The prediction methods for clean energy metals mainly include Dynamic Material Flow Analysis (DMFA), full cycle "S" shape law, departmental analysis prediction method, demand analogy, proportional relationship measurement algorithm, system dynamics method, regression analysis prediction, *etc*. Among them, DMFA is the most common multi-scenario analysis method. The prediction principles and relevant literature on various prediction methods are shown in Table 2.

Table 1. Requirements for clean energy metals to achieve "carbon reduction"

Type	Sector	Related energy metals
Low-carbon energy technology innovation	Wind energy	Cu, REE, Ni, Ge, Zn, Al, V, Mo, Nb, Co
	Hydro energy	Cu, Ge, Zn, Al
	Solar power	Cu, Al, Ga, Se, In, Ge, Te, Ag, Mo, Ge, Zn
	Electric vehicles and energy storage	Cu, Cd, Co, La, REE, Li, Ni, Al, Mg, V, Sn
	Nuclear energy	Cu, Ni, Cr, Ag, REE, V, Mo, Sn, Nb, Be, Ni, Co, Ge
	Biomass energy	Cu, Zn, Al
	Geothermal energy	Ni, Cr
	Power grid	Cu, Al
	Hydrogen energy	Ni, REE, Platinum Group Element, Al
Low-carbon fossil fuels	Natural gas	Fe, Cr, Al, Cu, Ni
	Coal	Fe, Cr, Al, Cu, Ni

Source: based on IEA[6]; Zhang *et al.*[7]; Shao and Zhang[2]; Shao *et al.*[3].

Table 2. Prediction methods for clean energy metals demand

Prediction methods	Method principle	Refs.
DMFA	Quantitative analysis of the dynamic evolution characteristics of various metal processes, calculation of the changes in flow and stock, and then estimation of the future demand for metals	[10-12]
Full cycle "S" shaped pattern	According to the "S" shaped correlation between per capita resource consumption and per capita GDP, and the relatively fixed per capita GDP values at the three transition points on the "S" shaped curve. The curve is divided into slow growth zone, fast growth zone, slow growth zone, and zero/negative growth zone. According to this theory, based on the predicted historical resource consumption trajectory of a country, constraint indicators are introduced, transition point parameters are selected, GDP growth plans are set, and the growth trend of per capita resource consumption with per capita GDP is predicted based on the predicted interval resource consumption growth mode. The preliminary prediction results are evaluated by reference indicators, and finally the prediction results are output.	[13-15]
SD method	By studying various feedback loops formed by various internal factors within the system, and collecting data and intelligence related to system behavior, computer simulation technology is used to make long-term predictions of large and giant systems	[16,17]
Regression analysis prediction	On the basis of analyzing the correlation between metal independent variables and dependent variables, a regression equation between variables is established. And the regression equation is used as a prediction model to predict the relationship between dependent variables based on the changes in the number of independent variables during the prediction period. Most of the relationships between dependent variables are expressed as correlation relationships	[18,19]

DMFA is mainly suitable for analyzing and modeling material flow processes, and has been widely applied in fields such as environmental regulation, energy conservation and emission reduction. This method comprehensively tracks the production, transportation, use, and disposal of substances in the socio-economic system, analyzing their material flow characteristics and environmental impacts. It requires a large amount of computation and comprehensive analysis and consideration of the interaction of multiple factors. The S-curve method is mainly applied to predict and analyze market demand, technological evolution, new product sales, and other fields. In general, the development process of a product or service is divided into different stages and uses curve-fitting methods to predict its growth trend. This method is suitable for fields with high market saturation and long product lifecycles. The System Dynamics (SD) method is mainly applicable to quantitative analysis and prediction of complex social systems, ecosystems, *etc*. This method effectively divides the system into multiple subsystems and establishes dynamic models between them, predicting future trends through simulation and other methods. This method is suitable for situations where the system structure is complex and involves the interaction of multiple factors. The regression analysis prediction method is mainly applicable to studying multiple factors that affect a certain indicator and establishing them as mathematical models for prediction. The basic idea is to use statistical methods for regression analysis of data, establish predictive models, and predict future trends. This method is suitable for situations with a wide range of data sources and multiple influencing factors.

