Fundamental Research 2 (2022) 392–395

Contents lists available at ScienceDirect

Fundamental Research

journal homepage: http://www.keaipublishing.com/en/journals/fundamental-research/

Perspective

Carbon neutrality needs a circular metal-energy nexus

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ARTICLE INFO

Article history:
Received 4 January 2022
Received in revised form 6 February 2022
Accepted 11 February 2022
Available online 26 February 2022

Keywords:
Carbon neutrality
Metal-energy nexus
Circular economy
Critical metals
Industrial ecology
Green system engineering

ABSTRACT

Carbon neutrality requires systematic transformations of both energy and metal systems. These transformations are not isolated but rather interlinked and interdependent, such that trade-offs between different strategies exist. Herein, we explore the critical interlinkages between energy and metal systems and further propose a circular metal-energy nexus to advance global coordinated actions towards a carbon-neutral future.

1. Introduction

Carbon neutrality is gaining international political traction to avert the pressing climate crisis, which will evoke a systematic transformation in all industrial and service sectors. Among these, materials and energy are critical provisioning systems that are pivotal to the key functions of modern society. Previous studies have highlighted the urgent need for low-carbon transition in the energy system (i.e., renewable energy expansion, electrification, negative emission technologies, energy efficiency, etc.) [1], or have only focused on the material system (i.e., material efficiency, eco-design, recycling, production technologies breakthroughs, etc.) [2,3]. Some of these proposed actions may reinforce, redistribute, or create new burdens that may intensify climate mitigation difficulties [4]. Nexus thinking has been proposed as a key approach to address these systematic challenges.

In the context of carbon neutrality, systems of material production and energy supply are becoming increasingly interlinked and interdependent [5], particularly metallic materials (metals) and renewable energy technologies [3,6]. Nevertheless, a nexus view of energy and material remains an important, yet unexplored research area. At present, material production (mainly steel and other metals as hard-to-abated energy consumers [1]) is an emergent large greenhouse gas(GHG) emitter [2] and the low-carbon energy transition is critical to "limiting global warming to 1.5 °C by 2050" [7]. Based on various real-world examples and preliminary assessments, this perspective aims to offer a deeper understanding of the critical interlinkages of energy and material (mainly metals) systems to alert emerging challenges and to inform effective carbon-neutral strategies.

2. Energy supply dependence on metals

Photovoltaics, wind turbines, electric vehicles, fuel cells, and other key infrastructures must be deployed on a large scale to achieve a carbon-neutral target. However, these infrastructures are much more material intensive (both in quantity and category, as shown in Fig. 1a). For instance, photovoltaic power requires up to 40 times more copper than fossil fuel combustion power, and onshore wind power requires 8-fold that of the mineral requirement of a gas-fired plant of the same capacity [5]. Notably, these low-carbon infrastructures also require large quantities of over 30 types of specialty raw materials (mainly metals), such as rare earths, cobalt, and lithium, which are widely considered by various governments as "critical materials (or critical metals)" because of their high technological importance as well as intensifying supply risks [5].

Consequently, the physical basis of the energy system will rapidly shift from carbon to metal (from coal and oil to rare earth, or lithium, etc.). Meanwhile, the energy sector can be expected to dominate the

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https://doi.org/10.1016/j.fmre.2022.02.003

