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VIEWPOINT

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Emerging roles of liquid metals in carbon neutrality

In September 2020, China committed to peaking its carbon dioxide emission before 2030 and achieving carbon neutrality before 2060. China, as one of the largest energy-consuming and carbon-emitting nation in the world, contributes to approximately one-third of the world's carbon dioxide emissions. In 2020, the total equivalent carbon dioxide emission in China was approximately 13 Gt, including 11 Gt from the energy industry. The primary sources of carbon emissions include power and heat generation, industry, transportation, and buildings, which constitute approximately 48%, 36%, 8%, and 5% of the carbon emissions in the energy system, respectively [1]. To achieve peak carbon dioxide emission by 2030, the following three aspects must be prioritized: improvement in energy efficiency, promotion of renewable energy, and reduction in coal consumption [2].

Technological innovation is a significant driving force for achieving carbon neutrality. Currently, low-melting-point liquid metals have emerged as an important research topic as they exhibit a strong potential to contribute to carbon neutrality [3]. The advantages of liquid metals, such as low melting point, high thermal/electrical conductivity, unique catalytic properties, fluidic nature, and non-toxicity, render them extremely suitable in the fields of green energy and carbon neutrality [4–11]. Herein, liquid metals refer to low-melting-point alloys (primarily Ga- and Bi-based alloys) and their composites. Based on different mechanisms, their use can significantly contribute to reducing carbon emissions from primary sources, including power generation, industry, transportation, and buildings. Typical liquid metal technologies for carbon neutrality are shown in Fig. 1.

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(1) Power generation

To achieve carbon neutrality, renewable energy generation (primarily wind and solar photovoltaics) is expected to increase 6-fold between 2020 and 2060, thereby contributing to approximately 80% of the total power generation in 2060 [1]. Owing to their superior convective heat transfer coefficient (> 10000 W/(m^2·K)), high boiling point (> 1500 °C), and electromagnetic driving characteristics, liquid metals can be used in solar-concentrating photovoltaic applications and dish solar-power generation [12]. High-performance liquid-metal cooling not only enhances the energy conversion efficiency of photovoltaic cells, but also improves the system stability. For example, such a system can manage a heat flux density of 100 W/cm^2 (i.e., a concentration level of approximately 1000 suns) and significantly increase the power output per cell area [13–15]. Moreover, liquid-metal convection based on Bi- or Sn-based alloys is particularly appropriate for high-temperature tower and dish solar thermal power systems (> 600 °C) [16]. Compared with molten salts, liquid metals exhibit higher boiling points and thermal conductivities, which makes it possible for high-temperature heat transfer and power generation with higher efficiency.

High-efficiency and low-cost energy storage systems are key for addressing the intermittency of wind and solar power. Liquid-metal batteries offer promising prospects in this regard owing to their flexible structure, low cost, facile cell fabrication, and long cycle life. Liquid-metal batteries are electrochemical cells composed of three liquid layers. Their liquid-liquid interface endows them with superior kinetic transfer characteristics and operations at high current densities of up to 2 A/cm^2 [17]. Their liquid-metal electrodes eliminate dendritic growth and make long cycle life possible. Typical liquid-metal batteries used for grid-scale energy storage are based on Mg–Sb, Li–Sb–Pb, Li–Sb–Sn, and Ca–Mg–Bi electrodes [18,19]. These batteries operate at high temperatures (200–600 °C). Furthermore, their energy densities and material costs are 100–200 Wh/kg and 60–300 \$/kWh, respectively [20]. Significant efforts devoted to electrode design and interfacial chemistry have enhanced the