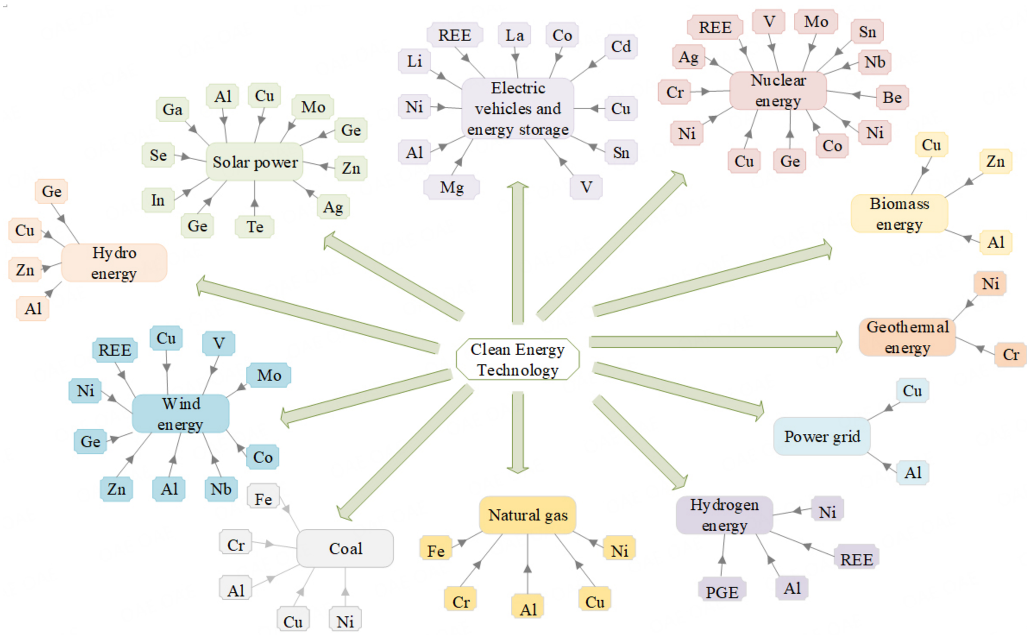

Figure 1. Clean energy technology and their supporting metals. Source: based on IEA[6].

Uncertainty in the prediction of clean energy metals

The future demand forecast for clean energy metals mainly faces uncertainty in climate policies and industry development. The uncertainty of climate policy mainly refers to the changes and adjustments in policies, regulations, and goals in the field of environment and energy by the international community and various countries. The formulation and revision of these policies and goals may have an impact on the demand for clean energy metals, such as the environmental protection and emission reduction policies of various governments, the signing and implementation of international agreements, and energy tax policies. The uncertainty usually has various factors such as politics, economy, and technology, and sometimes is also influenced by international situations and geopolitical factors. The uncertainty of industry development mainly refers to the uncertainty related to the clean energy market itself, including technological innovation, market competition, industry capital flow, consumer demand and so on. This uncertainty is closely related to market mechanisms and is more sensitive to market changes and competition. There is a connection between these two types of uncertainties, mainly reflected in: on the one hand, the uncertainty of climate policy will directly affect the demand and pattern of the clean energy metals market, leading to industry changes, technological innovation, and capital flows in the market; on the other hand, the uncertainty of industry development will in turn affect the formulation and revision of climate policies, thereby adjusting policy objectives and measures.

Scholars have set up a series of scenarios to address the uncertainty of climate policy and industry development. From the perspective of the uncertainty of climate policy, early research mainly set scenarios based on GDP, population, urbanization rate, copper intensity, product lifespan, and some conventional government policies[20-23]. In recent years, scholars have paid more attention to the GHG emission and temperature control requirements issued by relevant international organizations for scenario setting. Tokimatsu *et al.* set scenarios for controlling GHG emissions between 2010 and 2150 through energy and climate policies[24]. Elshkaki and Shen[25] set the IEA current policy scenario, IEA new policy scenario, IEA450 scenario, and National Development and Reform Commission scenario based on government policies, plans, and energy paths.

Habib *et al*. set a baseline scenario, moderate mitigation scenario, and severe mitigation scenario based on the goal of controlling temperature rise at 2 °C[26]. From the perspective of the uncertainty of industry development, Pehlken *et al.* set up dominant and diverse scenarios from the perspectives of consumer travel habits, public clean energy equipment, company development, and technological level[27]. Hao *et al.* may have set four scenarios based on the development of the automotive market and found that vehicle electrification in the heavy-duty segment will increase the demand for lithium, cobalt, and nickel[28]. Li *et al*. set three scenarios: optimistic, neutral, and pessimistic scenarios for China's automotive electrification goals and market share of various types of electric vehicles[29]. Wang *et al.* have found that regional differences in steel production have a critical impact on its global low-carbon process[30].

Evolution trend of clean energy metals demand

With the proposal of carbon reduction, energy transition has become an unavoidable topic. Scholars set different scenarios based on uncertainty in climate policies and industry development to predict the demand for clean energy metals. The general result is that the potential demand for critical minerals in the future is enormous, and the trend of expanding the supply and demand gap is gradually evident[31,32]. According to the calculations of IEA[6], it is expected that by 2040, the total demand for minerals from global clean energy technologies will double in the benchmark policy scenario (STEPS), quadruple in the sustainable development scenario (SDS), and increase sixfold by 2050. In May 2020, the World Bank released a report on "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition", which showed that in SDS, the overall demand for minerals will increase 30 times from 400,000 tons to 11.8 million tons between 2020 and 2040. Watari *et al.* concluded through extensive research that the demand for major metals in the 21st century may increase by 2-6 times[33]. The metal with the highest growth rate in 2050 compared to 2010 is aluminum, followed by critical metals such as copper, nickel, zinc, and lead. With the continuous development of the electric vehicle industry, the demand for lithium will show a rapid growth trend in the future[26,34-37], and may also become an important driving force for the nickel, aluminum, and copper markets. It is expected that the demand for these metals will account for 30.4%, 8.4%, and 6.3% of annual production by 2030[38]. Xu *et al.*, and Maise and Neef believe that by 2040, the future material demand for lithium, cobalt, and nickel in lithium-ion batteries for electric vehicles will exceed current raw material production[39,40].

