



Evolution of energy and metal demand driven by industrial revolutions and its trend analysis

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ABSTRACT

Industrial revolutions have a profound impact on energy and metal demand. Based on technological improvement, industrial transformation, and changes of energy and metal consumption in the United States, this paper identified the evolution characteristics of energy and metal demand driven by industrial revolutions, and analyzed the trends of energy and metal demand driven by the fourth industrial revolution which is happening currently. Results indicated that fossil fuels were the major energy sources which boosted up the past three industrial revolutions, whereas their consumption increased at a slowing pace as the economy was growing continually; after the third industrial revolution, the consumption of fossil fuels decoupled gradually with the economic growth. As the industrial structure transformed as the industrial revolutions went on, more and more metals were used in the industries, and the consumption of different metals showed different trends. In recent years, a new technological revolution has surged mainly driven by the overall application of new information technologies. The technological advance in information, new energies, new materials, etc., will speed up the industrial transformation and exert a deep effect on the demand of energy and metals. It can be inferred that the ratio of clean, non-polluting, renewable energy will rise while the ratio of fossil fuels will drop in the energy demand, and the demand of rare metals will perhaps enter a fast-growing period, while the demand of traditional bulk metals will fluctuate at mid-high levels. Following the new industrial revolution, China should adopt an energy transition strategy of developing low-carbon and free-carbon technologies simultaneously, reinforce the domestic and international metal supply system with the aim of enhancing global governance capability, strengthen the deep development of rich rare metals and broaden the overseas supply channels of scarce rare metals.

1. Introduction

Energy and metal resources are indispensable basic materials for the development of the industrial economy. As China enters an advanced stage of industrialization, the consumption of energy and mineral resources has slowed down, and the consumption growth rate of certain bulk minerals is successively reaching a peak; hence, the demand trend of mineral resources is undergoing drastic changes (Wen et al., 2019; Zheng et al., 2019). To promote sustainable development of the Chinese economy and ensure the security of energy and metal supply, it is of great importance to scientifically study and evaluate the trends in energy and metal consumption. Various factors influence energy and metal consumption. Quite a few studies have shown that per-capita energy or metal consumption has an S-shaped relationship with per-capita GDP; specifically, per-capita energy or metal consumption increases slowly before industrialization, increases rapidly

and reaches a peak during the industrialization stage, and tends to stabilize or decline subsequently (Wang et al., 2010; Menzie et al., 2003). However, the aforesaid S-shaped relationship cannot suitably explain the impact of technological progress on energy and metal consumption (Crowson, 2018). On the one hand, continuous technological progress can reduce the cost of energy and metal development, thus stimulating resource consumption. On the other hand, great technological changes may promote the germination and development of emerging industries, thus stimulating the transformation in resource consumption from existing resources to new resources (Langkau and Espinoza, 2018). Since the 2008 Global Financial Crisis, many countries worldwide have actively explored new economic growth points and accelerated the tackling of key scientific and technological problems. Hence, a new technological revolution is emerging. In tandem with the emerging technological revolution, many countries regard scientific and technological innovation as the core of their national

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development strategies and strive to achieve the commanding heights of future science, technology, and industry; hence, international scientific and technological competition is becoming increasingly fierce (Li et al., 2018). The emerging technological revolution may promote the advent of the Fourth Industrial Revolution, which is expected to have a profound impact on future energy and metal demand. Based on technological progress, industrial reform, and changes in energy and metal consumption arising from previous industrial revolutions, this study analyzes the characteristics of the evolution of energy and metal demand driven by industrial revolutions and evaluates the trends in technological innovation, industrial reform, and energy and metal demand in the context of the latest industrial revolution. The findings of this study will provide the foundation for ensuring the security of China’s energy and metal supply.

2. Methodology and data sources

Industrial revolutions originate from technological revolutions. Major technological innovations are initially adopted by several leading industrial sectors and are then gradually diffused to other industrial sectors, thus promoting changes in the industrial structure. As new economic sectors or new types of businesses emerge, some industries apply new technologies, improve production efficiency, or develop new production modes, which in turn lead to industrial upgrading. However, some industries shrink because of poor adaptability to the competition arising from new technological changes.

The natural resources required for industrial development vary along with the changes in industrial structure. Some substances in nature gain prominence as new resources due to the application of new technologies and the advent of new industries. The consumption of some types of natural resources increases due to industrial upgrading, while that of some types of natural resources decreases due to the shrinkage of original industries. Resource-based industries need to constantly adjust with the changes in the resource demand structure. In this context, industrial revolutions promote changes in resource demand in three stages: 1) Major technological innovations bring about a technological revolution; 2) the technological revolution promotes industrial changes; 3) industrial changes generate changes in resource demand (Fig. 1).

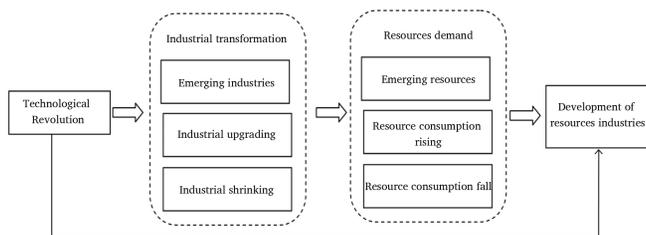


Fig. 1. The impact of the industrial revolution on the evolution of resource demand and the resource industry

Based on the historical data of resource extraction and consumption, the aforementioned three phases are used to analyze the characteristics of the evolution of resource demand driven by previous industrial revolutions. Two types of natural resources are involved in the evolution process—energy (e.g., coal, oil, natural gas, renewable energy, and nuclear energy) and metal minerals (e.g., ferrous metals, non-ferrous metals, precious metals, and rare metals).

The U.S. has been selected as the target country due to the following reasons. First, the U.S. has experienced all industrial revolutions in human history; moreover, economic development and industrial change in the U.S. have undergone a complete process. Second, the US abounds with natural resources in terms of both variety and

tal quantity; thus, it is highly representative. Third, the U.S. has a large population, a large territorial area, and a wide variety of industrial sectors. Its technological innovation and economic development have surpassed that of other countries since the end of the First Industrial Revolution. Fourth, the historical data (e.g., data on resource development and consumption over the past century) of the U.S. are complete. Fifth, the territorial area of the U.S. is approximately similar to that of China, and it ranks first in economic strength globally. Therefore, the US-oriented study results can be used by China as a basis.