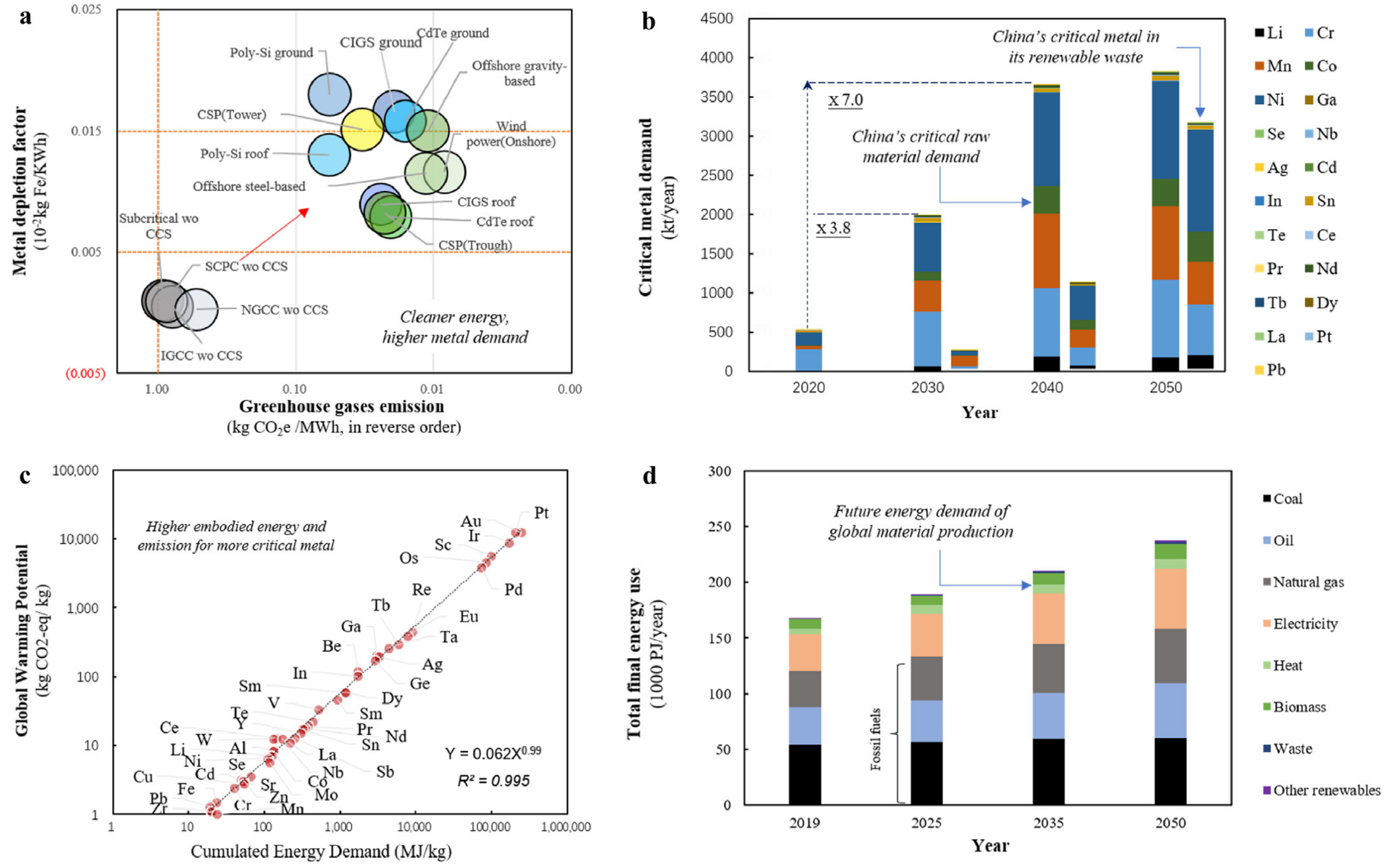

Fig. 1. The synergies and trade-offs of the materials and energy systems associated with carbon neutrality transition (The original data and their quantitative methods can be found in the *Supporting Material*. (a) the metal demand and carbon intensity of different energy-production technologies; (b) critical metal demand to support China's carbon neutrality; (c) The scale and relationship of energy use and carbon emission from the production of different metal types; (d) future energy demand of global material production under current technology mix assumption as described in Supporting Material)

global markets for these metals, and the IEA's assessment indicates that the annual demand for rare earths, lithium, cobalt, and nickel from 2020 to 2040, depending on material category, will expand by 7–42-fold [5]. This will increase further under a continued population, and affluence increase. However, most of these metals are geologically rare, scarce, and scattered [8], and their production capacities are difficult to quickly expand [6,8]. In this context, this huge metal demand gap will make it difficult, if not impossible, for the energy system to reach an ambitious carbon-neutral target.