ASSESSMENT OF THE SUPPLY CAPACITY OF CLEAN ENERGY METALS FOR ACHIEVING CARBON REDUCTION

Factors affecting the availability of clean energy metals

Geological factors

Figure 2 shows the five most important factors affecting the availability of clean energy metals. Geological factors are the primary factors affecting metals availability. Among them, mineral resource reserves are an important constraint indicator for availability evaluation, and the fundamental reason is the uneven distribution of minerals in the world, which is the biggest uncertainty factor affecting the availability of metals[41]. At present, the decrease in ore grade or resource quality usually leads to the extraction and processing of more ore in order to produce the same amount of mineral products[42]. When there are multiple economically valuable metals in an ore body, these metals may be reported as equivalent grades of a single metal. As mining intensity increases and ore grade decreases, it will also lead to a significant increase in energy, material, and water demand related to mineral production[43]. Therefore, in traditional availability evaluation, reserves and grade are important geological factors that affect availability. In addition, the mismatch between resource endowment advantages and mineral resource consumption is also an important factor affecting availability. China is the world's largest producer, consumer, and importer of mineral resources. However, due to the mismatch between its resource endowment and consumption, most

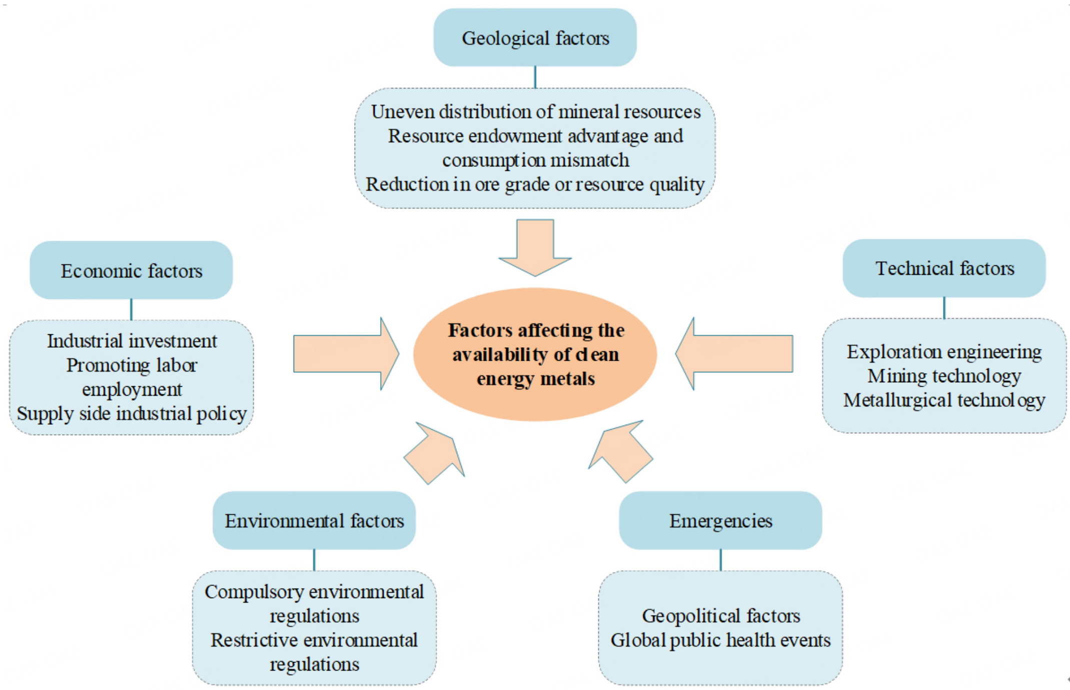

Figure 2. Factors affecting the availability of clean energy metals.

minerals can only rely on imports to meet domestic demand. The supply of mineral resources has been facing shortages, putting China in a disadvantageous global position[44].

Economic factors

Economic factors are important factors that affect availability, mainly on both sides of supply and demand. The fluctuation in the availability of mineral resources is partly due to the imbalance between supply and demand of mineral resources. In the case of known reserves, mineral companies need to consider economic factors to develop mining strategies to ensure the economic feasibility of the project. The National Development and Reform Commission (NDRC) and National Energy Administration of China plan to invest approximately $36 billion in the development of renewable energy over the next 5 years and create 130,000 employment opportunities in this field[45]. The increase in labor force can also improve the availability of mineral resources in China from a technical perspective. In addition, economic growth is closely related to environmental impacts, and with economic growth and human understanding of nature, further strategies and implemented policies will deepen or alleviate the pressure on resource availability to a certain extent[46].