Data on energy consumption and production were from the *Monthly Energy Review*, released by the U.S. Energy Information Administration (EIA) (U.S. Energy Information Administration, 2019). Data on the consumption and production of metal minerals were from *Historical Statistics for Mineral and Material Commodities in the United States*, released by the United States Geological Survey (Kelly and Matos, 2015). Data on the production of minerals (e.g., coal, steel, and copper) before 1900 were from the *Historical Statistics of the United States: Colonial Times to 1970*, released by the United States Bureau of the Census (U.S. Bureau of the Census, 1975). To ensure the integrity of data, the data on energy covered the years 1850 to 2018, and the data on metal minerals covered the years 1900 to 2015. Only the data of one or two mineral types from the earlier period were included in *The Historical Statistics of the United States: Minerals*.

3. Impact of the previous three industrial revolutions on resource demand

Human society has experienced three industrial revolutions. The First Industrial Revolution initially took place in Britain in the 1760s. In the United States, the First Industrial Revolution took place half a century after that in Britain. The U.S. experienced the Second Industrial Revolution from the 1860s to the 1920s and the Third Industrial Revolution from the 1940s to the 1970s.

3.1. First industrial revolution

In the United States, the First Industrial Revolution took place approximately from 1790 to 1860. Steam power technology and machinery manufacturing technology were key technological innovations that facilitated the First Industrial Revolution in Britain. The First Industrial Revolution in the U.S. was dominated by the introduction, imitation, and absorption of British advanced technologies. In 1789, the U.S. successfully imitated the British water spinning frame and set up the first spinning mill, taking the lead in using machines instead of manual labor in the textile industry. In 1817, the U.S.’s first steam engine factor was constructed and put into operation. Subsequently, machines were universally applied in many industries (e.g., wool textile, flour, food, and clothing industries) (Wang, 2015). The increasing demand for mechanization promoted the development of the machinery industry, and new machines (e.g., cotton gin, sewing machine, harvester, and steam-powered sailboats) were successively invented.

The popular application of steam engines brought about a power revolution as well as a rapid increase in coal demand. The U.S.’s coal output was less than 100,000 tons in 1800 and increased rapidly to 17.52 million tons in 1860, recording a 180-fold increase with an average annual growth rate of 9.3%. The First Industrial Revolution was a turning point, as human energy consumption underwent revolutionary changes. Firewood, which was a main source of energy consumption, was continuously replaced by coal. According to the U.S. EIA, coal consumption increased to 547 petajoules (PJ) in 1860, accounting for 16.4% of the total energy consumption (Figs. 2 and 3).

The development of the machinery industry resulted in an increasing demand for iron and steel, promoting the development of the iron and steel industry. The U.S. subsequently introduced iron-making technologies (e.g., hot blast stove and coke iron-making pro-

cess) and established its modern iron industry. The U.S.'s pig iron output increased from 49,000 tons (in 1810) to 745,000 tons (in 1860), recording an average annual growth rate of 8.0%.

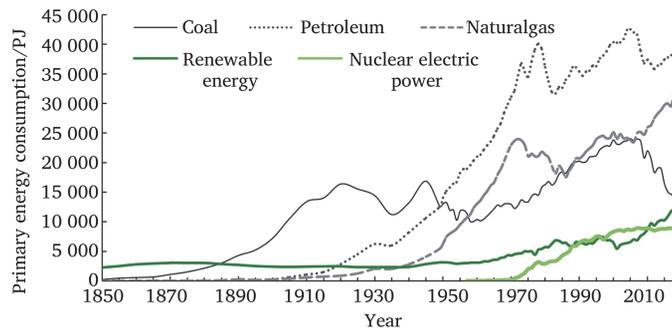


Fig. 2. Changes in U.S. energy consumption from 1850 to 2018

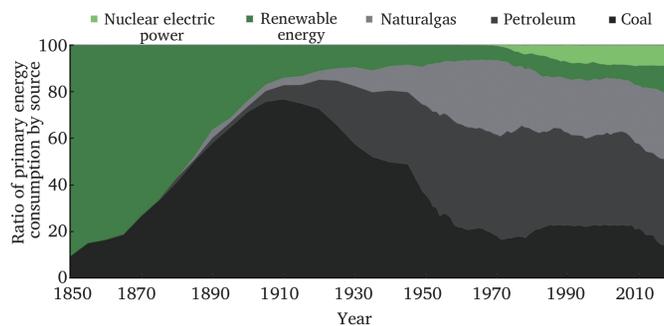


Fig. 3. Changes in U.S. energy consumption ratio from 1850 to 2018

3.2. Second industrial revolution

The Second Industrial Revolution is marked by core technological inventions such as electric power and internal combustion engine technology. The electric generator technology was invented in Germany in 1866 and was subsequently introduced by the United States. The incandescent lamp was invented in 1879 in the United States, the first commercial power station was established in 1882, and a company was established in 1886 to manufacture transformers and alternators. By 1892, more than 500 AC power stations had been established in the United States. Moreover, the United States introduced the internal combustion engine and automobile manufacturing technologies and invented the automobile production line technology.

Electric power technology and internal combustion engine technology has engendered several new industries, shifting the focus of the industrial sector from light to heavy industries. The electric power industry increasingly built power stations to provide electric power for residents, industrial and mining enterprises, and cities. In the United States, electrical manufacturing rose as an important export industry as automobiles began to be mass-produced in the early 20th century. Further, oil refining technology was used to refine gasoline for internal combustion engines, promoting the development of petroleum and chemical industries. The metallurgy, machine manufacturing, and transportation industries developed more rapidly along with technological changes (Liu, 2019). The development of the transport industry (e.g., ships, automobiles, and railways) and scale expansion of the machine manufacturing industry stimulated the development of the iron and steel industry (Ma, 2010).