Such metal constraints on energy transition can become severe at the national level, because critical metals are not equally distributed and produced among nations. China stands out as the largest global low-carbon technology manufacturer with ambitious climate plans. Fig. 1b presents our preliminary analysis of China's future critical metal demand in line with its carbon-neutral target. The details of the data source and quantification methods can be found in the Supporting Material, which indicate that the energy transition in China will require an approximately 8.6-fold increase in its consumption of over 20 types of critical metals, rising from 590 thousand tons (kt)/year by 2020 to 5106 kt/year by 2040. For specialty metals, a much higher growth rate is anticipated (e.g., 18-fold for lithium, 25-fold for cobalt, 7-fold for gallium, 11-fold for neodymium, and 5-fold for platinum). As one of the world's largest critical metal suppliers, Chinese production capacities alone cannot meet demand at such a scale. Consequently, it has become the largest importer of various critical metals, even rare earths. Thus, the transition to a low-carbon energy system will not be possible without countries along the metal supply chain cooperating more effectively.

3. Metals supply dependence on energy

Energy is needed at all stages of the metal life cycle, particularly in the production stages from mining to refinery (pyrometallurgical and hydrometallurgical) [3]. Currently, the energy required to produce metals is extremely carbon-intensive (Fig. 1c) because it is derived mostly from coal and other fuels. In addition, the carbon obtained from these fuels, as a reductive agent and feedstock, has been integral for some long-lived chemical and metallurgical processes [1], meaning that a simple shift of the energy carrier is not sufficient. Thus, metal production is among the sectors that are the most challenging to decarbonize and require significant mitigation efforts [1]. Moreover, most metals and their related products are consumed at an accelerated rate, which is expected to grow further because easy-to-mine deposits are being exploited quickly, and their demand is on the rise [2].

More directly, various critical metals are directly produced from fossil fuels as by-products or from host minerals, whose supply is governed by fossil fuel supply chains [8]. There is evidence that approximately 40% of germanium, 10% of vanadium, 36% of silver, and other elements such as gallium and rare earths are associated with fossil fuel extraction [9]. Thus, transitioning to a carbon-neutral energy system would not only increase metal demand, but may also weaken the supply of some critical metals. Without acknowledging such interdependencies, stricter climate policies (e.g., China's dual energy control policy) may further constrain metal production with higher energy costs and limited energy availability.

Nevertheless, the pathways of the metal and energy transitions are not well harmonized. Current low-carbon pathways of energy systems