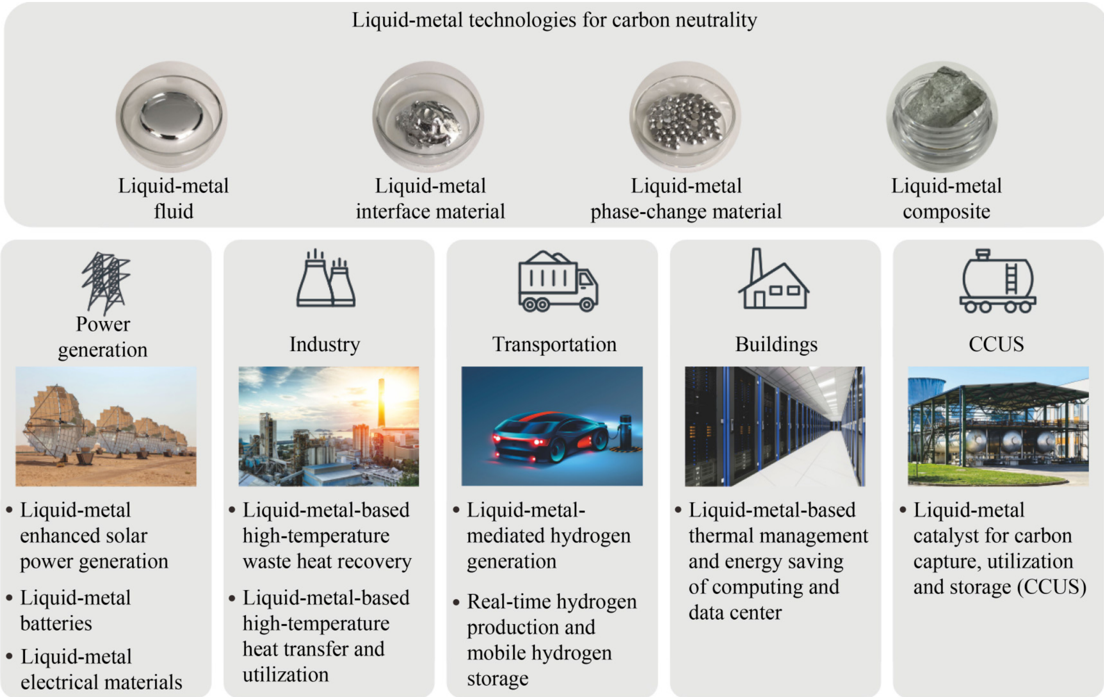

Fig. 1 Typical liquid-metal technologies for carbon neutrality.

potential of liquid-metal batteries as candidates for future large-scale energy storage systems.

Recently, liquid-metal electrical interface materials have garnered significant attention as alternatives for reducing power transmission loss. Their conductivities (approximately 5×10^6 S/m) are superior to those of the conventional conductive pastes [21]. Compared with conventional conductive pastes, liquid-metal electrical interface materials can reduce cable contact resistance by approximately 30%, thereby significantly reducing grid electrical losses and improving system safety. Because the grid line loss constitutes 3%–5% of the total transmitted electrical energy, the energy-saving effect of liquid-metal electrical interface materials in the power grid is expected to contribute to an annual CO_2 emission reduction of approximately 10 million tons [3].

(2) Industry

Herein, industry primarily refers to production of major bulk materials, such as crude steel, cement, aluminum, paper, and primary chemicals. Energy conservation is important to reduce industrial carbon emissions. In high-temperature industrial applications, liquid-metal waste heat recovery offers outstanding advantages, such as high convective heat transfer performance and excellent stability at high temperatures (> 1000 °C). Conventional rapid cooling of high-temperature steel slags is typically achieved by spraying quench water, which results in a significant heat wastage. Liquid-metal fluids can effectively cool steel slags from 1500 to 700 °C and produce saturated or superheated steam, which is subsequently used in steam turbines for power generation. For a typical liquid-metal-based waste heat recovery system with a steel slag processing capacity of approximately 50 tons per day, the annual revenue (steam production and water saving) can exceed US$ 200000, with a system cost of approximately US$ 500000. In terms of environmental benefits, more than 10000 tons of water can be conserved, and carbon emissions can be reduced by approximately 1000 tons per year [3].

(3) Transportation

Hydrogen powered fuel cell vehicles/boats/airplanes are important for long-distance transportation. Liquid metal-mediated hydrogen generation exhibits high energy density and environmentally friendly characteristics. Therefore, it is a promising method for supplying power to cars, underwater vehicles, airplanes, and rockets [22,23]. Liquid-metal-based hydrogen generation compounds (LMHGCs) are composed of Al and Ga–In–Sn alloys. LMHGCs, which cost 3–10 $/kg, can achieve a hydrogen yield of 1 m^3/kg when reacting with water [3]. Liquid-metal-mediated hydrogen generation makes on-demand and timely hydrogen production possible. This obviates the requirement of a hydrogen storage tank and avoids the risk of the high-pressure storage of flammable gases. Although LMHGCs produce approximately 40% less mechanical energy than gasoline and are relatively expensive, they offer an environmentally friendly driving process that does not involve greenhouse gas emissions [3]. Moreover, the reaction products can be recycled and the system can be optimized to further reduce costs.