With regard to energy consumption, coal consumption continued to grow rapidly, and oil and natural gas consumption surged. Coal mining and oil refining developed rapidly. From 1860 to 1920, coal output increased from 18 million tons to 584 million tons, with an av-

erage annual growth rate of 3%, and oil output increased from 500,000 barrels to 442.93 million barrels, with an average annual growth rate of 7%. In around 1885, coal consumption exceeded firewood consumption, and coal became the main source of energy supply instead of firewood (Fig. 2). In 1920, annual coal consumption increased to 16,358 PJ, accounting for more than 75% of the annual energy consumption (Fig. 3). As more oil fields were discovered, oil and natural gas became new sources of energy. Oil consumption increased from 3 PJ (1860) to 2,823 PJ (1920), accounting for 12.5% of the total energy consumption; natural gas was initially used in 1880, and natural gas consumption was 858 PJ in 1920, accounting for 3.8% of the total energy consumption.

With regard to metal consumption, the consumption of ferrous metals increased rapidly and that of some non-ferrous metals surged. The iron and steel industry developed rapidly along with a rapid growth in pig iron output. By the 1880s, the U.S. pig iron output reached more than 3.5 million tons, surpassing that of Britain and France and ranking first worldwide. There was a rapid increase in the consumption of ferrous metals (e.g., pig iron and manganese), which were closely related to the iron and steel industry. From 1900 to 1920, pig iron consumption increased from 13 million tons to 32.4 million tons, with an average annual growth rate of 7.1%; manganese consumption increased from 202,000 tons to 552,000 tons, with an average annual growth rate of 12.6% (Fig. 4 (A)). Driven by the development of the machine manufacturing industry, the consumption of non-ferrous metals (e.g., copper, lead, zinc, tungsten, tin, and antimony) began to surge (Figs. 4 (B) and (C)). From 1900 to 1920, copper consumption increased from 166,000 tons to 642,000 tons, with an average annual growth rate of 9.3%. Meanwhile, the consumption of gold and silver also began to increase. For example, gold consumption increased from 2.56 tons to 4.54 tons, with an average annual growth rate of 8.0% (Fig. 4 (D)).

3.3. Third industrial revolution

The Third Industrial Revolution took place in the US in the 1940s and was marked by the invention of new technologies such as electronic computers, automation, atomic energy, and astronautics. Existing technologies were continuously developed, integrated, and applied. The vacuum tube computer was invented in the United States in 1946, the integrated circuit computer, in 1965, and the large-scale integrated circuit computer, in 1975. Further, a breakthrough was made in atomic energy technology. Specifically, the world's first nuclear reactor was developed in 1942, and an atomic bomb was successfully produced in 1945. More than 600 nuclear reactors were built from 1950 to 1972. Additionally, space technology was invented and developed rapidly. The first man-made satellite was successfully launched in 1958, a manned satellite was launched in 1961, and men landed on the moon in 1969. The advent of new technologies (e.g., electronic computers, automation, and atomic energy) and intensive development of traditional technology clusters promoted the transformation from labor-intensive to technology-intensive industries in the US. This not only resulted in numerous emerging industries (e.g., computer manufacturing, nuclear, and aerospace industries), but also promoted an unprecedented rapid development of original industries (e.g., transportation equipment manufacturing, machine manufacturing, iron and steel, and chemistry), resulting in profound changes in human modes of production, life, and consumption.

With the rapid development of traditional industries and the advent of emerging industries, consumption of natural resources increased rapidly (Steffen et al., 2007; Steffen et al., 2015), with the development of natural resources undergoing massive acceleration. With regard to energy consumption, the consumption of oil and natural gas increased significantly, as oil and natural gas became the main source of energy supply instead of coal. Nuclear energy emerged as an energy source in the late 1950s. Coal consumption began to de-