Technical factors

The impact of technology on availability is mainly reflected in the development of low-grade minerals and the increase in ultimate recoverable reserves. Exploration technology directly affects the available reserves of mineral resources, and mining technology directly affects the available production of mineral resources. As proposed by Ali and Ghoneim[47], a silica exploration method using remote sensing data can significantly increase the available reserves of resources. Mining and beneficiation technology is an important factor affecting availability, among which beneficiation refers to the process of improving the value or quality of raw materials or minerals through various physical, chemical, or biological methods. Strengthen the research and promotion of new technologies and processes in the mining, selecting and smelting process, and continuously improve the comprehensive utilization level of mineral resources, such as biological beneficiation technology, fine-grained lean ore beneficiation technology, comprehensive utilization technology of polymetallic symbiotic ore, tailings reuse technology and so on. The formation of a group of independent intellectual property rights in catalytic reactions, equipment, process technology, and other aspects, creating one's own core competitive advantage, as well as the formation of core technologies and advanced equipment for comprehensive utilization of resources, are conducive to reducing the consumption of mineral resources and improving resource utilization efficiency.

Environmental factors

Environmental issues have always been an important factor affecting the development and utilization of mineral resources. Mining operations can lead to serious degradation of the land, water, and air environment. In addition to non-standard electricity use, heavy metal pollution, dust air pollution, Noise pollution and other problems will also occur in water sources[48]. Overall, the environmental factors that affect the availability of strategic critical minerals can be divided into two categories: compulsory and restrictive environmental regulations. Compulsory environmental factors refer to environmental policies that require mines to be shut down, such as the withdrawal policy of mining rights within China's ecological red line, which is a national strategy implemented by the Chinese government to protect ecologically sensitive areas and resources, aiming to ensure environmental sustainability, biodiversity conservation, and overall ecosystem well-being. Restrictive environmental factors mean that the speed and intensity of mineral resources development are affected by strict environmental policies, such as mine geology environmental remediation, *etc*. The introduction of these environmental policies requires enterprises to transform their extensive mining and processing methods, manage and restrict resource exploration and extraction, and thus reduce the availability of resources.

Emergencies

Some strategic critical minerals are often concentrated in individual resource countries and are more susceptible to the impact of unexpected events due to their accompanying small mineral characteristics. On the one hand, international geopolitical factors have a significant impact, such as civil wars in major resource countries or strategic support countries[49,50]. On the other hand, global public health events and other emergencies have a profound impact on it, such as the COVID-19 epidemic[51]. For example, China's mineral resources are mainly imported by sea. The overseas supply chain relies on the South China Sea, Pacific, and land routes, with the value of imports through the South China Sea route accounting for 68%. A single transportation channel can lead to high channel dependence and high safety risks. If sudden factors such as war or other natural disasters block transportation channels, more than half of mineral imports will be blocked and supply will be interrupted. When an emergency occurs, the availability of mineral resources will experience a sharp decrease. As the event continues, the availability will gradually decrease. After the event ends, the availability will gradually increase until it returns to its pre-time level. At the same time, the scale of unexpected events can also affect availability. When an emergency occurs in a resource country, if there are alternative resource countries, the availability of mineral resources is less affected. When some mineral resources are concentrated in a few resource countries, they can obtain new geopolitical leverage by cutting off the supply of critical metals, which poses a significant risk of supply interruption. Therefore, the duration and scale of emergencies have a significant impact on the availability of strategic critical minerals, and are important factors in the availability of strategic critical minerals.

Methods for analyzing the availability of clean energy metals

Based on the meaning of mineral resource availability, scholars have begun to explore analytical methods for mineral resource availability. Scholars estimate the availability of resources according to the reserves and mining output of mineral resources. Initially, academia and industry generally used the storage and extraction ratio of mineral resources to calculate the availability of mineral resources[52,53]. Due to the static characteristics and harsh assumptions of storage production ratio analysis, scholars later proposed the widely used Hubbert model, which draws a Hubbert curve based on resource extraction rate and total exploitable resources to analyze the availability of different mineral resources[54-56]. Recently, some scholars have combined the Hubbert model with other models to analyze the availability problem[57]. Wang *et al.* analyzed the availability of natural gas using the multi-cycle Hubbert model[56].

In addition to the Hubbert model, the Weng circle model (also known as the Poisson circle model)[41,58], the CAC curve[59-61], SD[17,62], and neural networks[63,64] are also considered effective methods for analyzing resource availability. The details are shown in Table 3.

Clean energy metals availability

The availability of clean energy metals is an important foundation and guarantee for achieving energy transition and low-carbon economy[74]. As a key material for new energy electric vehicles, the supply and demand of lithium-ion batteries have become a focus of attention[75]. The focus of the battery manufacturing industry has always been on China. For example, although Nevada's super factories are expected to reach 2020 gigawatts of production capacity by the end of 35, China's production capacity may be almost twice that by the same year[76]. However, facing a huge supply and demand gap, there is a higher possibility of lithium supply shortage in 2050 than in 2021[77]. With the support of secondary recovery and nickel-based element production, the supply of cobalt can better meet the demand of 2030[78]. Elshkaki *et al.* believe that under the premise of safety first, considering environmental pressure, the cumulative production of global copper will exceed its current reserves around 2040[79].