(4) Buildings

Heating and cooling constitute approximately 65% of the total energy consumption of buildings in China. For computing and data centers, cooling directly determines the energy consumption and carbon emissions. Liquid-metal thermal interface materials (TIMs) represent a significant advancement in the interfacial heat transfer field, and can efficiently cool high-power chips and reduce cooling power consumption. The thermal conductivities of liquid-metal TIMs (10–80 W/(m·K)) are much higher than those of conventional TIMs, thus guaranteeing a better cooling performance [24]. For a typical chip with a heat flux of 10 W/cm^2 used in a data center, the chip temperature can be reduced by 10 °C when liquid-metal TIMs are used instead of conventional silicone grease. Therefore, the supply air temperature of the cooling system can be increased, thereby resulting in a 20%–40% reduction in cooling energy consumption. Based on the considerable energy consumption of data centers, large-scale application of liquid-metal TIMs is expected to reduce carbon emissions by tens of millions of tons per year in China. Currently, liquid-metal TIMs are economically viable and valuable for building energy conservation applications, such as data centers, digital currency mining machines, and light emitting diodes.

(5) Carbon capture, utilization, and storage (CCUS)

By 2060, the CCUS technology will fully offset the remaining emissions from the industrial and transportation sectors. Liquid-metal catalysts can promote a continuous electrocatalytic reaction that converts CO_2 to solid carbon species at room temperature [25]. Liquid-metal catalysts are prepared using active metals (Ce) dissolved in low-melting-point metal solvents, such as Ga, Sn, Bi, and In. Because carbon floats continuously on the surface of a liquid metal, liquid-metal catalytic systems are extremely resistant to deactivation via coking, which is the primary problem encountered while using solid catalysts. For large-scale application, this negative emission technology can produce carbonaceous materials used as electrode materials for energy storage batteries. Therefore, this liquid-metal electrocatalytic process provides a practical method for carbon capture and utilization.

To achieve decarbonization of the entire energy system, a series of extensive techniques must be deployed while considering both the requirements of the energy system and the conditions in China. According to the carbon neutrality blueprint of 2060, approximately 40% of the techniques are still in the prototype stage [1], which provides an opportunity for the development of emerging liquid-metal-based carbon-neutral technologies. Their future outlook can be summarized as follows:

(1) Scientific and technical challenges. Currently, liquid metals are primarily used for academic research. To promote their industrial application, more investigations regarding material database, performance optimization, large-scale production, and long-term reliability, including low-temperature expansion, high-temperature corrosion, and oxidation failure, must be performed.

(2) Reserves and economic feasibility. Herein, liquid metals refer primarily to the low-melting-point Ga- and Bi-based alloys. Ga-based liquid metals generally have lower melting points (< 30 °C) and are more expensive (150–300 $/kg) than Bi-based liquid metals (50–100 $/kg). Therefore, Ga-based liquid metals are preferred for room-temperature applications with a high added value, such as interface materials [24] or room temperature liquid metal battery [26,27]. In contrast, Bi-based liquid metals are more suitable for high-temperature and cost-sensitive energy applications, such as solar thermal power generation. For large-scale applications, although Ga is expensive, the supply of Ga is comparable to that of Ni and Cu and exceeds that of Sn and Pb in the Earth's crust [27]. This indicates a potentially high supply and low cost in the future.

(3) Policy strategy. Considering the diversity of liquid-metal-based carbon-neutrality technologies, each technique should be evaluated to match the conditions (industrial layout and policy) and advantages (high Ga/In/Bi reserves and advanced manufacturing industry) of China. For technologies that involve significant initial investments, such as solar thermal power and waste heat recovery, appropriate economic policies can be implemented to promote these innovations. In terms of mature technologies with a high market competitiveness, such as liquid-metal TIMs, intellectual property protection and fair access to the market can facilitate the development and commercialization of these technologies.

Currently, liquid-metal technologies afford unique applications and advantages in achieving carbon neutrality. The global demand for beautiful ecology, as well as further collaboration among physicists, chemists, materials scientists, and engineers, will promote the development of liquid-metal technologies in the field of carbon neutrality.

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