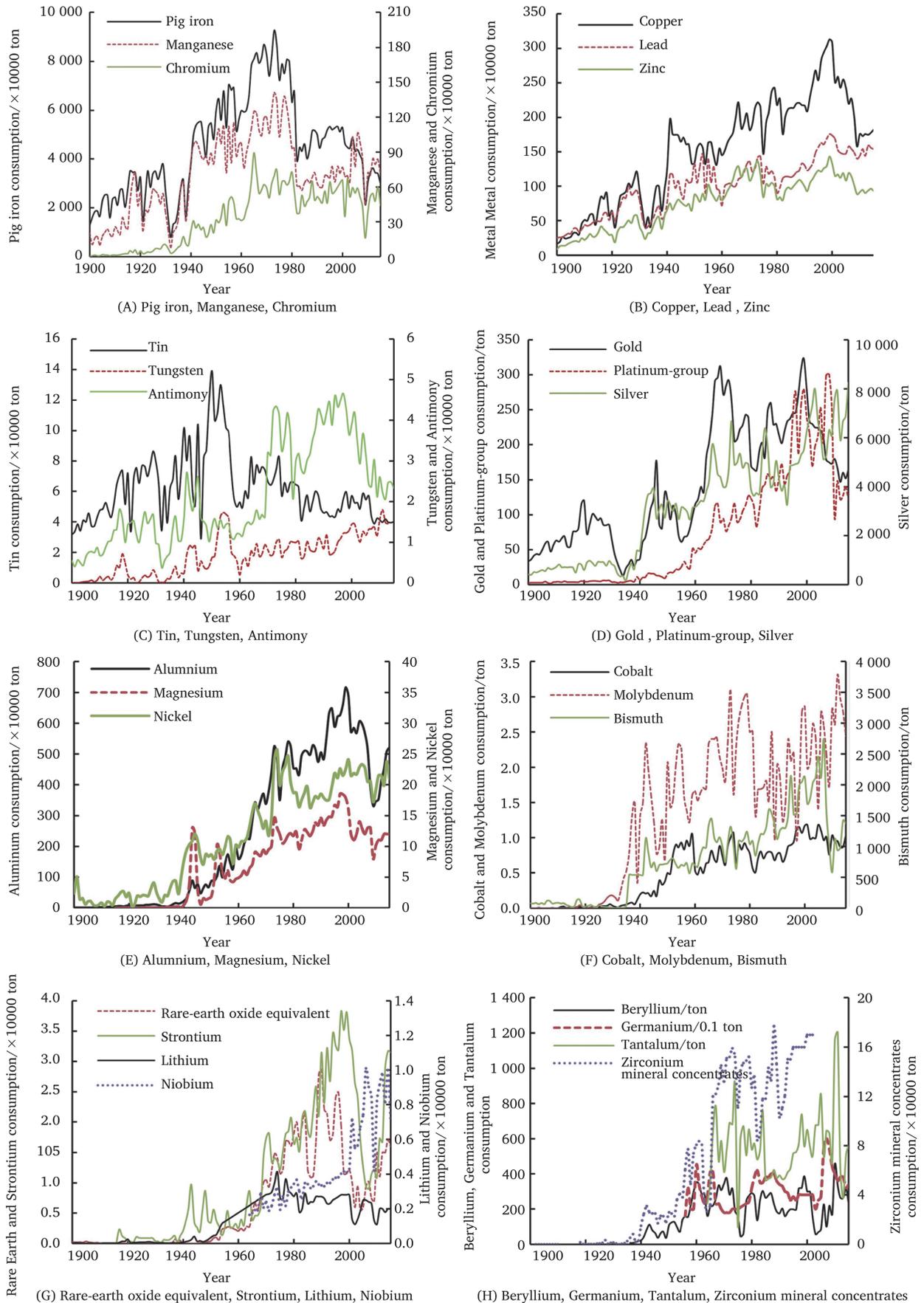


Fig. 4. Changes in U.S. metal consumption from 1900 to 2015

cline in the mid-1940s, and the proportion of coal consumption in the total energy consumption declined from 49.7% in 1940 to 19.8% in 1980. The consumption of oil and natural gas continued to rise rapidly, from 8,187 PJ and 2,812 PJ in 1940 to 36,088 PJ and 21,350 PJ, respectively, in 1980, with an average annual growth rate of 3.6% and 5.1%, respectively (Fig. 2). The proportion of the consumption of oil and natural gas in the total energy consumption increased from 30.8% and 10.6%, respectively, in 1940 to 43.8% and 25.9%, respectively, in 1980 (Fig. 3). The consumption of nuclear energy began to rise gradually in the late 1950s and accounted for 3.5% of the total energy consumption in 1980.

With regard to metal consumption, most types of metal minerals were used for industrial application, but they showed differential consumption growth trends. The consumption of ferrous metals (e. g., steel, manganese, and chromium) fluctuated as it peaked in the 1970s due to rapid growth and then declined (Fig. 4 (A)). Among the non-ferrous metals, the consumption of tin and mercury peaked in the 1950s to 1960s and then declined (Fig. 4 (C)). The consumption of copper, lead, zinc, and antimony continued to increase and reached a peak in the late 1990s (Fig. 4 (B)). Aluminum, magnesium, and nickel began being applied massively in the 1940s, and their consumption reached a peak in the late 1990s (Fig. 4 (E)). The consumption of cobalt, molybdenum, bismuth, and tungsten fluctuated upwards and has not yet reached a peak (Fig. 4 (F) and (C)). Among precious metals, the consumption of gold fluctuated within a peak range from the 1970s to the 1990s and declined in subsequent years. The consumption of silver and platinum group metals continued to fluctuate as it moved upwards; however, it has not yet reached a peak (Fig. 4 (D)). The application of rare-earth metals occurred later than that of other metals. Overall, rare-earth metals were massively applied after the 1950s. The consumption of rare-earth metals experienced a rapid growth in the 1970s and 1980s and fluctuated in subsequent years (Figs. 4 (G) and (H)).

3.4. Characteristics of the evolution in resource demand

The above analysis shows that the three industrial revolutions were driven by different leading technologies, resulting in numerous emerging industries and promoting rapid growth in demand for different resources (Table 1). The characteristics of the growth in resource demand can be summarized as follows.

First, in the first three industrial revolutions, fossil fuels were the dominant source of power, but the growth of fossil fuel consumption continued to decline; after the Third Industrial Revolution, economic growth was gradually decoupled from the growth of fossil fuel consumption. During the Second Industrial Revolution, a US\$1,000 increase in per-capita GDP (based on the constant price in 2011, similarly hereinafter) induced a 33.6 gigajoule (GJ) increase in per-capita fossil fuel consumption. During the Third Industrial Revolution, a US\$1,000 increase in per-capita GDP caused an 8.7 GJ increase in per-capita fossil fuel consumption. After 1980, per-capita fossil fuel consumption declined with the increase in per-capita GDP. Regarding the proportion of energy consumption, the proportion of fossil fuel consumption reached a peak in the late 1970s (more than 90%) and then declined slowly (Fig. 3). Regarding the quantity of energy consumption, the consumption of fossil fuels reached a peak in the early 21st century and declined slowly after 2005 (Fig. 2). The continuous declining trend in both the proportion and quantity of fossil fuel consumption shows that new technological changes may promote continuous growth of new energy supply in the 21st century.

Second, the advancements in previous industrial revolutions led to a radical transformation of the industrial structure; furthermore, more types of metals were consumed, with differential trends in metal consumption. In the First Industrial Revolution, the industrial structure was dominated by light and textile industries, and only the consumption of iron and steel increased rapidly. In the Second Indus-

trial Revolution, the industrial structure was dominated by heavy industries instead of light industries, and there was a rapid increase in the consumption of ferrous metals (including magnesium and iron), non-ferrous metals (including copper, lead, zinc, antimony, tin, and mercury) and precious metals (including gold and silver). In the Third Industrial Revolution, the industrial structure was dominated by technology-intensive industries instead of labor-intensive industries, and most types of metals were exploited and utilized, with differential consumption trends. Specifically, the consumption of ferrous metals (including iron, manganese, and chromium), non-ferrous metals (including copper, lead, zinc, antimony, tin, mercury, aluminum, magnesium, and nickel) and precious metals (including gold) reached a peak and then declined slowly. Other metals were utilized in the industrial economy in a later period, and their consumption either continued to grow or fluctuated; however, their consumption has not yet reached a peak. Considering the changing trends, the lifecycle of metal consumption can be approximately divided into the growth, peak, and decline periods (Fig. 6).