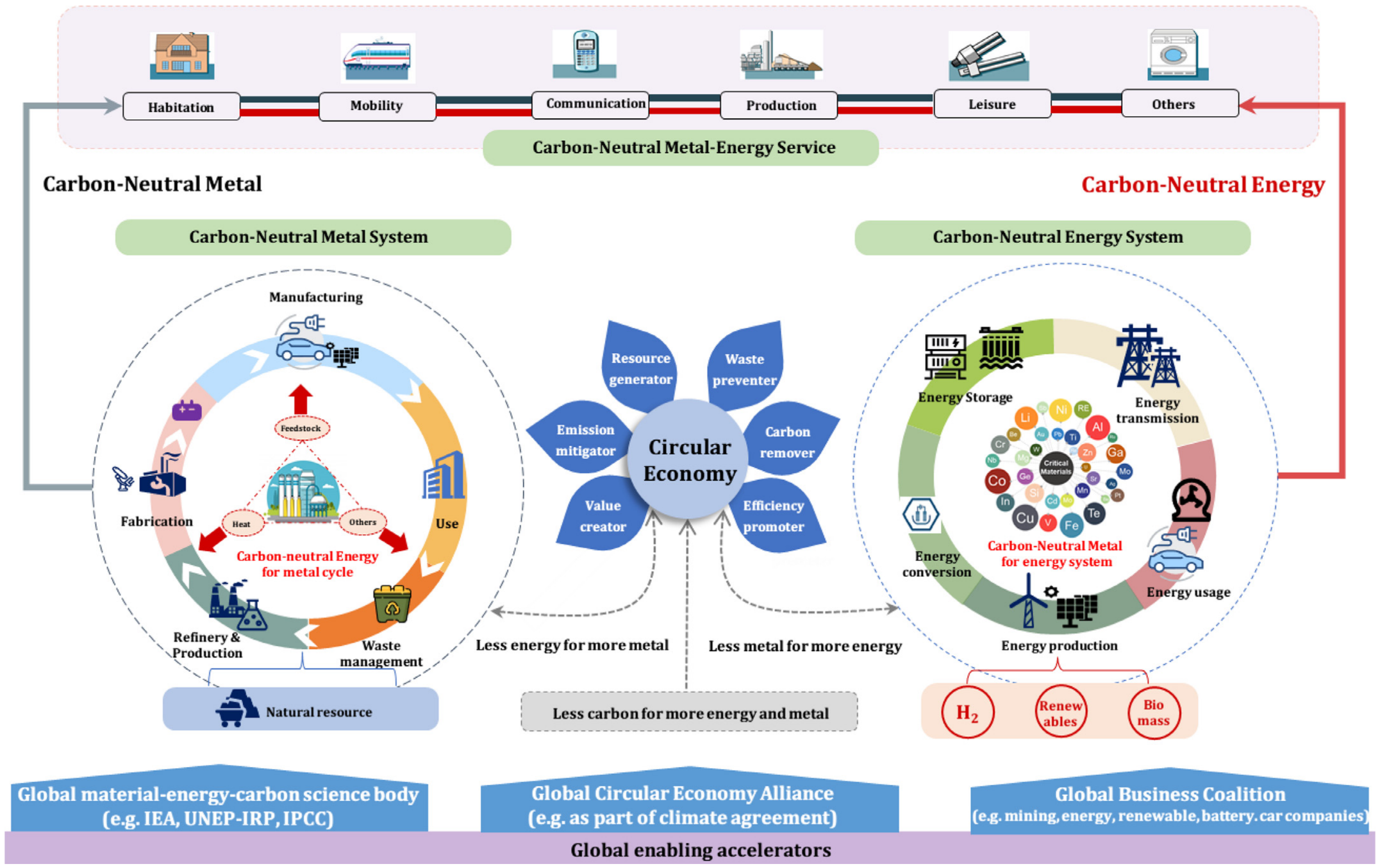

Fig. 2. Circular Metal-Energy Nexus framework to accelerate the carbon-neutral transition. (The transition to a carbon-neutral future can be facilitated not only through the expanded use of more diverse low-carbon energy sources and metals but also by relying on more circular designs of metals and energy sources as a whole)

are mainly focused on expanding renewables, electrification, storage, and coal(fuel) phasing-out [7]. However, material industries that require high-temperature heat with significant process emissions [3] may not be decarbonized based on predominant approaches. Additionally, industrial production processes are highly integrated; therefore, any change in one part of the process must be accompanied by changes in other parts. Industrial facilities have relatively long lifespans (up to 50 years), thereby making decarbonization costly. Without more efforts in steering energy transition towards material needs, the continued high levels of material production will induce a rapid increase in total energy demand, most of which will remain as fuel or hard-to-decarbonated emissions by 2050 (Fig. 1d).

4. Towards a circular metal-energy nexus

A carbon-neutral energy system (or carbon-neutral metal system) cannot be achieved separately, and a nexus-based understanding is urgently needed. The circular economy (CE) is a holistic vision for responding to these requirements simultaneously. It includes various strategies, such as better recycling, remanufacturing, and reuse, to ensure that products, materials, and components are of the highest utility and value at all times. Here, we propose a *circular metal-energy nexus* (C-MEN) to encourage the global implementation of CE strategies for the amplification of metal-energy services to provide various societal services towards carbon neutrality. As shown in Fig. 2, this C-MEN framework contains three key linkages: (a) the demand for carbon-neutral metals and energy to provide carbon-neutral services (i.e., habitation, mobility, communication, etc.); (b) the need for the carbon-neutral transition of both metal and energy systems by themselves for GHG reduction; (c) the implementation of CE to promote such carbon-neutral transition of energy, metal, and their joint system as a whole.