RISK EVOLUTION OF CLEAN ENERGY METALS SUPPLY TO ACHIEVE CARBON REDUCTION

Supply risk assessment system

Due to the limited literature directly targeting the supply security of clean energy metals, and considering the significant similarity of mineral resources in supply security, we also include literature on risk assessment of mineral resources supply other than clean energy metals in this section. In the early stage, evaluation indicators for the supply security of mineral resources were mainly proposed based on resource characteristics and application scope, as shown in Table 4. It mainly includes the stability, external dependence, market concentration ratio of resource countries[81-83], resource stocks, supply and demand, and prices[80,81]. Yao and Chang[91] constructed a 4-As quantitative evaluation framework for energy security from the perspectives of energy resource availability, technological applicability, social acceptance, and affordability. Song *et al.* constructed a new comprehensive indicator, namely the China Energy Security Index (CESI), based on the energy supply dimension, economic and technological dimension, and environmental dimension of energy security[92].

In recent years, the game among major countries has become increasingly fierce. Geopolitical events such as "Sino-US trade friction" and "Russia-Ukraine conflict" have caused great negative externality to the stability of global resource supply, and the clean energy metals market closely related to energy transition technology bears the brunt. In addition to supply risks caused by resource characteristics and technological factors, supply risks caused by trade and geopolitical risks have become undeniable factors and have affected the development of clean energy technologies and markets.

In terms of the evaluation methods for the safety of mineral resources supply, the research mainly focuses on qualitative analysis and quantitative analysis, as shown in Table 5. The qualitative analysis method

Table 3. Availability analysis methods (evaluation results)

Usage method	Method principle	Refs.
Production storage ratio	The ratio between mineral resource reserves and annual production, used to evaluate and predict the sustainable mining capacity of mineral resources	[52,53]
Hubbert model	A classic oil resource extraction prediction model that predicts future changes in oil production based on key indicators such as the inflection point (i.e., peak) of the oil production curve and oilfield development speed	[54-56]
Hubbert model + Copula function	On the basis of the Hubbert model, the Copula function is introduced to consider the correlation between multiple factors, thereby more accurately predicting changes in oil production	[56,57]
Generalized Weng's model	This model is an extension of the Weng Model and is suitable for various types of mineral resource evaluation and prediction. It can consider multiple factors, including the geological characteristics of the deposit, exploration degree, mining technology, market demand, *etc.*	[58,65,66]
Generalized Herfindahl model	It is mainly used to evaluate and predict the market competition pattern, and judge whether there is monopoly in the market by considering the market share and market concentration ratio of different manufacturers	[67-69]
Process for evaluating mine availability in the United States	It is a standard process used by the US government for mineral resource management and development, mainly involving geological exploration, reserve assessment, market demand analysis, and other aspects, in order to develop sustainable mineral resource management policies	[70]
Availability Analysis System	It is a sustainable development and management system for mineral resources based on GIS (Geographic Information System) and database technology, which can achieve spatial distribution and availability analysis of mineral resources, thereby better managing and developing these resources	[71,72]
Agent model	It is a model based on the interaction and game theory between agents, suitable for studying market competition, investment decision-making, and other issues	[73]
CAC curve	The CAC (Cumulative Abundance Curve) curve is used to evaluate the distribution of natural resources in different geographical locations or years, and to describe their details and distribution patterns by calculating the cumulative distribution of biological species or mineral resources	[59-61]
SD	It is a system analysis method based on system thinking, which can establish a dynamic equilibrium model of multiple systems, simulate and predict the evolution process of the system, in order to achieve system optimization and sustainable development	[17,62]
Nervous system	By utilizing the modeling and prediction capabilities of neural networks, complex data can be quickly processed and highly accurate prediction models can be established, which have wide applications in complex mineral resource mining and market prediction	[63,64]

Table 4. Evaluation Indicators for Mineral Supply Safety

Number	1	2	3	4	5	6	7	8	9	10
Proportion of reserves/production in the world	√	√	√				√		√	√
Reserve and production ratio	√	√	√	√			√	√	√	√
Externally dependent degree	√	√	√	√	√	√			√	√
Mine industrial capital investment	√				√	√	√			√
Resource country risk	√	√		√	√	√		√	√	√
Concentration ratio of production/ import	√	√	√	√	√	√	√	√	√	√
Price fluctuations	√	√		√	√	√	√		√	
Demand growth rate				√	√	√				
Recycling potential		√		√	√	√	√	√	√	√
Substitutability					√	√		√	√	√
Byproduct attributes					√	√		√		
Refs.	[80]	[81]	[82,83]	[84]	[85]	[86]	[87]	[88]	[89]	[90]

mainly relies on the knowledge and experience of experts to determine the degree of various resource supply risks. Quantitative analysis mostly involves selecting evaluation indicators and then using methods such as analytic hierarchy process, entropy method, and principal component analysis to assign weights to them. Then, the annual scores of a certain mineral are calculated longitudinally according to the time series, which enables the analysis of the magnitude of supply risk for each year. Alternatively, multiple minerals can be assessed horizontally to facilitate a comparison of the magnitude of supply risk among them[80,81].