Third, for certain metals with peak consumption, their consumption declined slowly but remained at a medium-high level from the perspective of consumption history. For example, the average annual consumption of pig iron was 81.13 million tons during the peak period and 34.46 million tons from 2006 to 2015, which was 42.5% of that during the peak period. The average annual consumption of manganese was 1.208 million tons during the peak period and 0.794 million t from 2006 to 2015, which was 65.7% of that during the peak period. This is particularly obvious with the consumption of non-ferrous metals. The average annual consumption of copper was 2.435 million tons during the peak period and 1.865 million tons from 2006 to 2015, which was 76.6% of that during the peak period. The average annual consumption of lead was 1.606 million tons during the peak period and 1.512 million tons from 2006 to 2015, which was 94.1% of that during the peak period. After the peak period, the consumption of metals still remained at a medium-high level due to the following reason: Upon completion of industrialization, the tertiary sector becomes the main source of economic growth instead of the secondary sector; however, the real economy dominated by manufacturing industries remains the cornerstone of economic development and plays an unshakable role in the national economy. The development of the real economy needs to be underpinned by a considerable amount of metal consumption.

4. Technological and industrial transformation and impact on resource demand in the Fourth Industrial Revolution

There are increasingly more indications that the world is entering a new stage of disruptive technological changes in the 21st century. The new round of global scientific and technological revolution is changing from the “point breakthrough” to the “line breakthrough” pattern, promoting the acceleration of industrial transformation. The process of the scientific and technological revolution presents an evolution pattern known as “one core and multiple wings”. “One core” refers to the in-depth as well as comprehensive applications of information technology, while “multiple wings” refer to diverse fields such as new energy technology, new material technology, biotechnology, and aerospace technology (Table 2). Many countries have implemented relevant strategies to encourage the industrialization of new technologies and to promote the new global industrial revolution.

4.1. Information technology and industrial transformation centered on digitalization, networking, and intelligence

In the past 20 years, new technologies such as digitization, networking, and intelligence have emerged. With in-depth and comprehensive applications, information technology will become the core infrastructure of industrial development, thereby changing fundamen-

Table 1
The characteristics of industrial revolution and resources demand evolution in industrial revolutions

Industrial Revolution	The First Industrial Revolution	The Second Industrial Revolution	The Third Industrial Revolution
Period	Late 18th century to 1850s	1860s to 1920s	1940s to 1970s
Leading Technologies	Steam power technology; machinery manufacturing technology	Electric power technology; internal combustion engine technology, electromagnetic communication technology	Electronic computer technology; automatic control technology, atomic energy technology, aerospace technology
Emerging Industries	Machinery manufacturing; coal mining industry; iron and steel smelting industry	Electrical industry; automobile industry; petroleum refining industry; chemical industry	Computer manufacturing; nuclear industry; aerospace and aviation industry
Key Resources	Coal; steel	Coal, petroleum; steel, manganese; Copper, lead, zinc, tungsten, tin, antimony; gold, silver	Petroleum, natural gas, nuclear power; ferrous metals such as iron and steel, manganese, chromium; non-ferrous metals such as copper, lead, zinc; precious metals such as gold and silver
Characteristics of the Resources Demand Evolution	Coal consumption grew rapidly, and firewood as the main source of energy consumption was continuously replaced.	The growth of coal became the main force underlying energy supply; the consumption of petroleum and natural gas started to rise.	The consumption of petroleum and natural gas increased substantially, surpassing coal to become the main force of energy supply; nuclear energy began to rise.
The Characteristics of the Metal Resources Demand Evolution	Demand for steel continued to grow.	The growth rate of ferrous metal consumption accelerated; some non-ferrous metal and ferrous metal consumption began to rise.	Ferrous metal consumption peaked in the 1970s; non-ferrous metal consumption diverged-some peaked and some showed volatile growth; gold consumption peaked, the consumption of silver and platinum-group metals fluctuated up; the consumption of rare metals fluctuated after increase.

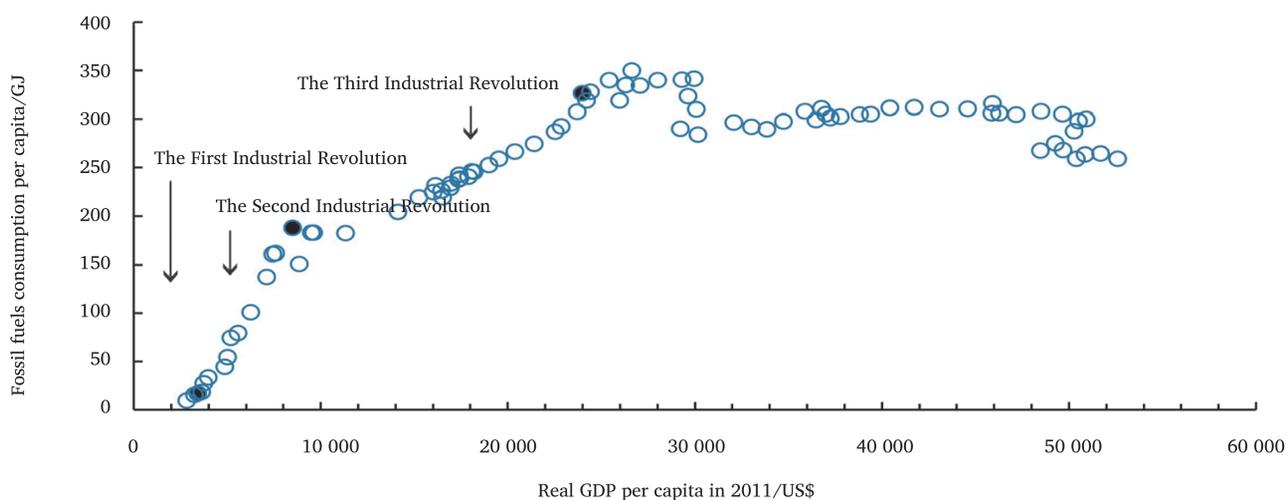


Fig. 5. U.S. per capita GDP and per capita fossil fuel consumption growth

tally the means of connection between humans, society, and economy.