Such a C-MEN framework can directly benefit the direct decarbonization of energy and metal systems as follows: first, it can help reduce critical metal demand ("less metal for more energy") through strategies such as material efficiency design, lifetime extension, service efficiency, and shared economy [2]. In addition, circular flows can reduce energy needs, and the development of a CE system for material reuse and recycling can accelerate renewable integration, particularly in hard-to-decarbonize sectors (e.g., 80% of that for steel production [1]). A shift to secondary metals may allow a greater percentage of the entire material system to be electrified from renewables [3]. Meanwhile, under CE guidance, some new models, such as the sharing economy, industrial symbiosis, and lightweight design, may significantly affect the supply and demand of energy as well as metals [2].

By linking CE to the metal-energy nexus, the C-MEN framework can also benefit the decarbonization of other services. According to the Ellen McArthur Foundation [10], efforts to combat climate change through energy system transitions can only address 55% of global GHG emissions, and the remainder, including material production, can be reduced through CE strategies. In addition, CE can help regenerate natural systems to sequester more carbon from the atmosphere [1]. In addition to protecting the environment, C-MEN is capable of providing financial benefits. For instance, strategies such as reusing, restoring, and remarketing modules, products, and components can help manufacturers minimize costs, increase profits, and enhance competitiveness [10]. In turn, this could attract higher investments and accelerate the move towards renewables.

In most cases, however, this CE-based thinking is not covered or perceived as an afterthought for low-carbon technology manufacturers. At present, massive quantities of critical metals and composites are being extracted, processed, and deployed in increasingly complex low-carbon technologies, yet there is no evidence that they are designed to be disassembled, recovered, and returned to the material and product value chain. If low-carbon infrastructure is not properly managed, waste crisis is inevitable (Fig. 1b). According to our estimates (Supporting Material), the market for recovered materials from low-carbon energy products alone could total $121 million by 2030 and $32 billion by 2040 in China. Nevertheless, if present low recycling rates continue, the retired battery waste, wind turbine blades, and solar panel modules instead could increase with an annual compound rate of 135% from 9.2 thousand tons to 3.96 million tons by 2040. Thus, a joint research-business-government effort under the C-MEN framework is required, as highlighted in Fig. 2.

5. Concluding remarks and global efforts

There is not much time to reverse the trend of ever-increasing GHG emissions. For a carbon-neutral future, all relevant stakeholders along the material and energy supply chains must work together to manage synergies and to plan their priorities. Material circularity at the global level can notably facilitate achieving energy transitions and climate targets. Globally coordinated efforts, such as technology transfer and emissions trading for material-intensive supply chains, are urgently needed because the climate crisis is a global challenge, and raw materials and low-carbon technologies are widely traded products in the international market.

Three global actions are proposed here to leverage such a circular metal-energy nexus (Fig. 2): first, a global organization that compiles CE energy knowledge and solutions from research and different international organizations (e.g., IEA, UNEP, IPCC) and spreads it to policymakers and businesses across the globe to provide a set of new analytical tools, policies, and approaches that support fully circular and carbon-neutral economies. In particular, the International Resource Panel (IRP) of the UNEP is a good candidate for this linkage. Second, a global CE platform is needed to promote cooperation and reduce conflicts among sectors and regions with respect to critical metal and renewable sources. The EU's proposal for a 'Global Circular Economy Alliance' can be incorporated into climate agreements for this purpose . Under such an alliance, some policy mandates (e.g., recycling standards and material choice regulations) and joint grants can be used to make early investments in the circular design and treatment of low-carbon products. Finally, we need to build a global business coalition composed of major mining, metallurgical, material, renewable energy, electric vehicles and batteries, finance, and waste management companies, which can act as the main promoters to ensure a low-carbon, circular, and stable international supply chain of metals and energy.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest in this work.

Acknowledgments

This study is supported by the National Natural Science Foundation of China (Grants No. 71904182, 41871204, and 71961147003). P.W. acknowledges support from the CAST Young Elite Scientist Sponsorship Program.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fmre.2022.02.003.

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