Table 5. Comparison of common methods for mineral supply safety assessment

Method	Advantage	Disadvantage
AHP	Complex decision-making problems can be transformed into multi-level, single-objective pairwise comparisons	Expert scoring is required to assist in operation, with strong subjectivity
Delphi method	Be able to fully leverage the experience and advantages of experts and gather ideas	There may be a certain degree of subjective one-sidedness, making it difficult to distinguish subtle differences in various indicators
Topsis	Method for detecting the distance between the evaluation object and the optimal solution	Highly influenced by the data itself
Principal Components	Can intuitively analyze the evaluation indicators that play a decisive role and have a significant impact on the comprehensive evaluation results	There is too much dependence on the main indicators, making it difficult to construct an evaluation index system
Entropy weight method	Comply with mathematical laws, have strict mathematical significance, and avoid subjectivity in weight assignment	Neglecting the importance of the indicators themselves may differ significantly from the expected results

Liao[93] constructed an evaluation index system for China's lithium supply security from four dimensions: resource extraction security, domestic supply and demand security, import market security, and resource country stability. They used the entropy-weighted TOPSIS model to evaluate the security trend of China's lithium resource supply. Zhou *et al.* first elaborated on the safety connotation of strategic mineral resources[89], and constructed a safety evaluation index system that includes three primary indicators: global resource supply stability (GSI), domestic resource economic security (DSI), and preferential coexistence (CEI), as well as six secondary indicators such as resource endowment, geopolitics, and demand. Taking lithium resources as an example, the safety of SM in China was evaluated.

Risks in clean energy metals supply caused by international trade

The global production of clean energy metals is mainly concentrated in several countries. According to IEA[6], DRC and South Africa both produce over 70% of cobalt and platinum, China produces 60% of global rare earth, Australia produces over 50% of lithium, and India, the Philippines, and Russia produce over 50% of global nickel. In addition to different resource endowments, manufacturing developed countries such as China, South Korea, Japan, and the United States will import these metals for industrial processing, ultimately consuming them in densely populated countries or regions such as the United States, the European Union, China, and India. Due to the uneven distribution of global mineral resources, international trade has become an important source of supply for global strategic mineral resources[94,95].

In recent years, some scholars have established international trade network models to study the global trade and competition patterns of different mineral resources, and select quantitative indicators such as degree, intensity, intermediation, and intimacy to study their trade patterns and evolution from different perspectives[96-99]. Other scholars have applied competitive networks to study the national competitive landscape and implicit supply risks of strategic resources, identifying the countries and regions with the most concentrated competitive relationships among minerals, as well as the factors that affect the stability of international mineral resource supply[100-102].

In the existing literature, the supply of clean energy metals triggered by international trade has the following points. First, the export and import concentration ratio is high, some resources are monopolistic, and trade is characterized by a “small world”. The trade is centered on countries with rich resources, and the core countries of trade have strong control over the entire trade network. Secondly, the trade network presents a clear core-edge structure, with a more uneven distribution of trade relations. Core countries trade frequently, while peripheral countries trade sparsely. The number of countries at the core of the trade network is increasing year by year, and the trade volume differences between countries are decreasing. Third, there is the Pareto principle in international trade. A few countries have the majority of trade relations, and about 90% of the competition intensity comes from about 10% of the competition relations. Finally, regional competition has shifted towards global competition, and countries tend to import mineral resources from countries closer to their own countries with a weaker trend. Competition between industry chains is gradually moving towards integration[100,101,103-106].

The impact of geopolitics on the risks of clean energy metals supply

After the "Russia-Ukraine conflict", the entire mineral resources market and global trade have been seriously impacted, and the geopolitical impact on the clean energy metals market has also received unprecedented attention. The risks caused by geopolitics mainly penetrate into various links of the resource industry chain from aspects such as resources, trade, technology, capital, *etc*.[93,107,108]. Usually, resource sovereignty parliaments engage in geopolitical competition by restricting resource supply and regulating trade, while high-tech countries engage in technological blockades, enterprise sanctions, and other means. These competition strategies can lead to reduced resource extraction, blocked or even interrupted trade channels, and have an impact on trade relations, resource prices, and capital markets[1,109], as shown in Table 6 below.

The impact of geopolitics on the risk of clean energy metals supply is mainly evaluated from two aspects: first, building a geopolitical risk index and using measurement methods to analyze its impact on resource market prices, capital markets, *etc*.[119-121]; The second is to use geopolitics as a dimension of comprehensive evaluation to evaluate critical metal supply risks[93,122]. Nassar, Brainard, Gulley, Manley, Matos, Lederer, Bird, Pineault, Alonso, Gambogi, and Fortier[123] studied the geopolitical risks of strategic mineral resources supply security from aspects such as trade relations, sharing mechanisms, and military cooperation, and comprehensively evaluated the supply risks of mineral products in the US manufacturing industry.