Digital technology is applied in diverse fields, promoting the comprehensive datamation of the economy and society. The utilization of big data has reached a new high, gaining status as a new technology, new scientific research paradigm, and new way of decision-making (Li et al., 2019). With the exponential increase in big data, the universal, reliable, efficient, and low-cost computing technology has become the pillar of information technology. Japan developed the basic quantum computer circuit successfully in 2003. The U.S. developed a supercomputer capable of 1,000 trillion calculations per second in 2008; moreover, they made the world's first carbon nanotube computer in 2013 and launched a 50-qubit IBM Q quantum computer system in 2017 (Li, 2018).

China developed the prototype of the Sunway Taihulight E supercomputer, which was capable of at least a billion-billion calculations per second in 2018. Computing technologies (including quantum computing, photon computing, and grid computing) are being developed incessantly.

Networking has changed the way information is acquired, exchanged, and consumed in modern society. New technologies (e.g., cloud computing, blockchain, Internet of Things (IoT), and mobile Internet) will promote constant innovation in the realm of social communication and in industrial modes. In 2013, the Ethereum blockchain platform was proposed in Canada. In 2015, the Linux Foundation launched the Hyperledger open source blockchain project. In 2017, Tencent (China) released the trusted blockchain platform TrustSQL. IoT is the core infrastructure in the Fourth Industrial Revolution. More than 80 billion devices are estimated to be interconnected globally in the next decade.

Smart technologies are rapidly developing. Continuous progress has been made in the technologies related to human-computer interactions, autonomous driving, emotion recognition, brain-computer interface, and bionic software robot; artificial intelligence and robotics will play an increasingly important role in the fields of manufacturing, transportation automation, and medical health. In 2013, the US was the first to realize brain-to-brain interface in humans. Moreover,

the European Union launched the Human Brain Project in 2013 to promote research and development (R&D) in neuroinformatics and neural computers. More than 40 sub-types of 7 types of service robots have been on trial or used for semi-commercial applications in Japan, the U.S., and Europe.

4.2. Clean, pollution-free, and renewable energy and industrial transformation

In the first three industrial revolutions, fossil fuels were the main sources of energy; greenhouse gases were massively emitted, resulting in problems such as global warming and ecological degradation. In 2015, the United Nations Climate Change Conference adopted the Paris Agreement, resolving to reduce greenhouse gas emissions and decelerate global warming. Developing clean, low-carbon, pollution-free, and renewable energy technologies has increasingly become an important energy development strategy among countries. New energy technologies and energy storage technologies may change the driving force of socioeconomic development.

Clean and low-carbon energy technology may change the current global energy supply and demand pattern. The breakthrough in shale gas development technology has changed the supply pattern of oil and gas resources in the US. With the rapid rise in shale gas output, the US became a net exporter of natural gas again after 60 years. Unconventional energy sources (e.g., natural gas hydrate, geothermal energy, solar energy, and nuclear fusion) have great application potential. Once a technological breakthrough is achieved, such unconven-

tional energy sources will change the energy supply and demand pattern more significantly than shale gas. In 2017, China successfully achieved a trial use of marine natural gas hydrates. In 2015, the US launched the Frontier Observatory for Research in Geothermal Energy. Large-scale commercial utilization of hot-dry-rock geothermal energy is highly anticipated (Ziagos et al., 2013)

Energy storage technologies play a crucial role in the energy revolution. Numerous energy storage technologies (e.g., compressed air energy storage, electrochemical energy storage, and superconducting magnetic energy storage) and devices or products (e.g., sodium-sulfur cell, flow cell, lithium-ion battery, and super capacitor) have been developed successfully in recent years. With continuous increase in the energy density of lithium-ion batteries, global electric vehicle output is likely to increase exponentially. Hydrogen energy technology has received increasing attention. Countries such as Japan, Germany, and the US render full support to the development of the hydrogen energy industry.

4.3. New materials, additive manufacturing, and industrial transformation

The development of new materials and multi-dimensional printing technologies will perhaps change the material basis for socioeconomic development. Graphene is thus far the thinnest, lightest, and toughest material with excellent electrical and thermal conductivity. Nano materials are considered to be the next revolution in the field of materials. Existing studies on nano materials mainly focused on nano batteries, biomaterials, and nano-metal catalysis. With advancements

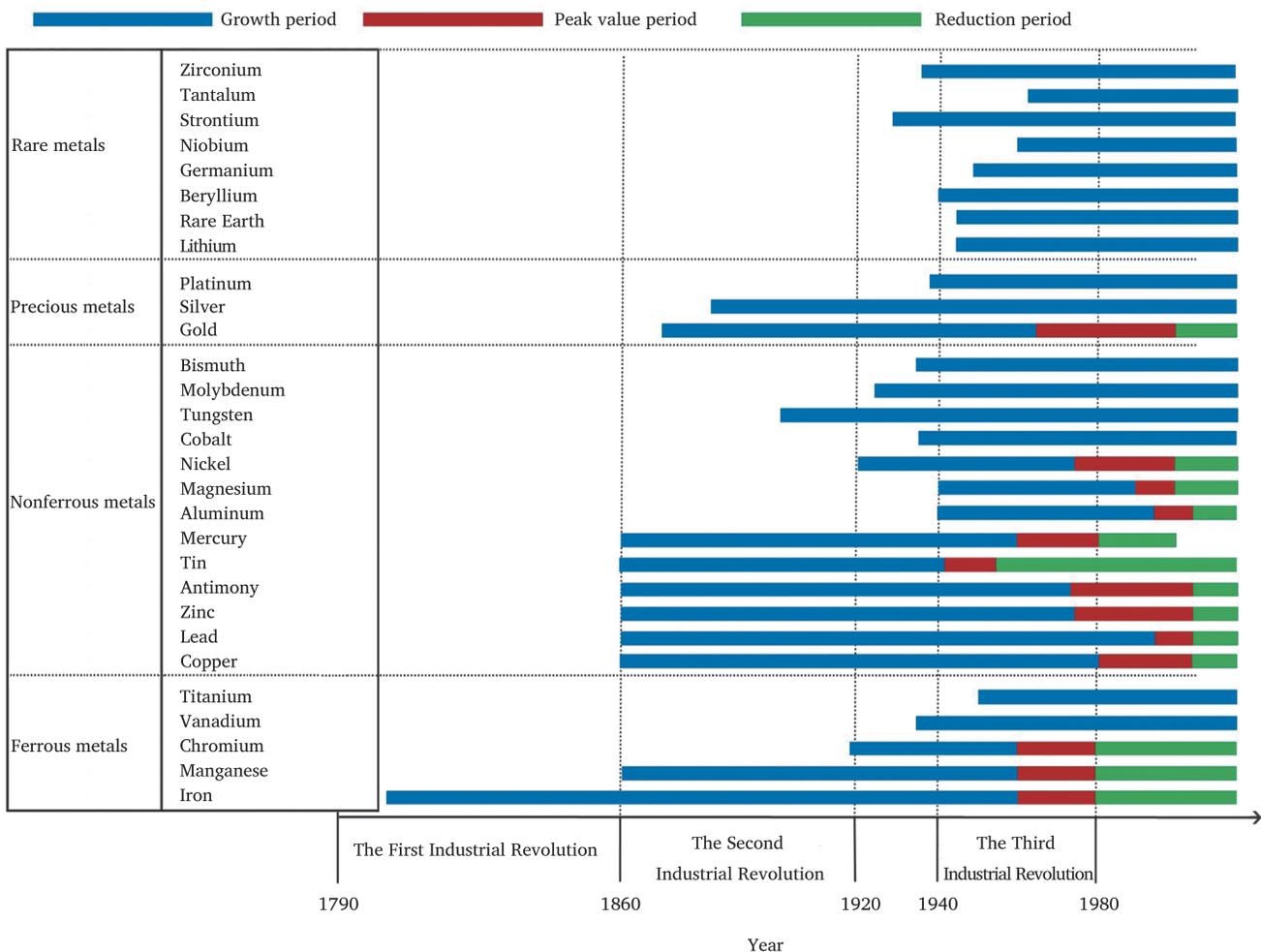


Figure 6. Changes in Metal Consumption in the United States in Different Periods

in additive manufacturing technologies (including 3D printing), nano materials may disrupt multiple industrial systems and change the manufacturing, transportation, and logistics industries significantly. Many countries are striving to achieve the heights of international competition in the field of materials. The US released the *Strategy for American Innovation* in 2015, resolving to develop various materials, such as new energy materials, biological and pharmaceutical materials, environment-friendly materials, nano materials, materials for advanced manufacturing, new-generation information, network technologies, electric vehicles, and wide bandgap semiconductor materials. The European Union formulated the *Europe 2020 Strategy* in 2010, resolving to promote R&D in low-carbon industry-related materials, information technology-related materials, biomaterials, and graphene. The UK released *The Future of Manufacturing: A New Era of Opportunity and Challenge for the UK* in 2013, focusing on the construction of innovation centers for new energy, smart systems, and material chemistry.

4.4. Evolution of future resource demand

The technologies for new information, new energy, and new materials will induce great changes in the industrial structure and resource requirement for industrial development, thus profoundly impacting future resource-based industries.

First, the proportion of the consumption of clean, pollution-free, and renewable energy will continue to increase, while that of fossil fuels will gradually decline. From 2000 to 2018, the total energy consumption in the US stabilized, with an average annual growth rate of 0.1%. The consumption of renewable energy grew at an average annual rate of 3.3%, and the consumption of nuclear energy grew at an aver-

age annual rate of 0.6%. In terms of the total energy consumption, the proportion of renewable energy consumption increased from 6.2% to 11.4%, and the proportion of nuclear energy consumption increased from 8.0% to 8.6% (Figure 3). Among renewable energy, the increase in the consumption of bioenergy, geothermal energy, and solar energy was particularly significant. According to *BP Energy Outlook* (2019), the proportion of renewable energy consumption in the global energy consumption will increase from 4% in 2017 to 15% in 2040 under a scenario of gradual transition, and to 29% in 2040 under a scenario of rapid transition. According to the forecast of the World Geothermal Congress, the proportion of geothermal power generation in global power generation will rise to 8.3% by 2050 (Bertani 2012).

Second, among the metal resources, the consumption of rare metals will witness rapid growth, whereas that of traditional bulk metals will still fluctuate at a medium-high level. Except for 13 metals (e.g., iron, manganese, and copper), the consumption of other metals has not reached a peak in the US. Even for metals (e.g., manganese) that have passed their peak consumption periods, the consumption of some of them has increased significantly in recent years. With the development and expansion of emerging industries (e.g., information, new energy, new materials, intelligent manufacturing, and aerospace), the demand for strategic emerging minerals represented by rare metals will increase rapidly. According to the forecast of the World Bank in 2017, the development of low-carbon technologies (e.g., wind energy, solar energy, and energy storage batteries) will cause an increase in demand for metals such as aluminum, copper, manganese, lithium, nickel, silver, and rare earths; by 2050, the demand for metals for energy storage batteries under the scenario of a global temperature rise of 2°C will be at least 10 times as much as that under the scenario of a global temperature rise of 4°C (World Bank Group, 2017).