CLEAN ENERGY METALS SUPPLY GUARANTEE AND POLICY SYSTEM FOR ACHIEVING CARBON REDUCTION

Policy review

The achievement of carbon reduction and the development of low-carbon energy technologies cannot be achieved without a stable and sustainable supply of clean energy metals. In response to the increasing demand for clean energy metals and rising supply risks, different countries have proposed a large number of supportive policies.

The United States has long been at the top of the resource interest chain. Relying on its enormous advantages in industry standard setting, technological level, funding, and international political relations in the clean energy industry, the United States has formulated a series of policies that are conducive to the security of resources and industry development. Due to China's vast industrial system, it requires a large amount of metal resources as support. However, China's own resource reserves are not sufficient to fully support current industrial activities. Therefore, on the one hand, China's policies improve strategic reserve policies, and on the other hand, enhance the resilience of the mineral resources supply chain to ensure that these resources are less affected by unexpected events. Due to the scarcity of domestic resources, Japan tends to propose policies to increase domestic reserves and recycle resources. As Australia and Canada are countries with rich resources, they will establish resource diplomacy through their own resource advantages and propose policies that are conducive to foreign investment.

Supply guarantee measures

In order to ensure the smooth transition of the energy system from fuel intensive to material intensive, countries and regions such as the United States, Australia, the European Union, Japan, and Canada have

Table 6. The competition behavior of geopolitical actors under geopolitical emergencies

Geopolitical emergencies	Competition behavior	Specific means and their impact	Refs.
Russia-Ukraine conflict	Resource export restrictions; Interruption of trade channels; Technical blockade; Capital controls	Prohibiting the import of oil, natural gas, and coal to Russia, exacerbating the global energy supply and demand conflict; Cancellation of routes to Russia, disrupting shipping activities in the Black Sea region; Restricting technology exports to Russia; Restricting financial market activities in Russia and freeze related assets	[110,111]
Sino-US trade friction	Resource export restrictions; Technical blockade	Increase trade tariffs between China and the United States, resulting in a decrease in China's high-tech product exports; Initiate chain transfer of foreign capital industry, and reduce technology spillover effect	[112,113]
Conflict minerals control policy	Resource export restrictions; Capital controls	Prevent enterprises from participating in the trade of conflict minerals; Cut off business dealings with mining enterprises in conflict areas	[114,115]
Indonesia's nickel ore export ban	Resource export restriction	Restricting the export of low-value nickel ore has led to a sharp expansion of global nickel ore smelting capacity and severe price fluctuations	[116,117]
The six-day war	Resource extraction restrictions; Interruption of trade channels	Rising risks in oil and gas resource extraction and trade; The Straits of Tiran was closed and the trade channel was blocked	[118]

successively introduced more comprehensive mineral resource strategies, as shown in Table 7. Overall, firstly, from the perspective of safety level testing, in order to improve the security of metal mineral supply, these countries have proposed policies related to the productivity, technological level, competitiveness, and maintenance of domestic resource security and stability of clean energy metals from multiple dimensions. Secondly, from the perspective of resource recovery and substitution, countries focus on developing new technologies to improve the recycling and processing capabilities of resources and enhance their substitutability. Thirdly, from the perspective of sustainable development, countries adopt energy-saving and emission reduction measures, pay attention to circular development, advocate environmental protection, and improve sustainability. Fourthly, from the perspective of increasing domestic supply, countries have proposed policies to enhance the exploration and mining capabilities of critical minerals, develop alternative technologies, and enhance recycling and resource recycling technologies. Fifth, from the perspective of the diversification of international supply, policies of various countries tend to increase overseas investment, establish resource diplomacy, and strengthen the global supply chain of important mineral resources in their own countries.

CONCLUSION

This paper starts with the process of carbon reduction, defines the connotation of clean energy metals, and considers the analysis methods for predicting the future demand for clean energy metals in the existing literature and the uncertainties faced in the future. At the same time, the analysis methods and influencing factors of the future availability of clean energy metals are analyzed. Furthermore, we analyze the significant impact of international trade and geopolitical factors on the risk of clean energy metal supply. Finally, ensuring the supply of clean energy metals during the process of achieving carbon reduction requires policy support. This article summarizes the policy measures proposed by major countries around the world.

In order to achieve carbon reduction targets, we suggest that further research on clean energy metals should also be carried out in the following aspects. First, due to the uneven global distribution of clean energy metals and the frequent occurrence of geopolitical events such as trade protectionism and resource nationalism, it is necessary to focus on how clean energy metals are affected by trade and geopolitics, the

 Shao *et al. Carbon Footprints* 2023;2:16 | https://dx.doi.org/10.20517/cf.2023.33

Table 7. Measures for ensuring clean energy metals supply in various countries

Country	Strategic objectives/tasks	
America	Safety level monitoring	Strengthen the monitoring and evaluation capabilities of global strategic materials, do well in intelligence collection work, solve the problem of funds required for domestic production and processing, and establish national defense reserves
	Resource recycling and substitution	Emphasize the development of mineral recycling and reprocessing technologies, as well as promoting mineral technology alternatives; Provide tax incentives to enterprises that mine, recycle, or recycle critical minerals and metals within the United States
	Sustainable development	Develop sustainability standards for critical minerals and develop a "Sustainable Development Plan for Critical Minerals"
	Increase domestic supply	Enhance the exploration and mining capabilities of critical minerals, expand access to important resources, increase research and development investment and technological innovation, and improve production capacity
	Diversified international supply	Increase overseas investment; Establishing an international supply chain alliance
China	Safety level monitoring	Deepen the reform of "streamlining management and serving", further improve mineral resource management, and promote the reform of mineral resource management, grasp digital security technology accurately
	Resource recycling and substitution	Develop and utilize advanced technology, turn "waste" into "treasure", and improve the utilization level of renewable resources; Further research and development of resource substitution technologies
	Sustainable development	Comprehensive investigation and evaluation of resources and green exploration; Promote green and low-carbon development in the national industrial sector; Reduce carbon emissions from the non-ferrous metal industry; Deepening industrial structure, energy conservation, emission reduction, and technological upgrading
	Increase domestic supply	Introduce incentive policies to enhance domestic exploration and development capabilities; Establish mineral resource reserves; Increase research and development efforts
	Diversified international supply	Develop a "going global" policy to increase foreign direct investment; Strengthen export controls; Introduce foreign capital; Diversify supply
European Union	Safety level monitoring	Organize and strengthen data collection and management across Europe
	Resource recycling and substitution	Waste recycling management; Innovating technology to improve the substitutability of traditional energy sources
	Sustainable development	Promote the effective utilization and recycling of critical minerals, making circular economy a priority area for the EU; Focus on circular economy and sustainable procurement
	Increase domestic supply	Research and innovation of raw materials; Improve skills and focus research on innovative exploration and mining technologies, recycling, raw material substitution, and resource efficiency
	Diversified international supply	Establish strategic partnerships with resource-rich countries covering mining, processing, and refining; Optimize the overseas supply chain of resources
Australia	Safety level monitoring	Conduct technological innovation; Enhance the security, productivity, and competitiveness of the resource sector
	Sustainable development	Produce sustainable resource products through rich environmental and labor practices
	Increase domestic supply	Increase investment in domestic resource projects to ensure investment, financing, and market access for important mineral projects; Expand the scope and capacity of resource exploration
	Diversified international supply	Promote and strengthen cooperation with relevant departments and international supply chains; Resource diplomacy
Japan	Safety level monitoring	Build a global cooperation network for overseas geological surveys; Strengthen overseas resource survey evaluation and information services
	Resource recycling and substitution	Promote recycling and research and development of recycling technologies; Actively develop alternative industries and implement resource substitution strategies
	Sustainable development	Build a resource-saving society and improve sustainability
	Increase domestic supply	Promote the development of alternative materials; Improve the reserve mechanism system and strengthen the reserve of critical raw materials
	Diversified international supply	Carry out extensive resource diplomacy to ensure the security of overseas resources and achieve diversified supply; Establish specialized agencies to organize and implement overseas geological survey strategies, and vigorously support overseas operations of Japanese mining companies; Adopt diversified overseas geological survey cooperation methods according to local conditions
Canada	Safety level monitoring	A complete and clear mining management system ensures transparency and predictability in mining development; Financial policies share survey risks
	Resource recycling	Maintain resource recycling and minimize waste; Retain the inherent characteristics of metals throughout the

and substitution	entire recycling process; Reuse and maintain their quality and functionality
Sustainable development	Reduce waste emissions and enhance sustainable development capabilities; Build future "low carbon footprint" mines, and manage the heritage of past mining activities; Protect the natural environment
Increase domestic supply	Improve the processing technology for critical minerals; Cultivate a highly skilled workforce with professional knowledge in fields such as mining technology, geological and biological sciences, artificial intelligence, and space science
Diversified international supply	Strengthen competitive advantage and enhance global leadership in mining industry

Resource source: Compiled and drawn by the research group.

impact mechanism, and how to address the impact of trade and geopolitical factors. Secondly, effective policy guarantee measures are crucial for countries to achieve their carbon reduction goals. There are many current policies, but there is little research on the effectiveness of policies. Future research also needs to evaluate the effectiveness of policies more to provide a basis for their continued implementation. Finally, existing literature lacks a comprehensive exploration of the sustainable supply of clean energy metals from the perspective of the entire industry chain. Future research should extend the global governance of clean energy metals from the original resource governance to the governance of the industry chain supply chain, and explore the mechanism innovation of countries participating in the global governance of clean energy metals.

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All authors declared that there are no conflicts of interest.

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