Table 2
Typical technological breakthroughs in key areas in recent years

Areas	Key Technologies	Typical Technological Breakthroughs
In-depth and Comprehensive Application of Information Technologies	Digital Technologies	Fundamental quantum computer circuits (Japan); Carbon Nanotube Computer (U.S.); IBM Q Quantum Computer with 50 qubits (U.S.); The first optical quantum computer (China) that surpasses the early classical computers; Shenwei E-class prototype (China) with the calculation speed exceeding tens of billions of times; practical quantum computers by Netherlands quantum technology research institutes (Netherlands)
	Networking Technologies	High-speed network technology using light transmission (Japan); Ethereum blockchain platform (Canada); Amazon Web Services (cloud computing platform) (U.S.); Huawei NarrowBand-Internet of Things (NB-IoT) chipset (China)
	Smart Technologies	Smart remote control ring (U.S.); Google AI robot AlphaGo (United States); Autonomous-driving ARGO car developed by the University of Parma (Italy); DJI drone flight control and pan-tilt technology (China); Dexterous robots by OpenAI, Carnegie Mellon University; Self-driving trucks from companies such as Otto (the United States); Heterogeneous chips for artificial general intelligence (China)
New Energy and Storage Technologies	New Energy Technologies	Shale gas development and hydraulic fracturing technologies (U.S.); Offshore natural gas hydrate production test technology (China); Hot dry rock enhanced geothermal system demonstration (U.S., U.K., etc.); The first storable solar power plant (Spain); Solar-powered aircraft "Sun Impulse" (Switzerland); The Advanced Superconducting Tokamak (EAST) nuclear fusion experimental device achieves 101.2-second steady-state long-pulse high confinement plasma operation (China); Solar thermal photovoltaic cells by Massachusetts Institute of Technology; Zero-carbon emission power generation technologies for natural gas by 8 Rivers Capital and other companies (United States); Terrestrial Energy's new nuclear reactor (Canada).
	Energy Storage Technologies	Honda's hydrogen energy-powered Clarity Fuel Cell vehicle (Japan); H-APU's cabinet-type energy storage system with lithium-iron phosphate cells (U.S.); Highview Power's megawatt-level liquid air energy storage (U.K.)
New Materials and Multi-dimensional Printing Technologies	New Materials Technologies	Preparation of graphene materials by mechanical peeling method (U.K.); MC10 flexible circuit boards (U.S.); Information storage nanomaterials with ultra-large-capacity (France, Switzerland); Polyolefin synthetic carbon fibers used by Oak Ridge National Laboratory uses (U.S.); Nanostructured materials by California Institute of Technology (U.S.); High-temperature bulk metallic glass based on material genetic engineering (China).
	Multi-dimensional Printing Technologies	ZCorp's high-definition, color 3D printer (Israel); Manufacture drone prototypes using 3D printing technology (Russia); Practical 3D metal printers by Desktop Metal and others (U.S.)

Notes: this table is organized according to the top ten breakthrough technologies of *MIT Science and Technology Review* in recent years, the Chinese Academy of Sciences, and the top ten scientific and technological developments in the world and in China.

5. Conclusion and suggestions

Industrial revolutions have a far-reaching impact on the demand for socioeconomic energy and metal resources. The first three industrial revolutions in the US have promoted the advent and growth of the consumption of energy sources, such as coal, oil, natural gas, and nuclear energy, and established an energy consumption structure dominated by fossil fuels.

With the advent and development of emerging technologies and industries (e.g., new information technology, new energy technology, and new material technology), the proportion of the consumption of clean, pollution-free, and renewable new energy in the total energy consumption will continue to increase, while the proportion of the consumption of fossil fuels will continue to decrease. The first three industrial revolutions have promoted the consumption of ferrous metals (e.g., iron and steel and manganese), non-ferrous metals (e.g., copper, lead, and zinc), precious metals (e.g., gold and silver), and rare metals (e.g., lithium and rare earth). The changes in the industrial structure have differential effects on the consumption of different metals. Specifically, the consumption of rare metals will witness rapid growth, whereas that of traditional bulk metals will still fluctuate at a medium-high level.

The evolution characteristics of US's resource demand driven by industrial revolutions provide useful insights and evidence for ensuring the security of China's energy and resources supply.

First, technological revolutions have promoted the transformation and upgrading of the energy consumption structure. New energy technologies are the key to the transformation from high-carbon energy consumption to low-carbon and even carbon-free energy consumption. The First and Second Industrial Revolutions promoted US's transformation in terms of its source of power from a firewood-dominated to a coal-dominated pattern. The Third Industrial Revolution promoted US's transformation in terms of its source of power to an oil and natural gas-dominated pattern. The ongoing technological revolution refocuses on renewable energy as US's source of power. Within a short period, China's industrialization has undergone the entire process of the first three industrial revolutions in the US and is characterized by compactness and rapidness. China's coal-dominated energy consumption structure is facing unprecedented challenges. Under the pressure of its carbon reduction commitment, China can attach equal importance to low-carbon development and carbon-free development to transform the energy consumption structure. Low-carbon development aims to offset the deficiency of previous energy development, namely, clean fossil fuel technologies are developed to control coal consumption, stabilize oil consumption, and increase natural gas consumption. Carbon-free development aims to provide correct guidance to energy development, namely, clean, pollution-free, and renewable new energy technologies are developed to promote the low-cost development of non-fossil energy.

Second, metal resources provide a major material basis for the development of the industrial economy. Thus, it is necessary to ensure long-term security of metal resource supply. Propelled by previous industrial revolutions, more and more types of metals have been utilized in the US's industrial economy. The consumption trends of different metals are different. However, the consumption of certain metals remains at a high level for a long time even if they have passed their peak consumption periods. Overall, China has entered the later stage of industrialization, during which the consumption of metal resources has slowed down, but still falls within the growth period. To ensure the security of metal resource supply, it is necessary to take appropriate measures: 1) strengthen geological exploration of domestic metal minerals and promote the recycling of metal resources; 2) implement the global strategy for metal mineral resource allocation and increase the governance capacity of metal mineral resource.

Third, the new round of industrial revolution will bring about rapid increase in the consumption of rare metals; the supply of rare metals will influence the prospect of strategic emerging industries. The US considers high technologies as an important cornerstone that affects its national security and global competitiveness. A secure supply of critical minerals including rare metals is of vital importance to the development of high-tech industries. In 2019, the US released *A Federal Strategy to Ensure a Reliable Supply of Critical Minerals*, to reduce its dependence on imports of critical minerals. In 2020, the USGS determined 23 critical minerals that may cause the greatest risk of disruption to the US's manufacturing supply chain, of which 13 critical minerals are mainly supplied from China (Nassar 2020). Amid the global contention for rare metals, China should intensify the R&D of superior rare metal minerals to support the development of the national strategic emerging industries. Moreover, China should expand the overseas sources of rare metals to reduce risks related to overseas supply.

Disclosure statement

The authors report that there are no potential conflicts of interest.

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